# Prices vs quantities for the development of clean technologies: The role of commitment

Juan-Pablo Montero*

February 18, 2010
*** FIRST DRAFT – INCOMPLETE***

**Abstract**

It is widely accepted that one of the most important characteristics of an effective climate policy is to provide firms with credible incentives to make long-run investments in R&D that can drastically reduce emissions. Recognizing that a government may be tempted to revise its policy design after innovations become available, this paper compares the performance of two policy instruments in such a setting: prices (uniform taxes) and quantities (tradeable pollution permits). In the case of drastic innovations, I show that the combination of (auctioned) permits and subsidies to firms adopting the new technology allows the regulator to implement the social optimum. Taxes, on the other hand, perform poorly because of commitment problems and the fact that subsidies provide no extra gain. In the case of modest innovations, a government that can commit to its policy design can still implement the social optimum with a combination of (auctioned) permits and subsidies. And if the government cannot commit, it makes no difference whether it uses prices or quantities.

## 1 Introduction

It is widely accepted that one of the most important characteristics of an effective climate policy is to provide firms and individuals with credible incentives to make the long-run

*Associate Professor of Economics at the Pontificia Universidad Catolica de Chile (jmontero@faceapuc.cl).

investments in R&D and capital equipment that will be needed to reduce emissions; see, for example, the articles in Aldy and Stavins (2007). A climate policy will be unable to induce such investments unless it is clear that the policy is likely to be enforced and is unlikely to be loosened up or repealed in the future.

There is a vast literature studying how different environmental policies provide firms with incentives to develop and adopt cleaner technologies (e.g., Requate, 2005; Popp et al., 2009). Following practical experience (Stavins, 2003), most studies look at the performance of relatively simple policy instruments aimed at polluting sources such as standards, linear (Pigouvian) taxes and tradeable permits. It is also generally assumed that R&D is carried out by the same polluting firms in an effort to reduce their abatement costs. If this is so and polluting firms are small (i.e., non-strategic), a completely informed regulator can implement the first-best amount of R&D and pollution by either using prices (i.e., linear tax) or quantities (i.e., tradeable permits).[1]

In this paper I focus on the more relevant problem for climate change, and for many other environmental problems as well, which is that innovations are developed by parties other than polluting firms (Requate, 2005). For simplicity I assume there is a single innovator who licenses its innovation to polluting sources facing an environmental policy that take the form of either prices or quantities; later I also allow the regulator to combine prices and quantities *a la* Roberts and Spence (1976). Central to the analysis of policy choice and design is the regulator's ability to credibly commit to its policy design for a long period so that the innovator can be adequately compensated for its investment (the choice of instrument cannot be revised).

The paper closest to mine is Laffont and Tirole (1996b) who consider a single innovator that with some probability can invent a pollution-free technology.[2] Polluting firms can either buy permits, adopt the pollution-free technology (when is available) or shut down production. The authors argue that stand-alone spot markets for pollution permits provide no R&D incentives at all because the regulator can expropriate the innovation ex-post by offering a competing "technology" (pollution permits) and putting an arbitrary downward pressure on the licensing price. They show then that the social optimum can be implemented by issuing options to pollute instead of permits. I depart from such

[1] See, for example, Laffont and Tirole (1996a). If there are spillovers the regulator is still indifferent between prices and quantities. Obviously, she is not if there are information asymmetries (Weitzman, 1974).

[2] Denicolo (1999) also builds upon Laffont and Tirole (1996) to asks questions similar to mine. Hepburn (2006) also offers a discussion of the importance of commitment and credibility for the choice between different policy instruments.

framework in several directions. First, I stick to simple instruments –taxes or (plain) permits– that eventually could be combined. Second, I model the invention as a more continuous process. This is important as we can distinguish between drastic innovations and more modest innovations.

After setting up the model in Section 2, I then explain, in Section 3, that prices and quantities are not always equivalent ex-post, that is, after the innovation has been developed (i.e., the no commitment case), but it very much depends on the type of innovation. Suppose, for example, that the innovator has developed a pollution-free technology. It is socially optimal ex-post to widely diffuse the technology and to completely phase out pollution. In a tax regime this can be done by lowering the tax level, possibly to zero if there are no adoption costs, and forcing the innovator to license its technology at or slightly below the tax level. This cannot be achieved with permits, so the innovator can retain a large part of its rents. Issuing more permits puts downward pressure on the licensing price but also lowers the price of existing permits (which remain in the market) making it impossible to simultaneously diffuse the pollution-free technology and phase out pollution. As we lower the quality of the innovation (i.e., the new technology can only remove a lower fraction of a firm's emissions) the trade-off between lowering the licensing price and allowing more pollution disappears because the innovator becomes "capacity constrained" in that its (lower-quality) technology perfectly complements with permits (unlike with the pollution-free technology a firm that adopts a lower-quality technology must also buy permits). Here, the regulator can implement the ex-post social optimum with either prices or quantities.

In Section 4 I consider the case in which the regulator can commit to its policy design. Commitment always improves welfare in a price regime by eliminating the regulator's incentives to expropriate the innovation ex-post. The same applies in a quantity regime that produces lower-quality technologies. Surprisingly, commitment may be detrimental for both the regulator and the innovator in a quantity regime with drastic innovations. In this case the government would not like to commit ex-ante but let the firm innovate first and issue permits after. When innovations are drastic the innovator and the regulator know that the latter will react with a very low issuance of permits (below the ex-ante first best) which encourages the innovator to develop those drastic technologies. The government does not want to commit to such low issuance of permits ex-ante because it will not induce as near the amount of innovation it does when the government moves ex-post. A numerical exercise illustrates some of the results.

In Section 5 I consider the possibility of combining prices and quantities; in particular, combining taxes or permits with a subsidy to polluting firms adopting the new technology (I also allow for imperfect monitoring). The use of subsidies offers no gain in a tax regime because taxes and subsidies are perfect substitutes for a regulatory point of view. On the other hand, permits and subsidies complement perfectly well so the government can implement the first best if it can commit to it. But even if the government cannot commit to its policy design it come close to implement the first-best for the case of very clean technologies. Ex-post the government does not want to remove the subsidies (and increase the number of permits) because it is the only in which it can induce the socially optimal diffusion of the new technology. When the new technology is of low quality the government wants to expropriate the innovator ex-post by removing the subsidies and increasing the number of permits. So in the absence of commitment (and for low-quality innovations) we are back to pure permits which are not different than taxes.

Extension to uncertainty is in Section 6. Many of the results of previous sections carry through. It is not obvious, however, how to combine permits and subsidies to achieve the first best. Section 7 concludes emphasizing the advantage of permits combined with subsidies over taxes. In the case of drastic innovations, the combination of permits and subsidies allow the regulator to implement the social optimum regardless of its ability to commit to future policies. In other words, its policy design is time consistent. Taxes on the other hand perform poorly —not so bad if governments can commit— because they work too good ex-post. In order to prevent the government to run large deficits as a result of the subsidies permits should be auctioned off. In the case of moderate innovations, a government that can commit to its policy design can still implement the social optimum with a combination of (auctioned) permits and subsidies, most likely running a surplus. And if the government cannot commit, it makes no difference whether it uses prices or quantities.

# 2 The model

## 2.1 Notation

There are two periods, $t = 1, 2$, a continuum of polluting firms of mass one. For notational simplicity I abstract from discounting and first-period pollution. In the absence of regulation each firm produces a unit of output for a perfectly competitive output market and emits one unit of pollution. A firm's valuation for polluting one unit is $\theta \in [0, 1]$, that is, $\theta$ is the profit obtained by the firm when producing and polluting one unit.

Alternatively, $\theta$ can be viewed as the firm's cost of abating pollution. Valuations are distributed according to the cumulative distribution $F(\theta)$, with density $f(\theta)$. I make the usual assumption that $(1 - F)/f$ is nonincreasing in order to ensure concavity of the social welfare function. In some places I will also use that the demand for pollution is not too convex, that is, $f(p) + pf'(p) > 0$.[3] The government does not observe an agent's individual valuation $\theta$ but knows the distribution $F$ and observes who pollutes and by how much.

I model the innovation in clean technologies in a relatively simple way. Among other things, I abstract from competition among potential innovators; that would only add complexity (and need for additional instruments) without altering the central message of the paper. Thus, I consider one potential innovator, who at private cost $I(x)$ incurred at date 1 can develop the technology $x \in [0, 1]$ that removes a fraction $x$ of a firm's emissions and where $I(0) = 0$, $I'(x) > 0$ and $I''(x) > 0$. In Section 6 I replace this deterministic R&D process by an stochastic one where at cost $I$ the innovator develops technology $x$ or superior with probability $G(x|I)$. Higher investment $I$ makes the development of a cleaner technology (i.e., higher $x$) more likely in the sense of first-order stochastic dominance: $\partial G(x|I)/\partial I \leq 0$. Both functions $I(x)$ and $G(x|I)$ are also known by the government. The technology $x$ becomes available at the beginning of date 2. Polluting firms pay a license fee $r$ to the innovator for the new technology and incur in an arbitrarily small but positive cost $\varepsilon$ to install it (for most part of the analysis we can set this adoption cost to zero). I am also implicitly assuming here that the innovator's invention cannot be imitated, either because it is not feasible or because it is protected by a patent.[4]

The social damage of an additional unit of pollution is constant and equal to $h < 1$, so even in the absence of innovation it is socially optimal to have some pollution. To rule out uninteresting cases, I further assume that $h$ is not too large; more specifically, $h < (1 - F(h))/f(h)$. This implies that an innovator with a pollution-free technology (i.e., $x = 1$) would, if unconstrained, price above $h$.[5]

The government's objective is to regulate pollution but also to provide the innovator with incentives to develop cleaner technologies. Following the environmental policy approaches we observe in practice (Stavins, 2003), I restrict attention to policy instruments

[3] The aggregate demand for pollution is $D(p) = 1 - F(p)$, where $p$ is the pollution price.

[4] Again, relaxing this last assumption would introduce new elements to the model without altering the central message of the paper.

[5] Since the new clean technology can be seen as a durable good (unless rented), we are implicitly assuming that the innovator is not fatally affected by the Coase conjecture. There are different ways in which this can happen, e.g., presence of arbitrarily small capacity costs (McAfee and Wiseman, 2008).

aimed at polluting firms; hence, I rule out that the government can sign an ex-ante contract (or negotiate ex-post) with the innovator.[6] More specifically, the government has two instruments at hand to regulate pollution in period 2: either a pollution tax $p$ per unit of pollution or an allocation of $q$ tradeable pollution permits. Permits are allocated for free or auctioned off to a perfectly competitive permits market. In Section 5, I allow these instruments to be combined with a subsidy $s$ to firms adopting the new technology. Note that unless $x = 1$, adopting firms still need to either buy permits or pay taxes to cover their $1 - x$ remaining emissions in period 2.

The government's potential commitment problem is captured by the fact that in period 2, and after the innovation has become available, the government can revise his period-1 policy design by either lowering the tax or issuing additional permits (in principle, it can also revise the policy upwards by either increasing the tax or buying back some permits). If the government decides to revise its policy design in period 2 I will assume that it does so before the innovator licenses his technology to firms. This timing assumes that the government has some minimum commitment power, e.g., that it can revise its policy design not so frequently.[7]

## 2.2 First-best

The government's first-best solution is given by the technology $x$ and pollution level $q$ (or pollution price $p$) that maximize the social welfare function

$$W = -hq + \int_p^1 \theta f(\theta) d\theta - I(x) \tag{1}$$

Since adoption is costless, it is socially optimal to have each operating firm installing $x$; hence, there is an immediate connection between $p$ and $q$

$$q = \int_p^1 (1-x) f(\theta) d\theta = (1-x)[1 - F(p)] \tag{2}$$

[6]REVISAR: As shown by Laffont and Tirole (1996b) the under-investment problem is readily solved if the government can sign an ex-ante contract with the innovator. Such contracts are rarely seen in practice, however, much less for clean technologies. Furthermore, those contracts are not free of commitment problems either. The current administration may refuse to respect a contract signed by the previous administration. This makes is more complicated if the regulator cannot observe investment.

[7]As discussed in more detail below, assuming a different timing (i.e, simultaneous move between the regulator and the innovator in period 2) can change matters.

Using (2), the first-order conditions for $p$ and $x$ are, respectively

$$h(1-x)-p=0 \tag{3}$$

$$h[1-F(p)]-I'(x)=0 \tag{4}$$

Denote by $x^*$ and $p^*$ the first-best technology and price levels that solve (3) and (4). Condition (3) says that the benefit from the last unit of output, $p^*$, is equal to its pollution damage, $h$ times the remaining emissions, $1-x^*$. Since $1-F(p^*)$ is industry output, condition (4), on the other hand, says that technology $x^*$ is stretched to the point where the marginal cost of doing so is exactly equal to the marginal benefit of having a cleaner industry.

# 3 Policies in the absence of commitment

Suppose the innovator has made available at period-2 technology $x$. After observing $x$ and before the innovator licenses his technology to firms, the government is ready to revise its policy. I first analyze prices, which is easier, and then quantities.

## 3.1 Prices

Let $p$ be the tax set by the government in period 2. Given technology $x$, the innovator's best response is to license his technology at price

$$r=\min\{px, r^m(x,p)\}$$

where $r^m(x,p)$ is the "unconstrained" monopoly price, which, assuming efficient rationing, is equal to

$$r^m(x,p)=\arg\max_r \pi=[1-F(r+p(1-x))]r$$

The monopoly price, however, is ruled out by assumptions (i) $(1-F(h))/f(h)>h$, and (ii) $(1-F(\theta)]/f(\theta)$ is nonincreasing.[8] Hence, the innovator's best response is to price at

[8] With these assumptions $\partial\pi/\partial r|_{r=p}=1-F(p)-f(p)p>0$ for all $p\in[0,h]$.

(slightly below) $px$ and sell to all active firms (i.e., $\theta \geq p$). This results in pollution

$$q(p, x) = (1 - x)[1 - F(p)] \tag{5}$$

Anticipating the inventor's price response and (5), the government's chooses the tax $p$ that solves

$$\max_p -hq(p, x) + \int_p^1 \theta f(\theta) d\theta$$

which leads to the first-order condition (3). It is not surprising that the tax instrument implements the ex-post social optimum since it can exert as much downward pressure on the license price as needed.[9] The innovator is forced to widely diffuse his technology (i.e., no rationing) at a price set by the government.

For the same reason the tax instrument works so well ex-post it works poorly ex-ante, i.e., it leaves insufficient rents with the innovator (and zero rents in case he develops the cleanest technology). Consequently, the innovator underinvests relative to the first-best, i.e., $I(x_p^{nc}) < I(x^*)$, where $x_p^{nc}$ denotes the technology developed under a price regime absent of commitment and is equal to

$$x_p^{nc} = \arg\max_x \{p(x)x[1 - F(p(x))] - I(x)\} \tag{6}$$

where $p(x) = h(1 - x)$. It is not difficult to show that $x_p^{nc} < x^*$.[10]

The underinvestment is such that the innovator will never develop anything cleaner than

$$\bar{x} = \frac{1}{2 - \bar{p} f(\bar{p})/(1 - F(\bar{p}))} < 1$$

(where $\bar{p} = h(1 - \bar{x})$) even if R&D is costless. The underinvestment occurs because the government cannot credibly commit not to expropriate the innovator's rents ex-post (a patent protects the inventor from potential imitators but not from the government).

## 3.2 Quantities

Let $q$ be the number of tradeable pollution permits issued by the government in period 2. To find the best the government can do as a function of the available technology $x$ it

[9] Note that if $x = 1$ the government will set $p$ slightly above zero, providing the innovator with enough room to undercut the government's price.

[10] Take the first-order condition that solves for $x_p^{nc}$, which is $h(1 - F(p)) - hx[2(1 - F(p)) - pf(p)] - I'(x) = 0$, and then notice that the term in square brackets is strictly positive, from the assumptions above.

is useful to start by finding the ex-post social optimum because, unlike with prices, it is not obvious that the regulator can always implement it with quantities. From (2) and (3), the socially optimal allocation of permits is (provided that all operating firms have installed the new technology)

$$q^*(x) = (1 - F(h(1-x)))(1-x) \tag{7}$$

This function is plotted in Figure 1.[11]

Consider now the optimal response of an innovator with technology $x$ and after $q$ permits have been issued by the government. When $q$ is sufficiently large, the innovator will find it optimal to ration the supply of the technology, that is, to set a license fee such that only a fraction of active firms adopt the new technology. More specifically, the innovator solves

$$\max_y \pi(y) = yp(x, q, y)x \tag{8}$$

where $y$ is the number of licenses sold in equilibrium, $p(x, q, y)$ is the equilibrium price of permits and $xp(\cdot) = r$ is the license fee charged by the innovator. Solving (8), we find that in this "rationing" equilibrium the innovator will sell

$$y^m = \frac{p(\cdot)f(p(\cdot))}{x} < 1 - F(p) \tag{9}$$

licenses at price $p(\cdot)x$. The equilibrium price of permits $p(x, q, y)$ is found from the market clearing condition in the permits market, that is

$$1 - F(p) = q + yx \tag{10}$$

Depending on $x$ and $q$, there will be a point where the innovator just rations his supply of the clean technology, i.e., where $y^m = 1 - F(p) = q/(1-x)$. Using (9) and (13), the combinations of $q$ and $x$ that just induce "rationing" are given by

$$F^{-1}\left(1 - \frac{q}{1-x}\right) f(F^{-1}(\cdot)) = \frac{qx}{1-x} \tag{11}$$

Denote by $q^r(x)$ the solution of (11), which is also plotted in Figure 1 along with function $q^*(x)$ (I will shortly come back to the observation that $q^r(x)$ necessarily crosses $q^*(x)$ at

[11] Note that $\partial q^*(x)/\partial x = -[1 - F(h(1-x))] + h(1-x)f(h(1-x)) < 0$

some interior value of $x$).[12] Thus, for any combination of $q$ and $x$ to the left of curve $q^r(x)$, the innovator is "capacity constrained" in that it sells his technology to all possible active firms, i.e., $y = q/(1-x) = 1 - F(p(\cdot))$. We can say that in this region permits and clean technology work as perfect complements. Conversely, for any combination of $q$ and $x$ to the right of $q^r(x)$, the innovator rations supply, i.e., $y < q/(1-x) = 1 - F(p(\cdot))$. Here permits are a perfect substitute for the new technology, so the innovator optimizes along the residual demand $1 - F(p) - q$ and the price of permits becomes independent of $x$ and given by (from (9) and (10))

$$p = \frac{1 - F(p) - q}{f(p)} \tag{12}$$

It remains to determine what is the government's best response for any given $x$ and anticipating the innovator's pricing reaction. To facilitate the discussion let $x$ technology level where $q^*(x)$ and $q^r(x)$ cross (see Figure 1), i.e.,

$$\hat{x} = \frac{\hat{p}f(\hat{p})}{1 - F(\hat{p})} \tag{13}$$

where $\hat{p} = h(1 - \hat{x})$. Furthermore, we will say that a technology development is drastic when $x > \hat{x}$ and modest when $x \leq \hat{x}$. Note that I am using the terms drastic and modest in a very loose way; for example, if $F(\theta)$ is uniform and $h = 1/3$ then $\hat{x} = 0.3$, which is not particularly clean. More importantly for our analysis, when the innovation is modest the government has no problems in implementing the ex-post social optimum: it will issue $q = q^*(x)$ permits, resulting in the first-best equilibrium price $h(1 - x)$.

The government's response is a bit more involved when the innovation is drastic. The government cannot longer implement the ex-post social optimum because that is in the innovator's rationing zone. So in principle, the government would pick a number of permits independent of $x$ as follows

$$q^0 = \arg\max_q \{-hq + \int_{p(q)}^{1} \theta f(\theta) d\theta\}$$

where $p(q)$ is implicitly given by (12). As shown in Figure 1, $q^0$ is always strictly smaller than $\hat{q} \equiv q^*(\hat{x})$ and in many cases is equal to zero;[13] for example, for a uniform $F$ and

[12] Note that if $F(\theta)$ is the uniform distribution then $q^r(x) = (1-x)/(1+x)$.

[13] In fact $q^0 < \hat{q} \Longleftrightarrow [1 - F(\hat{p})][f(\hat{p}) + \hat{p}f'(\hat{p})] + \hat{p}f^2(\hat{p}) > 0$, which holds for any demand function that is not too convex.

$h \geq 1/4$. However, since the government would like to come as close as possible to the (ex-post) first-best, it can do better and pick $q^r(x)$ instead of $q^0$ for those cases in which $q^r(x) > q^0$. Thus, the government's best response is to issue $q = q^r(x)$ when $x \in [\hat{x}, x^0]$ and $q = q^0$ when $x \in [x^0, 1]$. In what follows I neglect this latter case by assuming that $q^0 = 0$ (and hence $x^0 = 1$) (we are basically saying that $h$ is not too small; assuming otherwise would introduce more notation without adding much to the problem).[14]

We can summarize this discussion in the following proposition

**Proposition 1** *Prices and quantities are ex-post equivalent for "modest" innovations (i.e., when $x \leq \hat{x}$). When innovations are "drastic" (i.e., $x > \hat{x}$) quantities lead to less diffusion of the clean technology, less output, less pollution and more rents to the innovator.*

The proof is relegated to the appendix but it basically consists in showing that Figure 1 is qualitatively correct; more specifically, that $q^*(x)$ crosses $q^r(x)$ from above. To gain intuition for the proposition it helps starting with the case in which the innovator has developed a pollution-free technology, i.e., $x = 1$. It is ex-post socially optimal to diffuse the technology to all firms and to completely phase out pollution. In a tax regime this can be done by lowering the tax level to virtually zero (only slightly above the adoption cost $\varepsilon$) forcing the innovator to license its technology at even lower price (enough to cover the adoption cost). All firms adopt the new technology and pollution is completely phased out. It is clear that this same outcome cannot be achieved with quantities. One way to force the innovator to license its technology to all firms for "free" is by issuing $q \geq 1$ (i.e., total emissions in the absence of regulation) and setting $\varepsilon = 0$ (through an adoption subsidy perhaps; something we will come back in Section 5). One possible equilibrium in such scenario —after the government has issued $q \geq 1$ permits and the innovator has priced her technology at $r = 0$— is that all firms adopt the new technology and the totality of permits remain unused (this is the equilibrium adopted by Laffont and Tirole (1996b) in their Proposition 1 and where $\varepsilon = 0$). But another equally plausible equilibrium is that no firm adopts the new technology but instead all firms cover their emissions with (free) permits. Either equilibrium is equally good from the perspective of a firm but not from the government's. Obviously, there is also a continuum of equilibria with partial adoption.

[14] A worth observation perhaps for the case in which $q^0 > 0$ is that the government is willing to issue pollution above the ex-post social optimum when a highly clean technology (i.e., $x > x^0$) becomes available, only because that would increase industry output at the expense of reducing the diffusion of the new technology.

This multiplicity is eliminated here, however, because $\varepsilon > 0$.[15] Therefore, if the government issues $q \geq 1$,[16] the permit prices would collapse to zero and there would be nothing the innovator could do to outcompete the permits at non-negative profits. Furthermore, if the government issue $q < 1$ (but close to the unity) with the idea to generate a small but positive permit price that could report the innovator non-negative profits, the innovator would not sell to the entire industry (that would collapse the price to zero) but to a fraction of the residual demand $1 - q - F(p)$ at price (12). Therefore, the idea that the government can replicate with quantities what he can do with prices is simply not possible (unless one believes in an equilibrium where the totality of permits issued remain unused). Then, if a pollution-free technology comes available, the best the government can do is to issue no permits (because $q^0 = 0$) and let the innovator to price its technology at the monopoly price.

Unlike the tax, the quantity instrument is a costly instrument to exercise downward pressure on the license price for a pollution-free technology —or for any technology $x > \hat{x}$ for that matter— because the adoption of the technology does not remove the permits issued by the government. This provides the innovator with a credible protection against ex-post expropriation by the government. It is then immediate that

**Proposition 2** *In the absence of commitment quantities provide more incentives for the development of "drastic" technologies than do prices (and equal for "modest" technologies).*

In some cases, when $h$ is relatively low, incentives for the development of drastic technologies can be beyond first-best levels, leading to $x_q^{nc} > x^*$.[17]

Propositions 1 and 2 present a clear trade-off between prices and quantities that prevents an unambiguous welfare ranking in the absence of commitment: prices provide fewer innovation incentives for the development of drastic technologies but are always ex-post efficient (i.e., static efficient) unlike quantities.

[15] Timing is also a powerful refinement even when $\varepsilon = 0$. Since permits are allocated before the technology is licensed to firms, why would any firm bother adopting the new technology if it has already enough permits to cover its emissions?

[16] Note that according to this logic the government would also need to issue $q \geq 1$ if $x < 1$.

[17] For example, if $F$ is uniform, $h = 1/4$ and $I(x) = cx/(1-x)$ with $c = 0.01$, we have that $x^* = 0.79$ and $x_q^{nc} = 0.81$. But if $h = 1/2$, then $x^* = 0.85$.

### 3.3 Timing

We have assumed that the government enjoys some minimum commitment power that allows it to move first in period 2. This seems a reasonable assumption since policies are hardly changed so frequently; much less frequently than prices set by a private party. Yet, it is informative to ask what happens when government and innovator moves simultaneously in the second period. It turns out that prices look very much like quantities (there is no much of a change in the quantity regime). Take for example $x = 1$. If the innovator prices its technology at the monopoly price $1/f(0)$, the government's best response is to set the tax slightly above (for the same reason that $q^0 = 0$).

## 4 Commitment

Consider now a government that at date 1, and before the innovator engages in R&D, announces its policy for date 2 and commits not to revise it. We merge the analysis of both instruments.

### 4.1 Prices and quantities

To understand how instruments perform under commitment it is useful to start with the case in which R&D is almost costless. If so, it is socially optimal to develop a pollution-free technology, or nearly so, and completely phase out pollution. A committed government can achieve the first-best with prices; it needs to set the tax level slightly above zero just to let the innovator break the indifference between undertaking R&D and not. Once the pollution-free technology is developed, the innovator will sell it for almost nothing, serving all firms and completely phasing out pollution.

The same committed government can not achieve the first-best with quantities for the same reason that a government without commitment does not want to expropriate a pollution-free innovation ex-post. The committed government will find it optimal not to issue permits.[18] The innovator will then develop the pollution-free technology and ration its supply to the monopoly level. The price instrument (under commitment) has turned out to be more flexible in accommodating both objectives: providing R&D incentives —but not necessarily higher rents— and allowing wider diffusion of the new technology. The same rationale applies for less drastic innovations, therefore

[18] Strictly speaking, the commited government has more reason not to issue permits than one that is not because it moves first.

**Proposition 3** *Prices perform better than quantities when the government can commit not to revise its policy:* $W_q^c < W_p^c$ *and* $x_q^c < x_p^c < x^*$.

**Proof.** For the proof recall that $x^*$ and $p^*$ are the first-best technology and price levels as defined by the solution of (3) and (4). In a price regime with commitment, the government's optimal policy is

$$p^c = \arg\max_p \{-h[1-F(p)][1-x(p)] + \int_p^1 \theta f(\theta) d\theta - I(x(p))\}$$

where the function $x(p)$ is obtained from the innovator's R&D best-response (recall that $\pi = (1 - F(p))px$)

$$p(1 - F(p)) - I'(x) = 0 \tag{14}$$

Unless $x^* = 1$, it is clear from looking at (4) and (14) that since $x(p^*) < x^*$ the government will choose $p^c > h(1 - x_p^c) > h(1 - x^*)$ in order to bring $x_p^c \equiv x(p^c)$ closer to $x^*$.

On the other hand, the government's optimal policy in a quantity regime with commitment is

$$q^c = \arg\max_q \{-hq + \int_{p(q,x)}^1 \theta f(\theta) d\theta - I(x(q))\}$$

where $p(q, x)$ is the equilibrium price of permits as a function of $q$ and of $x$, if it applies, and $x(q)$ is the innovator's R&D response. Note that the innovator will never operate in the "rationing (or perfect substitute) zone" for any allocation $q$ because that would only increase R&D costs without altering ex-post profits ($\pi$). This implies that equilibrium price $p(q, x)$ is given by

$$1 - F(p(q, x)) = \frac{q}{1 - x} \tag{15}$$

and therefore

$$\frac{\partial p(q, x)}{\partial x} = -\frac{1 - F}{(1 - x)f} < 0 \tag{16}$$

In addition, the innovator's R&D best-response $x(q)$ can be obtained from the first-order condition

$$p(\cdot)(1 - F(p(\cdot)) + x[1 - F - p(\cdot)f]\frac{\partial p(\cdot)}{\partial x} - I'(x) = 0 \tag{17}$$

where $p(\cdot) = p(q, x)$. Denote by $x_q^c \equiv x(q^c)$ the solution of (17).

Rather than computing $p^c$ and $q^c$ and then comparing $W_p^c$ and $W_q^c$, I proceed differently. The second term in (17) is negative, so if the government wants to induce with the quantity instrument the same amount of R&D brought forward by the price instrument at its optimum level, i.e., $x(q) = x_p^c$, it must set $q$ such that $p(q, x) > p^c$

since $d[p(1-F(p)]/dp > 0$. But the welfare gain of doing so is negative (despite lower pollution) since $p^c > h(1-x_p^c)$ and hence

$$\frac{\partial}{\partial p}\left(-h(1-F(p))(1-x)+\int_p^1 \theta f(\theta)d\theta\right) = h(1-x)f(p) - pf(p) < 0$$

for all $p \geq h(1-x_p^c)$. Using similar arguments, it can be shown that $p(q^c, x_q^c) > h(1-x_q^c)$. If the government wants now to induce with the price instrument the same amount of R&D brought forward by the quantity instrument at its optimum level, i.e., $x(p) = x_q^c$, it must set $p$ below $p(q^c, x_q^c)$ with the corresponding welfare gain (note that the resulting $p$ would still be above $h(1-x_q^c)$). The price instrument can replicate the R&D outcome of the quantity instrument at a gain but not vice versa. It must then hold that $W_p^c > W_q^c$ and $x_p^c > x_q^c$. ■

The intuition for this results is nicely captured by expression (17). The quantity regime gives the innovator, through his choice of $x$, some flexibility to set the equilibrium price of permits and the total amount of output. This flexibility is a cost for the government who must depart even further from the first-best. And because of this same flexibility, the innovator's rents are necessarily higher under quantities. I present next some are other interesting results that are hard to communicate in closed-form solutions.

## 4.2 Additional (numerical) results comparing instruments

Table 1 shows some additional results using simple functional forms: $F$ uniform and $I(x) = cx/(1-x)$. I also set $h = 1/2$ and let $c$ vary from zero to 1/4, when it is optimal to carry no R&D. Neglect the last column for a moment (we will come back to it in the next section). Recall that "$n$" stands for commitment and "$nc$" for lack of commitment. The first block ($h = 0.5$ and $c = 0$) shows how the performance of taxes vary widely depending on whether the government can credibly commit or not. Permits, on the other hand, face (almost) no commitment problems at the "top", i.e., when the new technology is pollution-free or nearly so. In this particular example the government does not want to issue any permits both ex-ante and ex-post.

The second block ($h = 0.5$ and $c = 0.02$) still falls in the area of "drastic" innovations in the sense that the technology developed under the quantity regime is above $x^c$, the critical level above which the innovator is (partially) protected from expropriation, i.e., cannot be forced ex-post to diffuse its technology to the socially optimal level. It is also interesting to observe that commitment is detrimental for both the government and the innovator in a quantity regime with drastic innovations. In this particular case the government would not like to commit ex-ante but let the firm innovate first and issue permits later. When innovations are drastic the innovator and the regulator know that the latter will react with a very low issuance of permits, which is precisely what encourages the innovator to develop those drastic technologies. The government does not want to commit to such low issuance of permits ex-ante because it will not induce as near the amount of innovation it does when the government moves ex-post. In fact, if the government commits to $q = 0.154$ permits in period 1, the innovator develops an even lower technology, $x = 0.700$.

Numbers in blocks 1 and 2 also illustrate how ambiguous the welfare ranking in the absence of commitment can be. Quantities perform better when R&D costs justify the development of very clean technologies but prices perform better when R&D costs are relatively higher.

The third block ($h = 0.5$ and $c = 0.074$) marks the exact point at which two solutions are possible in a quantity regime without commitment. The innovator is indifferent between the two solutions (see innovator's rents) but the government is not; it strictly prefer the first solution, the one with the better innovation. In the first solution the innovator develops a technology that is above $x^c$ (in this example $x^c = 0.414$), preventing the government from ex-post expropriation in the sense of Figure 1 (i.e., issuing $q^r$ instead of $q^*$). Alternatively, in the second solution the innovator develops, at a lower cost, a lower technology that is below $x^c$ and rationally anticipates the government will issue $q^* < q^r$ in period 2. This second solution involves less R&D but also lower rents ex-post. Note that in a quantity regime without commitment we will never observe technologies in the range of $(1/3, 1/2)$, that is, $x > 1/2$ if $c < 0.074$ and $x < 1/3$ if $c > 0.074$. This technology discontinuity is absent in the price regime.

To complete the table, the fourth and fifth blocks ($h = 0.5$ and $c = 0.15$ and $h = 0.5$ and $c = 0.25$) correspond to cases of modest and no innovation respectively.

# 5 A hybrid instrument

So far we have assumed that the government must pick a single instrument, either prices of quantities. The first in proposing to combine prices and quantities were Roberts and Spence (1976) in the context of asymmetric information. Here however, the combination of taxes and permits provides no gain: taxes dominate permits under commitment and nullify them in its absence. Maintaining the assumption that the government can only target polluting sources, in this section I explore the welfare gain from adding a third instrument —a subsidy to polluting sources adopting the new technology— to be combined with either the tax or the permits. Let $s$ be the subsidy per unit of reduction paid to an adopting firm; thus, a firm adopting technology $x$ gets a total subsidy of $sx$ (the government can just announce this latter). At the end of the section I relax the assumption that the government perfectly monitors who is adopting the new technology.

## 5.1 Prices and subsidies

Regardless of whether the government can commit or not to its policy, after observing tax $p$, subsidy $s$ and technology $x$, the innovator licenses his technology at a price slightly below

$$px + sx = (p + s)x$$

which implies

**Proposition 4** *Subsidies add nothing to prices.*

Taxes and subsidies are perfect substitutes from a regulatory point of view.

## 5.2 Quantities and subsidies

The government combines $q$ permits with a subsidy $s$. To fix ideas, consider first the case in which the government can commit to its policy design $q$ and $s$.

**Proposition 5** *The government can implement the first-best $p^*$ and $x^*$ with the following policy design*

$$q^h = q^* = [1 - F(p^*)](1 - x^*)$$
$$s^h = \frac{1 - F(p^*)}{f(p^*)}x^*$$

**Proof.** All we need for the proof is to show that the above policy design induces the innovator to develop technology $x^*$. As with pure quantities, the innovator will never operate in the "rationing zone", so the equilibrium prices of permits $p(q, x)$ is given by (15). The innovator sells his technology $x$ for $p(q, x)x + sx$, then his (ex-ante) problem is

$$\max_x \pi(x; q, s) - I(x)$$

where $\pi(x; q, s) = [p(q, x) + s]x[1 - F(p(q, x)]$. Replacing $s^h$ and $\partial p/\partial x$, as given by (16), into the innovator's first-order condition we obtain the first-order condition (4). ■

Quantities and subsidies complement perfectly well. While quantities are aimed for static efficiency (for any given technology level), the subsidy plays the dual role of providing innovation rents and diffusion incentives. For instance, if R&D is costless, the innovator will anyway develop the pollution-free technology but it is the subsidy $s = 1/f(0)$ that generates its full diffusion. Conversely, if R&D costs call for more modest technologies (i.e., $x < x^c$), the subsidy plays no diffusion role (because the innovator is in the "capacity constrained" zone) but it does stimulate the innovator to develop a cleaner technology.

It is interesting to contrast this hybrid design with the first-best "permit and option" approach proposed by Laffont and Tirole (1996b), who only allow for pollution-free developments (with a probability increasing in the amount of R&D).[19] In their mechanism, the government sells at date 1 securities to polluting firms at some price $v$. The holder of such security is offered the following choice for date 2, which the government commits to: either she exercises an option to purchase a pollution permit at price $p_0 - \Delta$ (where $p_0$ is the first-best price in the absence of innovation) or she redeems the security to the government and receives $\Delta$ for it. As the probability of developing the free-pollution technology goes to one, $v$ becomes a subsidy equal to the size of the welfare gain from the innovation. In that sense there is a close connection with the hybrid mechanism.

The hybrid policy raises other questions. One is about government's budget. Even if pollution permits are auctioned off, the collected revenues are not enough to cover for the subsidy expenditures for very clean technologies (note that if $x^* = x^c$, then $p^* = s^h$). The last column of Table 1 shows some numbers. Closely related to the above is the question about the time consistency of the hybrid instrument and more generally about the form of the hybrid policy in the absence of commitment. Since the hybrid policy is ex-post socially optimal, in principle the government would not be tempted to change it ex-post as long as subsidies constitute lump sum transfers. But if there is an arbitrarily small but positive cost of public funds, the government would like to reduce the subsidy ex-post: eliminate it when $x \leq x^c$ and bring it down to the level that just induces full diffusion when $x > x^c$. Anticipating this commitment problem, the innovator will not invest as much in R&D. The good news is that for pollution-free technologies (or nearly so) the government does not (or barely does) adjust the subsidy; retaining the R&D

[19] They also consider a positive shadow cost of public funds.

incentives at the top.

### 5.3 Imperfect monitoring

Subsidies are sometimes criticized in that they may fail to reach the right individuals. Suppose the government cannot exactly tell whether a firm's pollution reduction was the result of the adoption the new technology —in which case the firm is entitled to the subsidy— or a cease in operations (or internal abatement at cost $\theta$ using conventional technologies). Let $\phi$ be the probability the government can tell whether a firm is legitimately entitled to receive the subsidy or not. If $s$ is the subsidy (per unit of reduction) announced at date 1 (together with the allocation $q$) and $p$ is the equilibrium price of permits, in equilibrium we will have that firms with valuation $\theta \geq p + (1-\phi)s$ are adopting the new technology and firms with valuation $\theta < p + (1-\phi)s$ are shutting down operations and claiming the subsidy. Only a fraction $1-\phi$ of these latter firms end up receiving the subsidy (there is no penalty fee for dishonest behavior).

The government's problem is now to choose $q$ and $s$ so as to solve

$$\max_{q,s}\{-hq + \int_{p+(1-\phi)s}^{1} \theta f(\theta)d\theta - I(x(q,s))\}$$

where $p$ is the equilibrium price of permits and given by (the innovator has not abandoned the "capacity constrained" zone)

$$p(q,x,s,\phi) = F^{-1}(1-q/(1-x)) - (1-\phi)s$$

When $\phi$ is not too low, the government can still implement the first-best; it allocates $q^*$ permits and moves the subsidy upward to account for imperfect monitoring

$$s_{im}^{h} = \frac{1}{\phi}\frac{1-F(p^*)}{f(p^*)}x^*$$

Since the solution is efficient, $p + (1-\phi)s = h(1-x^*)$. Furthermore, for this solution to be valid, it must hold that $p \geq 0$ or

$$\frac{\phi}{1-\phi} \geq \frac{1-F(p^*)}{p^* f(p^*)}x^* \tag{18}$$

The larger the subsidy the higher the effort the government must undertake to prevent cheating. If (18) does not hold, the government adjusts both the subsidy $s$ and $q$.

To the extend that $\phi$ is not to low, imperfect monitoring does not introduce distortions. That can change if imperfect information is model in such a way that low-valuation firms need to do some costly adjustment to hide behind higher-valuation ones; for example, all firms need to emit $1-x$ to be considered for the subsidy. One possibility to deal with this distortion is to think in a mechanism where the regulator can allocate both permits and subsidies simultaneously. At the end the mechanism may resemble the auction mechanism in Montero (2008).

# 6 Uncertainty

So far we have assumed that the R&D process is fully deterministic, which is not entirely realistic. Suppose now that at private cost $I$ incurred at date 1 the innovator develops a technology $x$ which is distributed according to the cumulative distribution function $G(x|I)$, with density $g(x|I)$. I assume that higher investment $I$ makes the development of a cleaner technology (i.e., higher $x$) more likely in the sense of first-order stochastic dominance: $\partial G(x|I)/\partial I \leq 0$. The government knows function $G(x|I)$ but does not observe investment $I$; thus, even if feasible, it cannot write a contract with the innovator on $I$. Uncertainty introduces new challenges to the government because the more uncertainty the R&D process is the less likely the government wants to commit ex-ante to a rigid policy whether it is based on prices, quantities or a combination of quantities and subsidies.

## 6.1 First-best

The first best is given by the ex-post policy function $p^*(x) = h(1-x)$ and the ex-ante investment

$$I^* = \arg\max_I E\left[W(I|p^*(x))\right] = \int_0^1 \left\{-h[1-F(p^*(x))](1-x) + \int_{p^*(x)}^1 \theta f(\theta)d\theta\right\} g(x|I)dx - I$$

Integrating by parts, we obtain that the socially optimal amount of investment solves

$$\int_0^1 -h[1-F(p^*(x))]\frac{\partial G(x|I)}{\partial I}dx - 1 = 0$$

which has the same interpretation of (4).

## 6.2 Prices vs quantities

The introduction of uncertainty does not change much of the trade-off in the choice of prices and quantities in the absence of commitment. If the government does not want to (or cannot) commit, we know that ex-post social optimum can be implemented with either prices or quantities to the extent that $x \leq \hat{x}$; if $x > \hat{x}$, the optimal quantity response is $q^r(x) < q^*(x)$. Because of the latter inefficiency, investment will be higher under quantities. In fact, the amount of investment $I$ in any policy regime is given by

$$-\int_0^1 \pi_k'(x) \frac{\partial G(x|I)}{\partial I} dx - 1 = 0$$

where $\pi_k(x) = p(x)x[1-F(p(x))]$ are the innovator's rents as a function of the technology developed under policy $k = p$, $q$ and $p(x)$ is either the tax or the equilibrium price of permits. It is clear from the from the ex-post analysis of Section 3 that $\pi_p'(x) = \pi_q'(x)$ for $x \leq \hat{x}$ and $\pi_p'(x) < \pi_q'(x)$ for $x \geq \hat{x}$. Note that $\pi_p'(x)$ becomes negative for higher values of $x$,[20] so eventually we can have a corner with $I_p^{nc} = 0$. We can then establish

**Proposition 6** $I_p^{nc} < I_q^{nc} < I^*$.

The proof is in the Appendix. Note that under deterministic R&D there may be cases in which the innovator invests beyond R&D first-best levels. That never happens here because the innovator does not control the outcome of the innovation.

We could extend this discussion to the case in which the government would like to commit —provided it has the ability to— to a rigid policy ex-ante; perhaps, because uncertainty is not that large. Proposition 3 readily extends to the case of uncertainty.

## 6.3 Hybrid instrument

As in the certainty case, we want to explore whether the combination of permits and subsidies can implement the first-best. We want to find ex-post price and subsidy functions that can do both: be efficient ex-post and provide first-best investment incentives

[20] $\pi_p'(x) < 0$ for values of $x > \tilde{x}$, where $0 < \tilde{x} < 1$ and solves

$$\frac{1 - F(p^*(x))}{p^*(x) f(p^*(x))} = -\frac{x}{1 - 2x}$$

ex-ante. For the latter, we need the ex-post functions be such that

$$\pi'(x) = h[1 - F(h(1 - x))]$$

for all $x$. One policy candidate that is the ex-post efficient combination of permits and subsidies that generate the following rents for the innovator

$$\pi(x) = \begin{cases} p^*(x)x[1 - F(p^*(x))] & \text{if } x \leq \hat{x} \\ [p^*(x) + s(x)]x[1 - F(p^*(x))] & \text{if } x > \hat{x} \end{cases}$$

where

$$s(x) = \frac{1 - F(h(1 - x))}{f(h(1 - x))}x - h(1 - x)$$

Note that $s(\hat{x}) = 0$. Unfortunately, this ex-post efficient policy can generate too many rents, leading to too much investment. It remains to be investigated what is the optimal mechanism that can be designed assuming that the policy instruments are exclusively aimed at polluting sources (this is work in progress).

# 7 Conclusions

I conclude by emphasizing the advantage of permits combined with subsidies over taxes. In the case of drastic innovations (i.e., pollution-free innovations or nearly so), the combination of permits and subsidies allow the regulator to implement the social optimum regardless of its ability to commit to its original policy design. Taxes on the other hand do not perform as well —not bad if the government can commit— because they work too good ex-post. In order to prevent the government to run large deficits as a result of the subsidies permits should be auctioned off. In the case of moderate innovations, a government that can commit to its policy design can still implement the social optimum with a combination of (auctioned) permits and subsidies, most likely running a surplus. If the government cannot commit (because subsidies are not pure transfers), it makes no difference whether to use prices or quantities.

# References


[1] Aldy, J. and R. Stavins, eds., (2007), *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, Cambridge University Press.

[2] Denicolo, V. (1999), Pollution-reducing innovations under taxes or permits, *Oxford Economic Papers* 51, 184-199.

[3] Hepburn, C. (2005), Regulation by prices, quantities, or both: A review of instrument choice, *Oxford Review of Economic Policy* 22, 226-247.

[4] Laffont, J.-J and J. Tirole (1996a), Pollution permits and compliance strategies, *Journal of Public Economics* 62, 85-126.

[5] Laffont, J.-J. and J. Tirole (1996b), Pollution permits and environmental innovation, *Journal of Public Economics* 62, 127-140.

[6] McAfee, P., and T. Wiseman (2008), Capacity choice counters the Coase Conjecture, *Review of Economic Studies* 75, 317-332.

[7] Montero, J.-P. (2008), A simple auction mechanism for the optimal allocation of the commons, *American Economic Review* 98, 496-518.

[8] Popp, D., R. Newell and A. Jaffe (2009), Energy, the environment, and technological change, NBER working paper.

[9] Requate, T. (2005), Dynamics incentives by environmental policy instruments–a survey, *Ecological Economics* 54, 175-195.

[10] Roberts, M. and M. Spence (1976), Effluent charges and licenses under uncertainty, *Journal of Public Economics* 5, 193-208.

[11] Weitzman, M. (1974), Prices vs. quantities, *Review of Economic Studies* 41, 477-491.

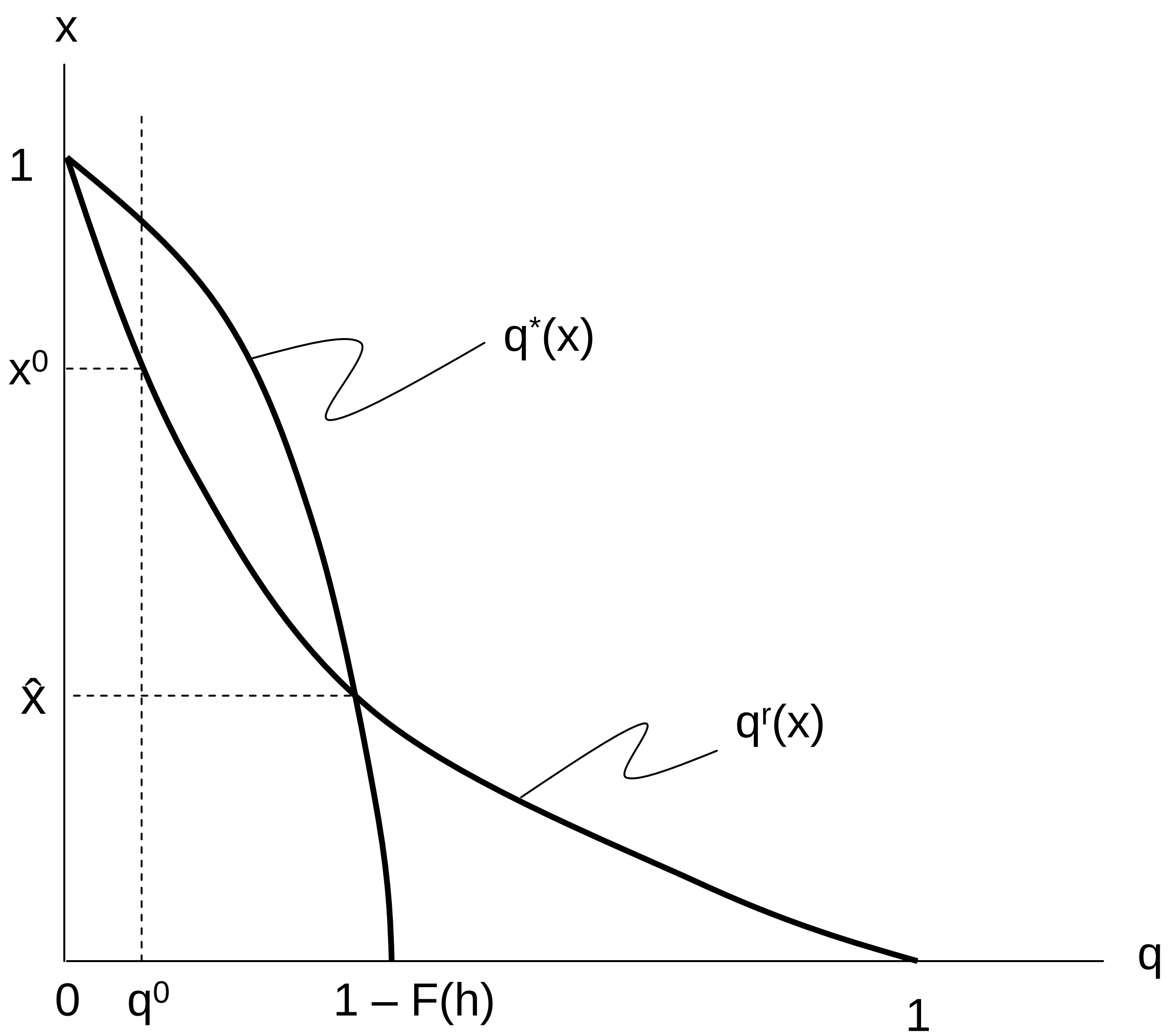


Figure 1. Regulator and innovator’s ex-post responses

Table 1. Policy performance for different levels of R&D costs (h = 0.5)

| | **first-best** | **permits--c** | **permits--nc** | **permits--nc (2nd sol.)** | **taxes--c** | **taxes--nc** | **permits & subsidy--c** |
|---|---|---|---|---|---|---|---|
| **c=0** | | | | | | | |
| innovation x | 1.000 | 1.000 | 1.000 | | 1.000 | 0.577 | 1.000 |
| pollution q | 0.000 | 0.000 | 0.000 | | 0.000 | 0.333 | 0.000 |
| price/tax p | 0.000 | 0.500 | 0.500 | | 0.000 | 0.211 | 0.000 |
| subsidy s | | | | | | | 1.000 |
| innovator's rent $\pi$ | 0.000 | 0.250 | 0.250 | | 0.000 | 0.096 | 1.000 |
| welfare W | 0.500 | 0.375 | 0.375 | | 0.500 | 0.311 | 0.500 |
| govt. surplus | | | | | | | -1.000 |
| | | | | | | | |
| **c=0.02** | | | | | | | |
| innovation x | 0.789 | 0.621 | 0.734 | | 0.672 | 0.483 | 0.789 |
| pollution q | 0.189 | 0.212 | 0.154 | | 0.246 | 0.383 | 0.189 |
| price/tax p | 0.106 | 0.441 | 0.423 | | 0.248 | 0.258 | 0.106 |
| subsidy s | | | | | | | 0.705 |
| innovator's rent $\pi$ | 0.000 | 0.120 | 0.124 | | 0.084 | 0.074 | 0.497 |
| welfare W | 0.325 | 0.264 | 0.279 | | 0.305 | 0.256 | 0.325 |
| govt. surplus | | | | | | | -0.477 |
| | | | | | | | |
| **c=0.074** | | | | | | | |
| innovation x | 0.565 | 0.376 | 0.500 | 0.333 | 0.423 | 0.333 | 0.565 |
| pollution q | 0.341 | 0.360 | 0.333 | 0.444 | 0.383 | 0.444 | 0.341 |
| price/tax p | 0.218 | 0.423 | 0.333 | 0.333 | 0.335 | 0.333 | 0.218 |
| subsidy s | | | | | | | 0.442 |
| innovator's rent $\pi$ | 0.000 | 0.047 | 0.037 | 0.037 | 0.040 | 0.037 | 0.195 |
| welfare W | 0.210 | 0.186 | 0.204 | 0.185 | 0.198 | 0.185 | 0.210 |
| govt. surplus | | | | | | | -0.121 |
| | | | | | | | |
| **c=0.15** | | | | | | | |
| innovation x | 0.328 | 0.191 | 0.183 | | 0.212 | 0.183 | 0.328 |
| pollution q | 0.446 | 0.455 | 0.483 | | 0.465 | 0.483 | 0.446 |
| price/tax p | 0.336 | 0.437 | 0.408 | | 0.410 | 0.408 | 0.336 |
| subsidy s | | | | | | | 0.218 |
| innovator's rent $\pi$ | 0.000 | 0.012 | 0.011 | | 0.011 | 0.011 | 0.047 |
| welfare W | 0.147 | 0.141 | 0.141 | | 0.143 | 0.141 | 0.147 |
| govt. surplus | | | | | | | 0.103 |
| | | | | | | | |
| **c=0.25** | | | | | | | |
| innovation x | 0.000 | 0.000 | 0.000 | | 0.000 | 0.000 | 0.000 |
| pollution q | 0.500 | 0.500 | 0.500 | | 0.500 | 0.500 | 0.500 |
| price/tax p | 0.500 | 0.500 | 0.500 | | 0.500 | 0.500 | 0.500 |
| subsidy s | | | | | | | 0.000 |
| innovator's rent $\pi$ | 0.000 | 0.000 | 0.000 | | 0.000 | 0.000 | 0.000 |
| welfare W | 0.125 | 0.125 | 0.125 | | 0.125 | 0.125 | 0.125 |
| govt. surplus | | | | | | | 0.250 |