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Unintended Impacts of Multiple Instruments on Technology Adoption

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Abstract

There are many situations where environmental authorities use a mix of environmental policy instruments, rather than one single instrument, to address environmental concerns. For example, one instrument may be used to reduce overall emissions of a pollutant while another is used to address specific seasonal concerns. Very little work has been done on the economic impacts of the application of multiple instruments. This paper investigates the unintended impacts of the interaction of a tradable permits scheme with direct seasonal regulations on the rate of adoption of advanced abatement technologies.

Key Words: Technology adoption, environmental policy, tradable permits, emission standards, interaction of policies.

JEL CODES: O33, Q53, Q55 y Q58.

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I. INTRODUCTION

In some cases, the damages caused by emissions of pollutants depend almost exclusively on their magnitude and on the number of persons whose location makes them vulnerable to the effects. However, under many other circumstances, the effects of a given discharge depend on variables beyond the control of those directly involved. For example, amount of water and speed of flow are critical determinants of a river's assimilative capacity. Similarly, emission levels that are acceptable and rather harmless under usual conditions can become intolerable under some meteorological conditions. This is the case in some cities like Mexico City and Santiago, Chile, where temperature inversion may prevent air pollution from leaving the atmosphere during winter months, causing occasional environmental crises that prompt the imposition of emergency measures to improve air quality to a satisfactory level. Typically, these crises cannot be predicted far in advance or with any degree of certainty – we can only be certain that at some unforeseen time they will recur.

In most cases, it is virtually impossible to change environmental regulations on short notice. Thus, if one policy is used as the only means of control, it would have to be set at a level that is high enough to maintain the pollution at acceptable levels during emergency periods. In certain circumstances, such a policy may be unacceptably costly to society. Bawa (1975) showed that the pollution control policy that minimizes total social costs (stationary social costs plus short-term emergency costs) is a mixed policy in which market-based instruments are used to control the long-run equilibrium level of pollution and direct controls are used to maintain the pollution below some predetermined threshold during short-term emergencies. If enforcement is effective, direct controls can induce, with little uncertainty, the prescribed alterations in pollution activities, while the use of market-based policies leads firms to use cleaner technologies in the long run.

One important disadvantage of direct controls is their poor dynamic properties. In fact, the theory of environmental regulation suggests that since economic instruments induce firms to re-optimize their levels of abatement, they create more effective technology adoption incentives than conventional regulatory standards. Thus, it is worth asking whether or not interaction of policies alters the economic incentives provided through market-based instruments, especially if the incidence of environmental crises and the "relative use" of direct controls within the mix vary. The present paper analyzes the unintended impacts of the interaction between tradable permits and short-term emission standards on the rate of adoption of advanced abatement technologies.

Under this setting, adoption benefits can be decomposed into a "net abatement effect" and a "permit price effect." The "net abatement effect" accounts for the increased adoption savings resulting from the additional abatement induced by a situation of environmental distress. The "permit price effect" accounts for the negative effect of increased availability of technology on the permit price, which encourages trading and discourages adoption. Then, both effects set against themselves and the final rate of adoption depends on the extent to which each effect offsets the other and on the incidence of environmental crises.

If the incidence of environmental crises is exogenous, then a mix of market-based policies and emission standards does not maximize social welfare. Indeed, if the incidence of environmental crises is low, then a mix of tradable permits and emission standards leads to an inefficiently large price effect and to a rate of adoption that is lower than the optimal. Similarly, if the incidence is high, then the mix induces an inefficiently small price effect, leading firms to overinvest. However, if the incidence is low and it can be reduced even further through adoption of new technology, then the previous results do not hold and the mixed policy could offer a higher level of social welfare than alternative approaches.

This paper is organized as follows. The next section introduces the adoption model. Section 3 analyzes the adoption incentives under direct regulations and market-based policies separately and under mixed policies. Section 4 compares the total welfare induced by mixed approaches when the incidence of environmental emergencies is exogenous. Section 5 compares the total welfare when the incidence of environmental emergencies can be affected by the rate of adoption. Section 6 presents a numerical example to illustrate the main results. Section 7 concludes the paper.

II. THE MODEL

Consider a competitive industry consisting of a continuum of firms of mass 1. Aggregate emissions without environmental regulation are normalized to unity. Normally, the environmental authority auctions off $[1-\overline{q}_n]$ emissions, where $\overline{q_n}$ represents the desired level of abatement. Each firm must decide whether to buy permits at the market clearing price x to cover its emissions, or to abate them. Due to meteorological conditions, critical episodes of bad air quality are declared with exogenous probability μ, where μ corresponds to the rate of critical episodes per unit of time. To avoid the negative impacts of such episodes, the environmental authority implements a more demanding direct regulation during these environmental emergencies, compelling firms to further decrease their levels of emissions. The direct regulation takes the form of a uniform emission standard equal to $[1-\overline{q_c}]$, with $[\overline{q_c} > \overline{q}_n]$.

Current abatement costs are homogeneous with total abatement costs equal to cq_i^2, where q_i represents firm *i*'s abatement. Firms can invest in an advanced technology, leading to lower abatement costs $\tilde{c}q_i^2$ $[\tilde{c} < c]$. Buying and installing the new technology causes a fixed cost $k_i \sim U[0,1]$.

Let π^B and π^A denote the firms' profit flows before and after technology adoption. Firms will adopt new technology as long as the adoption benefits (i.e., the difference in profits associated with the decreased abatement costs) offset the adoption costs. Then, the following arbitrage condition must hold for the marginal adopter:

(1) $$\left[\pi^A - \pi^B\right] = \Delta\pi = \widehat{k_i}$$
.

Define λ as the rate of firms adopting the new technology:

(2) $$\lambda = \int_0^{\widehat{k_i}} f(k_i)dk = 1 - F(\widehat{k_i}) = 1 - F(\pi^B - \pi^A) = \frac{\Delta\pi}{\Delta k} = \Delta\pi\ .$$

Notice that since firm profits strongly depend on the choice and stringency of environmental policies, the rate of firms adopting the new technology is endogenous.

III. INTERACTION OF ENVIRONMENTAL POLICIES AND THE RATE OF ADOPTION

3.1 Adoption Incentives Under Direct Regulations and Auctioned Tradable Permits

Several researchers have found that the incentive to adopt new technologies is greater under market-based instruments than under direct regulations [See Milliman and Prince (1989); Jung, Krutilla and Boyd (1996); Keohane (1999); and Nelissen and Requate (2004)]. This superiority of market-based policies relies on the fact that firms re-optimize their abatement levels once new technology is available, which leads to larger savings attributable to the adoption decision. If direct regulations are used, firms will enjoy a lower abatement cost only for the emissions they were abating initially. Thus, in this setting, the cost savings resulting from using new technology when firms are restricted to emit no more than $\bar{q}$ units of emissions are given by the difference in total abatement cost due to making an emission reduction to that level:

(3) $$\Delta\pi^{EE} = (\lambda)^{EE} = \left[(c - \tilde{c})(\bar{q})^2 \right].$$

Let us compare with the incentives provided by market-based policies. Let x denote the "equilibrium permit price" of emissions. When adopters make abatement decisions, they solve the following problem:

(4) $$\min_{q^A} L_1^A = \left\{\tilde{c}(q^A)^2 + x(1-q^A)\right\},$$

where q^A is the level of emissions abated and L_1^A is the minimized sum of abatement costs and payments for non-reduced emissions. The first order condition (FOC) is given by:

(5) $$2\tilde{c}(q^A) = x.$$

That is, adopters reduce emissions until the marginal abatement cost of the new technology equals the price of emissions.

Non-adopters face a similar problem, but with a higher marginal abatement cost:

(6) $$\min_{q^{NA}} L^{NA}{}_1 = \left\{c(q^{NA})^2 + x(1-q^{NA})\right\}.$$

The first order condition (FOC) is given by:

(7) $$2c(q^{NA}) = x.$$

Thereby, non-adopters' optimal level of abatement q^{NA} is lower than that of adopters because of higher marginal abatement costs.

Substituting the FOCs into the minimization problem, the adoption profits and the rate of adoption are given by:

(8) $$\Delta\pi^{TP} = \lambda^{TP} = x^2\alpha,$$

with $\alpha = \left[\frac{1}{4\tilde{c}} - \frac{1}{4c}\right] > 0$ and $x^2\alpha > \left[(c-\tilde{c})(\bar{q})^2\right]$[1].

If the industry is regulated by permits, the market clearing on the permit market requires:

(9) $$\bar{q} = \lambda(x)\left[q^A(x)\right] + \left[1-\lambda(x)\right]\left[q^{NA}(x)\right].$$

Substituting (5) and (7) into (9) and differentiating (9) with respect to x and λ yields:

(10) $$\frac{dx}{d\lambda} = -\frac{\alpha x}{\lambda\alpha + \frac{1}{4c}} < 0 .$$

Then the permit price will drop with adoption since the diffusion of the cost-reducing technology lowers the aggregate marginal abatement costs. This price effect induces more efficient adoption decisions and prevents overinvesting since firms with higher costs of adoption have the opportunity to buy cheaper permits instead of investing in new technology.[2]

3.2 Adoption Incentives Under A Mixed Scheme of Tradable Permits and Direct Regulations

Lets us now compare the adoption incentives when mixed policies are used.

It is assumed that environmental emergencies occur with probability μ and that firms are compelled to abate $\overline{q_c}$ units of emissions during these periods. Then the adopters' problem

[1] In line with most of the literature on the subject, I assume parameters such that for the same level of stringency, the cost savings provided by tradable permits are larger than those provided by emission standards.
[2] This price effect tends to also support the use of taxes instead of tradable permits to speed up the diffusion of new technology. The fact that the emissions price is fixed by the regulator under the tax while it depends on the firm behavior under permits creates a wedge between the tax and the permit systems and between the different rates of adoption they induce.

is to minimize the sum of (1) abatement costs and payments for non-reduced emissions during normal days and (2) the abatement costs of achieving the emergency standard.

(11) $$\min_{q_n^A} L_2^{A} = (1-\mu)\left\{\tilde{c}(q_n^A)^2 + x_c(1-q_n^A)\right\} + \mu\left\{\tilde{c}(\overline{q_c})^2 + x_c(1-\overline{q_c})\right\},$$

where x^c denotes the "equilibrium permit price" of emissions when both policies are applied and $q_n^A \leq \overline{q_c}$.

The first order condition (FOC) for the optimal level of emission reduction is given by:

(12) $$2\tilde{c}(q_n^A) = x_c .$$

Notice that the FOC does not change due to the interaction of policy instruments. That is, adopters abate emissions until the marginal abatement cost of the new technology equals the price of emissions.

Again, non-adopters face a similar problem, but with a higher marginal abatement cost:

(13) $$\min_{q_n^{NA}} L_2^{NA} = (1-\mu)\left\{c(q_n^{NA})^2 + x_c(1-q_n^{NA})\right\} + \mu\left\{c(\overline{q_c})^2 + x(1-\overline{q_c})\right\},$$

(14) $$2c(q_n^{NA}) = x_c .$$

Substituting the FOC into the minimization problem, the adoption profits and the rate of adoption λ^c become:

(15) $$\Delta\pi = \lambda^c = (1-\mu)(x_c)^2\alpha + \mu\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2 .$$

Differentiating λ^c with respect to μ and re-organizing terms yields:

(16) $$\frac{\partial \lambda^{c}}{\partial \mu} = \underbrace{\left\{ \underbrace{\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2}_{\substack{AdoptionSavings\\ Under\\ EnvironmentalEmergencies}} - \underbrace{\left[\alpha\,(x_c)^2\right]}_{\substack{AdoptionSavings\\ UnderNormalDays}} \right\}}_{NetAbatementEffect} + \underbrace{2(1-\mu)(x_c)\frac{\partial x_c}{\partial \mu}\alpha}_{PriceEffect}.$$

In (16), the term in brackets on the right-hand side represents the net effect of the more stringent direct regulation under environmental emergencies on the adoption savings, i.e., “net abatement effect,” while the second term on the right-hand side of (15) gives account of the effects of the implementation of the direct regulation on the permit price, i.e., “permit price effect”.[3]

Market clearing in the permit market requires total abatement to be equal to the weighted abatement done by adopters and non-adopters. Then, substituting the optimal rate of adoption into the market-clearing condition, we can solve for the market price x^c and for the effect of environmental emergencies on the permit price.

(17) $$\overline{q_n} = \lambda(x,\mu)\left[q_n^{A}(x_c)\right] + \left[1-\lambda(x,\mu)\right]\left[q_n^{NA}(x_c)\right]$$

Substituting (15) into (17), differentiating with respect to x_c and μ and solving for $dx_c / d\mu$, yields [see Appendix A]:

(18) $$\frac{dx_c}{d\mu} = \frac{\alpha x_c\left[\left[\alpha\,(x_c)^2\right] - \left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2\right]}{\underbrace{3(1-\mu)(x_c)^2\alpha^2 + \mu(c-\tilde{c})(\overline{q_c})^2\alpha + \frac{1}{4c}}_{>0}}.$$

[3] $\frac{\partial (x_c)^2}{\partial \mu} = \frac{\partial (x_c)^2}{\partial \lambda}\frac{\partial \lambda}{\partial \mu}$

Since the denominator is positive, the sign of $\frac{dx_c}{d\mu}$ depends on the net adoption savings.

Substituting (18) into (16) yields:

$$\frac{\partial \lambda^c}{\partial \mu} = \underbrace{\left\{ \underbrace{\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2}_{\substack{AdoptionSavings \\ Under \\ EnvironmentalEmergencies}} - \underbrace{\left[\alpha (x_c)^2\right]}_{\substack{AdoptionSavings \\ UnderNormalDays}} \right\}}_{NetAbatementEffect} \underbrace{+2(1-\mu)(x^c)^2\alpha^2 \frac{\left[\left[\alpha (x^c)^2\right] - \left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2\right]}{3(1-\mu)(x^c)^2\alpha^2 + \mu(c-\tilde{c})(\overline{q_c})^2\alpha + \frac{1}{4c}}}_{\Pr iceEffect} \quad (19)$$

Thereby, if the adoption savings under the emission standard are larger than those firms realize under trading permits, then the “net abatement effect” is positive while the “permit price effect” is negative. Similarly, if the savings under tradable permits are larger than those under the emission standard, then the “permit price effect” is positive while the “net abatement effect” is negative. Then the comparison between adoption savings under emission standards and permits critically depends on the “relative” stringency of the direct regulation. If the emergency emission standard is the most demanding policy, then adoption savings under environmental emergencies are larger than those under normal days, and the “net abatement effect” is positive while the “permit price effect” is negative.

So, the “permit price effect” partially offsets the “net abatement effect,” reducing the rate of adoption. The price effect is negative since the higher rate of adoption induced by more stringent direct regulation lowers the aggregate marginal abatement cost and therefore lowers the permit price. This decrease in the permit price reduces the rate of adoption since in order to achieve the environmental regulation, firms prefer to buy "cheaper" permits instead of buying the new technology. The more stringent the emission standard, the larger the decrease in the permit price and the larger the impact on the rate of adoption.

Clearly, the magnitude of the "permit price effect" also depends on the probability of environmental emergencies occurring. If μ increases, the relative importance of the "permit price effect" decreases since the chances of using permits instead of buying the new technology are very low.

Proposition 1: The rate of adoption under the mix of tradable permits and emission standards increases with the incidence of environmental emergencies at an increasing rate.

Proof:

Let β_0 denote the "net abatement effect" and $\beta_1 = (x_c)^2\alpha$ and $\beta_2 = \left[c - \tilde{c}\right](\overline{q_c})^2$ the adoption savings under permits and under the emission standard, respectively. Then $\frac{\partial \lambda^c}{\partial \mu}$ can be re-written as:

(20) $$\frac{\partial \lambda^c}{\partial \mu} = \beta_0 \left[1 - \frac{2\beta_1 \alpha}{3\beta_1 \alpha + \frac{1}{(1-\mu)} \left[\beta_2 \mu \alpha + \frac{1}{4c} \right]} \right] = 0,$$

where $\left[\frac{2\beta_1 \alpha}{3\beta_1 \alpha + \frac{1}{(1-\mu)} \left[\beta_2 \mu \alpha + \frac{1}{4c} \right]} \right] > 0$.

Thus, the effect of the incidence of environmental emergencies is expressed as a function of the "net abatement effect" times 1 less the "permit price effect." Notice that when $\mu \to 1$, the "permit price effect" tends to zero and $\frac{\partial \lambda^c}{\partial \mu} |_{\mu \to 1} \to \beta_0$. Thus, if the probability of an environmental emergency occurring is high, then the degree of substitution between the use of permits and the purchase of new technology is small since it is not profitable to purchase permits than can't be used regularly. Adopting abatement technology is therefore the only alternative available to meet the environmental regulation, and the adoption savings are the largest.

On the other hand, when $\mu \to 0$, the degree of substitution between the use of permits and the purchase of new technology is high, and so is the permit price effect. Then $\frac{\partial \lambda^c}{\partial \mu} |_{\mu \to 0} \to \beta_0 \left[1 - \frac{2\beta_1 \alpha}{3\beta_1 \alpha + \frac{1}{4c}} \right] < \beta_0$. Thus, if the probability of an environmental emergency occurring decreases, then the degree of substitution between the use of permits and the purchase of the technology increases, and so does the negative impact of the "permit price effect" on the rate of adoption.

The intuition behind this result is straightforward. The "net abatement effect" is positive and overcomes the negative "permit price effect." Since the "permit price effect" decreases with the incidence of environmental emergencies, the total effect increases at an increasing rate.

3.3 Adoption Incentives Under a System of Differentiated Tradable Permits

Let us assume that instead of applying a direct regulation to control critical episodes, the environmental authority uses differentiated tradable permits. A "regular" trading program is intended to encourage an emissions reduction equal to $\overline{q_n}$ during normal days, while an emergency tradable permit program is intended to encourage a reduction equal to $\overline{q_c}$ during environmental emergencies. The adopters' problem becomes to minimize the sum of abatement costs and payments for non-reduced emissions during normal days plus the sum of abatement costs and payments for non-reduced emissions during environmental emergencies.

(21) $$\min_{q_n^A, q_c^A} L_3^A = (1-\mu)\left\{\tilde{c}(q_n^A)^2 + x_n(1-q_n^A)\right\} + \mu\left\{\tilde{c}(q_c^A)^2 + x_s(1-q_c^A)\right\},$$

where x_n is the "permit price" of emissions during normal days and x_s corresponds to the "equilibrium permit price" of emissions during environmental emergencies.

The FOCs for the optimal level of emissions reduction under the regular and the emergency program are given by:

(22) $$\begin{aligned} 2\tilde{c}(q_n{}^A) &= x_n \\ 2\tilde{c}(q_c{}^A) &= x_s \end{aligned}.$$

That is, in each "state," the marginal abatement cost of the new technology equals the price of emissions.

As usual, non-adopters face a similar problem but with a higher marginal abatement cost, leading to the usual FOCs:

(23) $$2c(q_n{}^{NA}) = x_n\,,$$

$$2c(q_c{}^{NA}) = x_s\,.$$

Using the FOC for the optimal level of emissions reduction, we can solve for the adoption profits and the rate of adoption:

(24) $$\Delta\pi = \lambda^{2TPP} = \left[(1-\mu)(x_n)^2 + \mu(x_s)^2\right]\alpha\,.$$

Differentiating (24) with respect to μ and re-organizing terms yields:

(25)
$$\frac{\partial \lambda^{2TPP}}{\partial \mu} = \underbrace{\left[\underbrace{(x_s)^2 \alpha}_{\substack{AdoptionSavings \\ Under \\ EnvironmentalEmergencies}} - \underbrace{(x_n)^2 \alpha}_{\substack{AdoptionSavings \\ UnderNormalDays}} \right]}_{NetAbatementEffect} + \left[2\mu\alpha(x_s) \underbrace{\frac{\partial (x_s)}{\partial \mu}}_{\substack{PriceEffect \\ Under \\ EnvironmentalEmergencies}} + 2(1-\mu)\alpha(x_n) \underbrace{\frac{\partial (x_n)}{\partial \mu}}_{\substack{PriceEffect \\ UnderNormalDays}} \right].$$

The first term in brackets on the right-hand side of (25) represents the net effect of the environmental emergency regulation on the adoption savings, or the "net abatement effect," while the second term on the right-hand side of (26) gives account of the indirect effect of environmental emergencies on the permit price during environmental emergencies and normal days.

The market clearing in the permit markets requires total abatement to be equal to the weighted abatement done by adopters and non adopters in each state:

(26) $$\overline{q_c} = \lambda^{2TPP}(x_s, \mu)\left[q_c{}^A(x_s) \right] + \left[1 - \lambda^{2TPP}(x_s, \mu) \right]\left[q_c{}^{NA}(x_s) \right],$$

(27) $$\overline{q_n} = \lambda^{2TPP}(x_n, \mu)\left[q_n{}^A(x_n) \right] + \left[1 - \lambda^{2TPP}(x_n, \mu) \right]\left[q_n{}^{NA}(x_n) \right].$$

And since the required emissions reduction is larger under environmental emergencies [$\overline{q_c} < \overline{q}_n$], the permit price that clears "the market of environmental emergencies" is larger, leading to a positive "net abatement effect."

Substituting λ^{2TPP} into (26) and differentiating with respect to x_S and μ, we obtain a solution for $dx_s / d\mu$. By analogy, substituting λ^{2TPP} into (27) and differentiating with respect to x_n and μ, we obtain a solution for $dx_n / d\mu$ (see Appendix B):

(28)

$$\frac{\partial \lambda^{2TPP}}{\partial \mu} = \underbrace{\left[(x_s)^2 \alpha - (x_n)^2 \alpha \right]}_{NetAbatementEffect} -$$

$$\left[\underbrace{2\mu\alpha(x_s) \frac{\alpha(x_s)\left[(x_s)^2\alpha - (x_n)^2\alpha\right]}{3\mu(x_s)^2\alpha^2 + (1-\mu)(x_n)^2\alpha^2 + \frac{1}{4c}}}_{\substack{PriceEffect \\ Under \\ EnvironmentalEmergencies}} + 2(1-\mu)\alpha(x_n) \underbrace{\frac{\alpha(x_n)\left[(x_s)^2\alpha - (x_n)^2\alpha\right]}{3(1-\mu)(x_n)^2\alpha^2 + \mu(x_s)^2\alpha^2 + \frac{1}{4c}}}_{\substack{PriceEffect \\ UnderNormalDays}} \right]$$

Therefore, since the adoption savings are larger during environmental emergencies than during normal days, the “net abatement effect” is positive while the “permit price effects” during environmental emergencies and normal days are negative and offset the “net abatement effect.”

Again, permit price effects are negative since permit prices drop when technology is adopted. The lower price stimulates additional permit trading and less adoption since firms prefer to buy permits instead of investing in technology. Notice that the permit price effect during environmental emergencies is larger since a more stringent policy induces larger adoption savings, therefore inducing a higher adoption rate and a larger reduction of the permit price.

Proposition 2: The rate of adoption under differentiated tradable permits increases with the incidence of environmental emergencies at a decreasing rate.

Proof:

Let γ_0 denote the "net abatement effect" and $\gamma_1 = (x_n)^2\alpha$ and $\gamma_2 = (x_S)^2\alpha$ the adoption savings during normal days and environmental emergencies, respectively. Then $\frac{\partial \lambda 2^{TPP}}{\partial \mu}$ can be re-written as:

$$\frac{\partial \lambda^{2TTP}}{\partial \mu} = \gamma_0 \left[1 - \frac{2\alpha\gamma_2}{3\alpha\gamma_2 + \frac{1}{\mu}\left[(1-\mu)\alpha\gamma_1 + \frac{1}{4c}\right]} - \frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{(1-\mu)}\left[\mu\alpha\gamma_2 + \frac{1}{4c}\right]} \right], \tag{29}$$

where $\frac{2\alpha\gamma_2}{3\alpha\gamma_2 + \frac{1}{\mu}\left[(1-\mu)\alpha\gamma_1 + \frac{1}{4c}\right]} > 0$ and $\frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{(1-\mu)}\left[\mu\alpha\gamma_2 + \frac{1}{4c}\right]} > 0$.

Thus, the effect of the incidence of environmental emergencies is expressed as a function of the "net abatement effect" times 1 less the permit price effect during environmental emergencies and during normal days.

Notice that when $\mu \to 1$, the permit price effect during normal days tends to zero, while during days of environmental emergencies it is at a maximum and $\frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\to 1} \to \gamma_0 \left[1 - \frac{2\alpha\gamma_2}{3\alpha\gamma_2 + \frac{1}{4c}}\right]$.

On the other hand, when $\mu \to 0$, the permit price effect during environmental emergencies tends to zero, while during normal days it is at a maximum and $\frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\to 0} \to \gamma_0 \left[1 - \frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{4c}}\right]$

Notice that the price effect during environmental emergencies is larger than during normal days since the adoption savings during environmental emergencies are larger [$\gamma_2 > \gamma_1$].That is, the larger adoption savings induce a higher adoption rate and a larger reduction of the permit price, which offsets the net abatement effect. The positive effect of the incidence of environmental emergencies on the rate of adoption is therefore higher when $\mu \to 0$, or $\frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\to 0} > \frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\to 1}$.

Finally, notice that $\frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\to 0} > \frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\neq 0}$. That is, $\forall \mu \neq 0$, the total "price effect" (the weighted addition of the price effect during environmental emergencies and normal days) is larger than the price effect during normal days, which implies that the rate of adoption increases with the incidence of environmental emergencies the most when $\mu \to 0$.

Thus, the rate of adoption increases with the incidence of environmental emergencies, but at a decreasing rate.

Proposition 3: The rate of adoption under a mix of tradable permits and emission standards is lower/higher than or the same as the rate of adoption under a mix of tradable permit programs. If $\mu < \mu^*$*, the rate of adoption under a mix of tradable permits and emission standards is lower than the rate of adoption under a mix of tradable permit programs. The reverse holds if* $\mu > \mu^*$ *.*

Proof: Let us compare the rates of adoption in (15) and (24):

$$\lambda^c = (1-\mu)(x_c)^2 \alpha + \mu\left[c - \tilde{c}\right]\left[\overline{q_c}\right]^2,$$

$$\lambda^{2TPP} = (1-\mu)(x_n)^2 \alpha + \mu(x_S)^2 \alpha .$$

During normal days, the adoption incentives provided by a mixed system of tradable permits are smaller than those provided by a mix of tradable permits and emission standards. The reverse holds during environmental emergencies. That is, $(x_S)^2 \alpha > (c-\tilde{c})(\overline{q_c})^2$ and $(x_N)^2 \alpha < (x_c)^2 \alpha \quad \forall \mu \neq 0$.

There is therefore a critical value of μ determining which mix of policies induces the larger adoption savings and the higher rate of adoption:

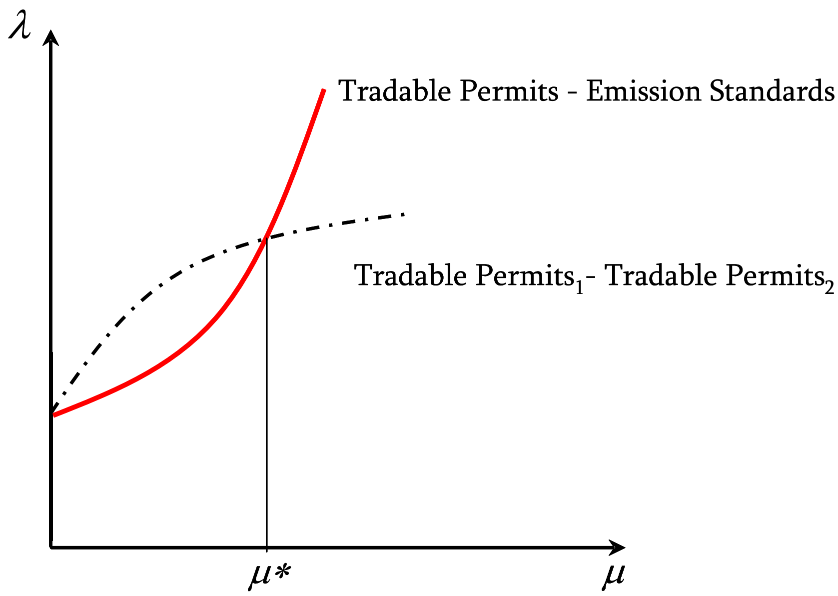
(30)
$$\mu^* = \frac{\alpha\left[(x_c)^2 - (x_n)^2\right]}{\underbrace{\alpha\left[(x_c)^2 - (x_n)^2\right]}_{>0} - \underbrace{\left[(c-\tilde{c})(\overline{q}_c)^2 - (x_s)^2\alpha\right]}_{<0}} > 0 .$$

If $\mu < \mu^*$, the larger adoption savings provided by a mix of tradable permits and emission standard during normal days offset the smaller savings under environmental emergencies, and this mixed policy induces a higher rate of adoption. The reverse holds if $\mu > \mu^*$.

Notice that when $\mu \to 0$, the negative impact of the price effect is larger under a mix of tradable permits and emission standards. That is, $\left|\frac{\partial \lambda^c}{\partial x_c}|_{\mu\to 0}\right| > \left|\frac{\partial \lambda^{2TPP}}{\partial x_n}|_{\mu\to 0}\right|$. Since the net abatement effect is smaller under this mix, the response of the rate of adoption to the incidence of environmental emergencies is also smaller, $\frac{\partial \lambda^c}{\partial \mu}|_{\mu\to 0} < \frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu\to 0}$ (see Appendix C). But as μ increases, the price effect disappears in the case of a mix of tradable permits and emission standards, while it increases in the case of a mixed system of tradable permits. Therefore, λ^c increases at an increasing rate with the incidence of environmental emergencies, while λ^{2TPP} increases at a decreasing rate.

Figure N° 1 sketches proposition # 3. The intuition behind this result is as follows. In the absence of episodes of environmental distress, the incentives provided by the mixed policies coincide; as do the rates of adoption. If $\mu < \mu^*$, the larger adoption savings induced by a mix of tradable permits and emission standards produce a larger permit price effect, which offsets the savings and reduces the rate of adoption. But as μ increases, the permit price effect tends to zero, leading the adoption rate to increase. On the other hand, the total price effect increases with μ when a mixed system of tradable permits is implemented. The larger price effect increasingly offsets the net adoption savings, leading the adoption rate to decrease with μ.

Figure N° 1: Adoption Rate Comparison



Finally, notice that the numerator in (30) gives account of the extra adoption savings induced by a mix of tradable permits and emission standards (TPP-EE) during normal days, while the denominator gives account of the total extra adoption savings induced by a mix of TPP-EE (that is, during normal and emergency days). Then the larger the extra adoption savings induced by TPP-EE during normal days, the higher the critical value of μ.

IV. WELFARE COMPARISON

It is worth asking which mix produces the maximum social welfare, considering abatement benefits, abatement costs, as well as the investment cost related to the use of new technology. Let us assume that the abatement benefits during environmental emergencies and normal days are given by $B^c(q) = \gamma_0 *(q) - \gamma_1 *(q)^2$ and $B^n(q_n) = \beta_0 *(q) - \beta_1 *(q)^2$, with $\gamma_0 - 2\gamma_1 *(q) > \beta_0 - 2\beta_1 *(q)$; $(B^c(q))' \geq 0$; $(B^n(q))' \geq 0$; $(B^c(q))'' \leq 0$ and $(B^n(q))'' \leq 0$.

Social welfare is then given by:

$$
\begin{aligned}
W = \mu\Big[\gamma_0[\lambda q_c^A + (1-\lambda)q_c^{NA}] - \gamma_1[\lambda q_c^A + (1-\lambda)q_c^{NA}]^2 - \lambda\tilde{c}(q_c^A)^2 - (1-\lambda)c(q_c^{NA})^2\Big] \\
+[1-\mu]\Big[\beta_0[\lambda q_n^A + (1-\lambda)q_n^{NA}] - \beta_1[\lambda q_n^A + (1-\lambda)q_n^{NA}]^2 - \lambda\tilde{c}(q_n^A)^2 - (1-\lambda)c(q_n^{NA})^2\Big] - \int_0^\lambda kdk
\end{aligned} \tag{31}
$$

Minimizing (31) with respect to $[q_c^A, q_c^{NA}, q_n^A, q_n^{NA}\lambda]$, we obtain the following FOCs:

$$q_c^A : \gamma_0 - 2\gamma_1\left[\lambda q_c^A + (1-\lambda)q_c^{NA}\right] = 2\tilde{c}(q_c^A), \tag{32}$$

$$q_c^{NA} : \gamma_0 - 2\gamma_1\left[\lambda q_c^A + (1-\lambda)q_c^{NA}\right] = 2c(q_c^{NA}), \tag{33}$$

$$q_n^A : \beta_0 - 2\beta_1\left[\lambda q_n^A + (1-\lambda)q_n^{NA}\right] = 2\tilde{c}(q_n^A), \tag{34}$$

$$q_n^{NA} : \beta_0 - 2\beta_1\left[\lambda q_n^A + (1-\lambda)q_n^{NA}\right] = 2c(q_n^{NA}), \tag{35}$$

$$
\begin{aligned}
\lambda : \lambda = \mu\Big[\gamma_0[q_c^A - q_c^{NA}] - 2\gamma_1 A[q_c^A - q_c^{NA}] + c(q_c^{NA})^2 - \tilde{c}(q_c^A)^2\Big] \\
+[1-\mu]\Big[\beta_0[q_n^A - q_n^{NA}] - 2\beta_1 B[q_n^A - q_n^{NA}] + c(q_n^{NA})^2 - \tilde{c}(q_n^A)^2\Big],
\end{aligned} \tag{36}
$$

with $A=\left[\lambda q_c^A+(1-\lambda)q_c^{NA}\right]$ being the total abatement during environmental emergencies and $B=\left[\lambda q_n^A+(1-\lambda)q_n^{NA}\right]$ being the total abatement during normal days.

Thus, from 32-33 and 34-35 we observe that social welfare is maximized when adopters' marginal abatement costs are the same as the non-adopters' in each state, and that this is exactly the outcome produced by a mix of tradable permit programs.

From (36) we observe that the optimal rate of adoption equates the marginal cost of adoption with the marginal expected benefit in terms of increasing abatement across firms during environmental emergencies and normal days and of reducing the abatement costs. Thus, the optimal rate of adoption depends on the parameters of the abatement benefit function and on the abatement costs. The flatter the abatement benefit functions, the larger the expected benefit of abatement and the higher the optimal rate of adoption. In terms of abatement costs, the lower the abatement costs of a new technology, the higher the optimal rate of adoption.

Proposition 4: Social welfare is maximized when a mix of tradable permit programs is implemented.

Proof: Substituting 32-35 into (36) we obtain the following expression for the optimal rate of adoption (see Appendix D):

(37) $\lambda^{*} = \left[\mu(x_c)^2 + (1-\mu)(x_n)^2 \right] \alpha$.

That is, the optimal rate of adoption coincides with the rate of adoption induced by a mix of tradable permit programs. Then a mixed system of tradable permit programs induces a rate of adoption that maximizes welfare. The intuition behind this result is as follows. Under tradable permits, diffusion of the cost-reducing technology lowers the aggregate marginal abatement costs and therefore lowers the permit price. This price signal prevents firms from overinvesting in abatement technology if cheaper permits are available, encouraging a solution such that the marginal cost of adoption equals the marginal expected social net benefit. If a mixed scheme of tradable permits and emission standards is employed, the price signals are distorted. If $\mu < \mu^{*}$, the larger price effect induced by this mix leads to a rate of adoption that is lower than the optimal. On the other hand, if $\mu > \mu^{*}$, the inefficiently smaller price effect induced by this mix leads firms to overinvest.

V. OPTIMAL ADOPTION RATE DURING ENDOGENOUS ENVIRONMENTAL EMERGENCIES

In the previous analysis, the incidence of environmental emergencies is exogenous. However, if a significant fraction of firms adopt more "environmentally friendly" technologies, it is possible that the probability of environmental crises decreases with the rate of adoption. Then the socially optimal policy in a static setting (i.e., the policy that minimizes total abatement costs) could no longer be optimal. To analyze this case, let us assume that the probability of environmental emergencies occurring depends on the rate of adoption according to function $\mu(\lambda)$, with $\mu'(\lambda)<0$ and $\mu''(\lambda)<0$. That is, the incidence of environmental emergencies decreases with the rate of adoption at a decreasing rate.

The rate of adoption that maximizes social welfare solves the following problem:

(38)

$$
\begin{aligned}
Max_{\lambda}W = {} & \mu(\lambda)\Big[\gamma_0[\lambda q_c^A+(1-\lambda)q_c^{NA}]-\gamma_1[\lambda q_c^A+(1-\lambda)q_c^{NA}]^2-\lambda\tilde{c}(q_c^A)^2-(1-\lambda)c(q_c^{NA})^2\Big] \\
& +\big[1-\mu(\lambda)\big]\Big[\beta_0[\lambda q_n^A+(1-\lambda)q_n^{NA}]-\beta_1[\lambda q_n^A+(1-\lambda)q_n^{NA}]^2-\lambda\tilde{c}(q_n^A)^2-(1-\lambda)c(q_n^{NA})^2\Big]-\int_0^{\lambda}kdk
\end{aligned}
$$

While the FOC for $[q_c^A, q_c^{NA}, q_n^A, q_n^{NA}]$ remains unchanged, the FOC for the optimal rate of adoption solves:

(39)

$$
\lambda^* = \lambda^{2TPP} + \underbrace{\mu'(\lambda)}_{<0}\underbrace{\left\{\begin{array}{l}\underbrace{\gamma_0[\lambda q_c^A+(1-\lambda)q_c^{NA}]-\gamma_1[\lambda q_c^A+(1-\lambda)q_c^{NA}]^2-\beta_0[\lambda q_n^A+(1-\lambda)q_n^{NA}]+\beta_1[\lambda q_n^A+(1-\lambda)q_n^{NA}]^2}_{\substack{Benefit\\ ofIncreasedAbatement}} \\ -\underbrace{\Big[\big[\lambda\tilde{c}(q_c^A)^2+[1-\lambda]c(q_c^{NA})^2\big]-\big[\lambda\tilde{c}(q_N^A)^2+[1-\lambda]c(q_N^{NA})^2\big]\Big]}_{\substack{Cost\\ ofIncreasedAbatement}}\end{array}\right\}}_{>0}
$$

The second term in brackets on the right-hand side of (39) accounts for the effect of the adoption rate on the incidence of environmental emergencies, and is equal to the marginal productivity of adoption in terms of reducing such incidence times the net benefit of the increased abatement. Thus, if the net benefit of the increased abatement is positive, then the optimal rate of adoption is lower than the rate induced by a mixed system of tradable permits.

Proposition 5: If the probability of environmental emergencies decreases with the rate of adoption, then the optimal rate of adoption is lower than the rate of adoption induced by a system of trading programs.

Proof: From (39) it is straightforward that the optimal rate of adoption is lower than the rate of adoption induced by a system of tradable permits insofar as $\mu'(\lambda) < 0$ and the net benefit of the increased abatement is positive. The larger the effect of adoption in terms of decreasing the probability of emergencies, the larger the discrepancy between the optimal rate of adoption and the rate of adoption induced by a system of tradable permits. By analogy, the larger the net benefit of increased abatement, the larger the discrepancy between the optimal rate of adoption and the rate of adoption induced by a mixed policy.

The intuition behind this result is as follows: The optimal rate of adoption increases with the expected benefits of abatement. Since the abatement benefits during normal days are smaller and since the adoption rate increases the incidence of normal days, the optimal rate decreases in order to offset the reduced expected abatement benefits.

Proposition 6: If the probability of environmental emergencies decreases with the rate of adoption and if the incidence of environmental emergencies is low, then total welfare *under a mixed system of tradable permits is lower/higher than or the same as under a mix of tradable permits and emission standards.*

Proof: Let us compute total welfare under a mix of tradable permits and emission standards. Substituting (12) and (14) into (38), we obtain:

(40)
$$\begin{aligned} W^{c} &= \mu(\lambda^{c})\Big[\gamma_{0}[\overline{q_{c}}]-\gamma_{1}[\overline{q_{c}}]^{2}+\lambda^{c}\Big[(c-\tilde{c})(\overline{q_{c}})^{2}\Big]-c(\overline{q_{c}})^{2}\Big] \\ &+\Big[1-\mu(\lambda^{c})\Big]\left[\beta_{0}[\overline{q_{n}}]-\beta_{1}[\overline{q_{n}}]^{2}-\lambda^{c}\Big[(x_{c})^{2}\alpha\Big]+\frac{(x_{c})^{2}}{4c}\right]-\frac{\Big[\lambda^{c}\Big]^{2}}{2}. \end{aligned}$$

By analogy, substituting (22) and (23) into (38), we obtain total welfare under a mixed system of tradable permits:

(41)
$$\begin{aligned} W^{2TPP} &= \mu(\lambda^{2TPP})\left[\gamma_{0}[\overline{q_{c}}]-\gamma_{1}[\overline{q_{c}}]^{2}-\lambda^{2TPP}\Big[(x_{s})^{2}\alpha\Big]+\frac{(x_{s})^{2}}{4c}\right] \\ &+\Big[1-\mu(\lambda^{2TPP})\Big]\left[\beta_{0}[\overline{q_{n}}]-\beta_{1}[\overline{q_{n}}]^{2}-\lambda^{2TPP}\Big[(x_{n})^{2}\alpha\Big]+\frac{(x_{n})^{2}}{4c}\right]-\frac{\Big[\lambda^{2TPP}\Big]^{2}}{2}. \end{aligned}$$

Let us assume that $\mu < \mu^{*}$. That is, the rate of adoption induced by a mix of tradable permits and emission standards is lower than that induced by a mixed system of tradable permits. As stated in equation (42), since $\mu(\lambda^{c}) > \mu(\lambda^{2TPP})$, the incremental welfare induced by a mix of tradable permits and emission standards ΔW is positive insofar as the larger expected abatement benefits and the lower investment costs offset the higher abatement costs.

$$\Delta W = \underbrace{\left[\mu(\lambda^{c}) - \mu(\lambda^{2TPP})\right]\left[\left[\gamma_0(\overline{q_c}) - \gamma_1(\overline{q_c})^2\right] - \left[\beta_0(\overline{q_n}) - \beta_1(\overline{q_n})^2\right]\right]}_{\substack{ExpectedBenefitsof\\ \text{Im}\,provedEnvironmentalQuality}} - \tag{42}$$

$$\underbrace{\left[\begin{array}{l} \mu(\lambda^{2TPP})\left[\lambda^{2TPP}(x_s)^2\alpha + \dfrac{(x_s)^2}{4c}\right] - \mu(\lambda^{c})\left[\lambda^{c}(c-\tilde{c})(\overline{q_c})^2 + c(\overline{q_c})^2\right] \\ +\left[1-\mu(\lambda^{2TPP})\right]\left[\lambda^{2TPP}(x_n)^2\alpha + \dfrac{(x_n)^2}{4c}\right] - \left[1-\mu(\lambda^{c})\right]\left[\lambda^{c}(x_c)^2\alpha + \dfrac{(x_c)^2}{4c}\right] \end{array}\right]}_{\substack{ExpectedAbatementCosts\\ of\ \text{Im}\,proved\\ EnvironmentalQuality}}$$

$$+\underbrace{\left[\frac{\left[\lambda^{c}\right]^2}{2} - \frac{\left[\lambda^{2TPP}\right]^2}{2}\right]}_{InvestmentSavings}$$

Thus, the sign of ΔW strongly depends on the parameters of the damage function and on the responsiveness of the incidence of environmental emergencies to changes in the rate of adoption. The larger the abatement benefits during environmental emergencies, the larger the ΔW. By analogy, the larger the effect of the rate of adoption reducing the probability of environmental emergencies, the larger the ΔW.

VI. NUMERICAL EXAMPLE

In order to illustrate the results, the following numerical example compares the rate of adoption and total welfare under a mix of tradable permits and emission standards and a mixed system of tradable permits. Parameters are chosen to ensure an interior solution. i.e., adoption savings range in the interval $\left[0,1\right]$. The value of the parameters is presented in Table N° 1.

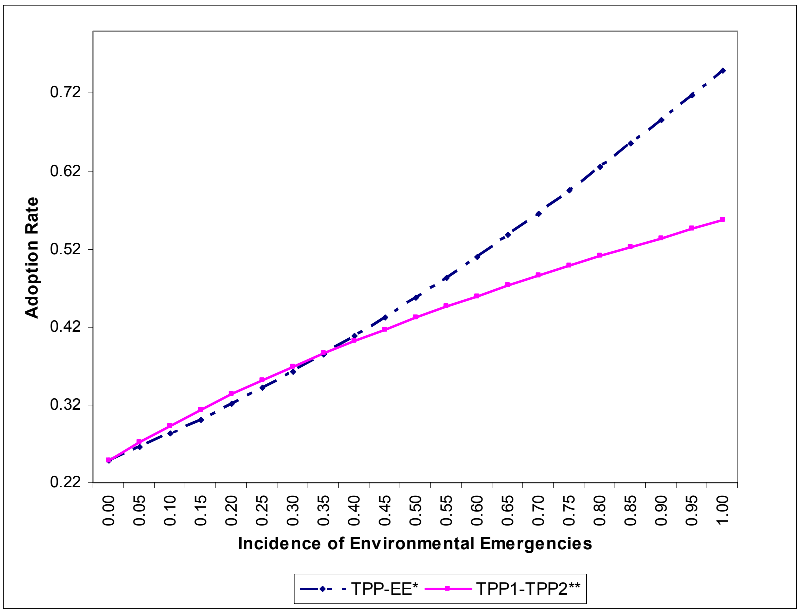
Table N° 1: Simulation Parameters

Abatement benefits normal days	$B^n(q) = 3*q - q^2$
Abatement benefits emergency days $B^c(q) = 5*q - 0.05*q^2$	
Non-adopters' abatement cost	$5*q^2$
Adopters' abatement cost	$2*q^2$
Emission reduction during normal days	$\overline{q_n} = 0.25$
Emission reduction during emergency days	$\overline{q_c} = 0.5$

Notice that the abatement benefit function during environmental emergencies is flatter than that during normal days, leading to a higher level of required abatement. Thus, 25% of total emissions must be reduced during normal days and 50% during contingencies.

Figure N ° 2 sketches the rate of adoption under both mixes when the probability of environmental emergencies is exogenous. As expected, there is a critical value of the incidence of environmental emergencies that determines which mix of policies induces the highest rate of adoption. If $\mu < 38\%$, the rate of adoption under the mix of tradable permits and emission standards is lower; the reverse holds when $\mu > 38\%$.

Figure N° 2: Adoption Rate under Different Mixes of Policies

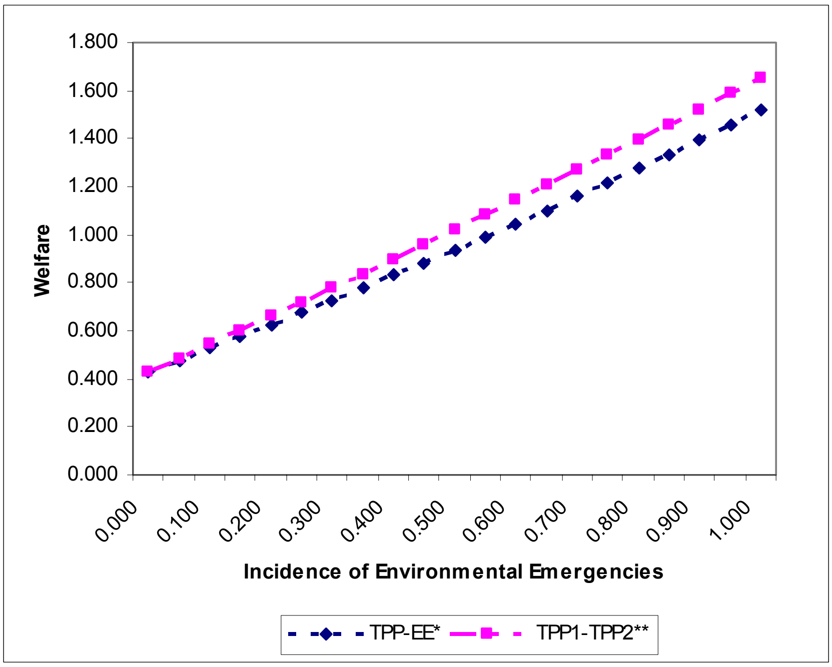


(*)TPP-EE: Mix of tradable permits and emission standards

(**) TPP1-TPP2: Mixed system of tradable permits

Figure N° 3 sketches total welfare under both mixes of policies. As expected, a mix of tradable permit programs maximizes total welfare, since less abatement costs and investment costs are required to achieve the same aggregate emission reduction.

Figure N° 3: Welfare under Different Mixes of Policies

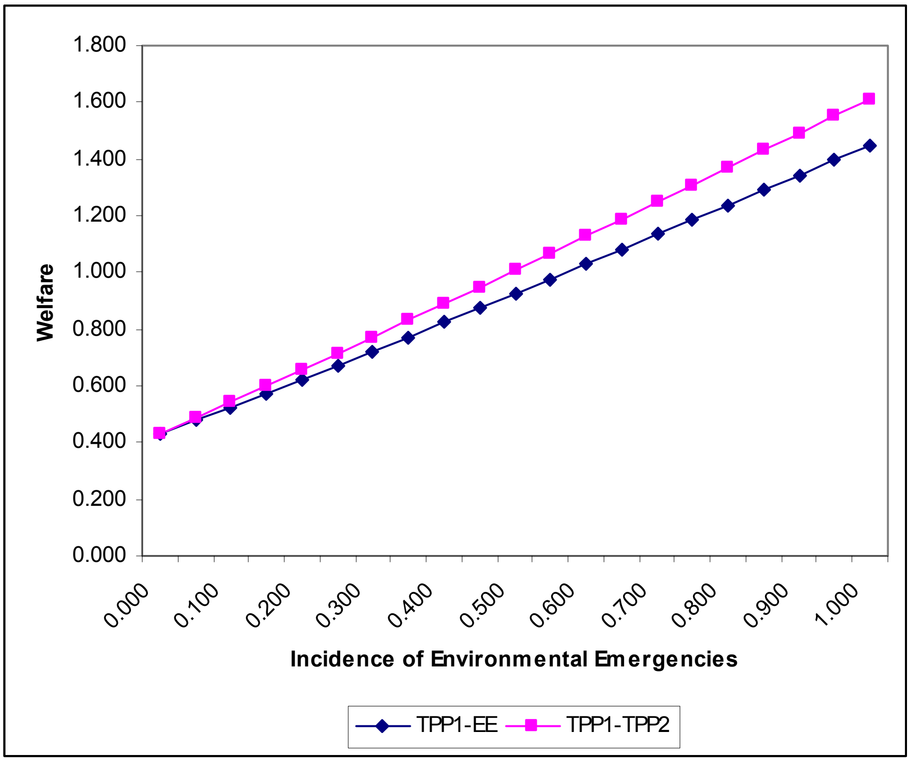


(*)TPP-EE: Mix of tradable permits and emission standards

(**) TPP1-TPP2: Mixed system of tradable permits

Finally, N° 4 sketches total welfare under both mixes of policies when the incidence of environmental emergencies is endogenous. I assume that the incidence of environmental emergencies decreases with the rate of adoption according to the function $\mu(\lambda) = \mu^*(1-0.2\lambda^2)$. Thus, $\mu'(\lambda) < 0$ and $\mu''(\lambda) < 0$. For the selected parameters, the mixed system of tradable permits produces the largest social welfare.

Figure N° 4: Welfare under Different Mixes of Policies When the Incidence of Environmental Emergencies is Endogenous



VII. CONCLUSIONS AND FURTHER RESEARCH

This paper analyzes the unintended impacts of the interaction of tradable permits with seasonal direct regulations on the rate of adoption of advanced abatement technologies. It is shown that if the incidence of environmental emergencies is exogenous, then mixing direct regulations with tradable permits induces an inefficient rate of adoption, while the use of a system of tradable permits maximizes social welfare. On the other hand, if the incidence of environmental emergencies is endogenous, then the mix of tradable permits and emission standards could eventually offer a higher level of social welfare than the alternative approach.

The results rely on the assumption that transaction and monitoring and enforcement costs are similar in different mixed policies. If this is true, social welfare depends on the comparison between net abatement benefits and investment costs. However, if a higher availability of a new technology could reduce the costs of monitoring and enforcing, social welfare maximization could require a higher rate of adoption. On the other hand, if implementing an environmental emergency market is too costly, then the efficiency gains of implementing a mixed system of tradable permits should be disregarded.

This paper addresses the effects of the interaction between emission standards and tradable permit policies. Both are quantity policies that assure that a fixed level of abatement will be attained in the end, regardless of the total abatement costs required for that purpose. If price policies were used instead, then the emission price would be fixed by the regulator from the beginning and would not depend on firms' adoption decisions. The lack of a negative price effect would therefore induce a higher rate of adoption, which could be sub-optimal.

In conclusion, it is not obvious that an additional policy instrument would preserve the efficiency properties of the existent policy. The best "complementary" policy should preserve the benefits of the existing policy to the greatest possible extent and should be administratively feasible at a reasonable cost. Further research is required to clarify the compatibility among policy instruments and what "mix" of instruments is optimal when dealing with situations that require the use of more than one policy.

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Appendix A

The rate of adoption under a mix of tradable permits and direct regulations is given by:

(A1) $$\Delta\pi = \lambda^c = (1-\mu)(x_c)^2\alpha + \mu\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2.$$

Differentiating λ^c with respect to μ and re-organizing terms yields:

(A2) $$\frac{\partial\lambda^c}{\partial\mu} = \underbrace{\left\{ \underbrace{\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2}_{\substack{AdoptionSavings \\ Under \\ EnvironmentalEmergencies}} - \underbrace{\left[\alpha\,(x_c)^2\right]}_{\substack{AdoptionSavings \\ UnderNormalDays}} \right\}}_{NetAbatementEffect} + \underbrace{2(1-\mu)(\alpha x_c)\frac{\partial x_c}{\partial\mu}}_{PriceEffect}.$$

On the other hand, market clearing in the permit market requires total abatement to be equal to the weighted abatement done by adopters and non-adopters:

(A3) $$\overline{q_n} = \lambda^c(x_c,\mu)\left[q_n^A(x_c)\right] + \left[1-\lambda(x_c,\mu)\right]\left[q_n^{NA}(x_c)\right],$$

with $q_n^A(x_c) = \dfrac{(x_c)}{2\tilde{c}}$ and $q_n^{NA}(x_c) = \dfrac{(x_c)}{2c}$.

Substituting $\lambda^c, q_n^A(x_c)$, and $q_n^{NA}(x_c)$ into (A3), we obtain:

(A4) $$\begin{aligned} \overline{q_n} &= \left[(1-\mu)(x_c)^2\alpha + \mu\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2\right]\left[\frac{x_c}{2\tilde{c}}\right] + \\ &\left[1-\left[(1-\mu)(x_c)^2\alpha + \mu\left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2\right]\right]\left[\frac{x_c}{2c}\right] \end{aligned}.$$

Differentiating with respect to x_c and μ and solving for $dx_c / d\mu$ yields:

(A5) $$\frac{dx_c}{d\mu} = \frac{\alpha x_c\left[\left[\alpha(x_c)^2\right] - \left[c-\tilde{c}\right]\left[\overline{q_c}\right]^2\right]}{\underbrace{3(1-\mu)(x_c)^2\alpha^2 + \mu(c-\tilde{c})(\overline{q_c})^2\alpha + \frac{1}{4c}}_{>0}}.$$

Appendix B

The rate of adoption under a mix of differentiated tradable permits and direct regulations is given by:

(B1) $$\Delta\pi = \lambda^{2TPP} = \left[(1-\mu)(x_n)^2 + \mu(x_s)^2\right]\alpha.$$

Differentiating (B1) with respect to μ and re-organizing terms yields:

(B2) $$\frac{\partial\lambda^{2TPP}}{\partial\mu} = \underbrace{\left[\underbrace{(x_s)^2\alpha}_{\substack{AdoptionSavings\\Under\\EnvironmentalEmergencies}} - \underbrace{(x_n)^2\alpha}_{\substack{AdoptionSavings\\UnderNormalDays}}\right]}_{NetAbatementEffect} + \left[2\mu(x_s)\underbrace{\frac{\partial(x_s)}{\partial\mu}}_{\substack{PriceEffect\\Under\\EnvironmentalEmergencies}} + 2(1-\mu)(x_n)\underbrace{\frac{\partial(x_n)}{\partial\mu}}_{\substack{PriceEffect\\UnderNormalDays}}\right]\alpha.$$

On the other hand, market clearing in the permit markets requires total abatement to be equal to the weighted abatement done by adopters and non-adopters in each state:

(B3) $$\overline{q_n} = \lambda^{2TPP}(x_n,\mu)\left[q_n{}^{A}(x_n)\right] + \left[1-\lambda^{2TPP}(x_n,\mu)\right]\left[q_n{}^{NA}(x_n)\right],$$

(B4) $$\overline{q_c} = \lambda^{2TPP}(x_s,\mu)\left[q_c{}^{A}(x_s)\right] + \left[1-\lambda^{2TPP}(x_s,\mu)\right]\left[q_c{}^{NA}(x_s)\right],$$

with $q_n^A(x_n) = \dfrac{(x_n)}{2\tilde{c}}$; $q_n^{NA}(x_n) = \dfrac{(x_n)}{2c}$; $q_c^A(x_s) = \dfrac{(x_s)}{2\tilde{c}}$ and $q_c^{NA}(x_s) = \dfrac{(x_s)}{2c}$.

Substituting $\lambda^{2TPP}, q_n^A(x_n)$ and $q_n^{NA}(x_n)$ into (B3), we obtain:

(B5) $$\begin{aligned}&\overline{q_n} = \left[\mu(x_s)^2\alpha + (1-\mu)(x_n)^2\alpha\right]\left[\frac{x_n}{2\tilde{c}}\right] + \\ &\left[1-\left[\mu(x_s)^2\alpha + (1-\mu)(x_n)^2\alpha\right]\right]\left[\frac{x_n}{2c}\right]\end{aligned}.$$

Differentiating with respect to x_n and μ, and solving for $dx_n / d\mu$ yields:

(B6) $$\frac{dx_n}{d\mu} = -\frac{2\alpha x_n\left[(x_s)^2\alpha - (x_n)^2\alpha\right]}{2\mu(x_s)^2\alpha^2 + 6(1-\mu)(x_n)^2\alpha^2 + \dfrac{1}{2c}} < 0.$$

Substituting $\lambda^{2TPP}, q_c^A(x_s)$, and $q_c^{NA}(x_s)$ into (B3), we obtain:

(B7) $$\begin{aligned}&\overline{q_c} = \left[\mu(x_s)^2\alpha + (1-\mu)(x_n)^2\alpha\right]\left[\frac{x_s}{2\tilde{c}}\right] + \\ &\left[1-\left[\mu(x_s)^2\alpha + (1-\mu)(x_n)^2\alpha\right]\right]\left[\frac{x_s}{2c}\right]\end{aligned}.$$

Differentiating with respect to x_s and μ, and solving for $dx_s / d\mu$ yields:

(B8) $$\frac{dx_s}{d\mu} = -\frac{2\alpha x_s\left[(x_s)^2\alpha - (x_n)^2\alpha\right]}{2(1-\mu)(x_n)^2\alpha^2 + 6\mu(x_s)^2\alpha^2 + \dfrac{1}{2c}} < 0.$$

Substituting (B6) and (B8) into (B2) yields:

(B9)

$$\frac{\partial \lambda^{2TPP}}{\partial \mu} = \underbrace{\left[(x_s)^2 \alpha - (x_n)^2 \alpha \right]}_{NetAbatementEffect} -$$

$$\left[\underbrace{2\mu\alpha(x_s) \frac{\alpha(x_s)\left[(x_s)^2 \alpha - (x_n)^2 \alpha \right]}{3\mu(x_s)^2\alpha^2 + (1-\mu)(x_n)^2\alpha^2 + \frac{1}{4c}}}_{\substack{PriceEffect \\ UnderContingencies}} + \underbrace{2(1-\mu)\alpha(x_n) \frac{\alpha(x_n)\left[(x_s)^2 \alpha - (x_n)^2 \alpha \right]}{3(1-\mu)(x_n)^2\alpha^2 + \mu(x_s)^2\alpha^2 + \frac{1}{4c}}}_{\substack{PriceEffect \\ UnderNormalDays}} \right]$$

Appendix C

The effect of changes in the incidence of environmental emergencies on the rate of adoption is given by:

$$\text{(C1)} \qquad \frac{\partial \lambda^c}{\partial \mu} = \underbrace{\left\{ \left[c - \tilde{c} \right] \left[\overline{q_c} \right]^2 - \left[\alpha (x_c)^2 \right] \right\}}_{NetAbamentEffect} + \underbrace{\frac{2(1-\mu)(x^c)^2\alpha^2 \left[\left[\alpha (x^c)^2 \right] - \left[c - \tilde{c} \right] \left[\overline{q_c} \right]^2 \right]}{3(1-\mu)(x^c)^2\alpha^2 + \mu(c-\tilde{c})(\overline{q_c})^2\alpha + \frac{1}{4c}}}_{PriceEffect}.$$

Let β_0 denote the "net abatement effect" and $\beta_1 = (x_c)^2\alpha$ and $\beta_2 = \left[c - \tilde{c} \right](\overline{q_c})^2$ the adoption savings under permits and under the emission standard, respectively. Then, (C1) can be re-written as:

$$\text{(C2)} \qquad \frac{\partial \lambda^c}{\partial \mu} = \beta_0 \left[1 - \frac{2\beta_1\alpha}{3\beta_1\alpha + \frac{1}{(1-\mu)}\left[\beta_2\mu\alpha + \frac{1}{4c} \right]} \right] = 0.$$

Computing (C2) when $\mu \to 0$ yields:

(C3) $$\frac{\partial \lambda^{c}}{\partial \mu}\Big|_{\mu=0} \to \beta_0 \left[1 - \frac{2\beta_1\alpha}{3\beta_1\alpha + \frac{1}{4c}} \right].$$

On the other hand, if a mixed system of tradable permits is used, this effect is given by:

(C4) $$\frac{\partial \lambda^{2TPP}}{\partial \mu} = \underbrace{\left[(x_s)^2\alpha - (x_n)^2\alpha \right]}_{NetAbatementEffect} - \left[\underbrace{\frac{2\mu\alpha^2(x_s)^2\left[(x_s)^2\alpha - (x_n)^2\alpha \right]}{3\mu(x_s)^2\alpha^2 + (1-\mu)(x_n)^2\alpha^2 + \frac{1}{4c}}}_{\substack{PriceEffect \\ EnvironmentalEmergencies}} + \underbrace{\frac{2(1-\mu)\alpha^2(x_n)^2\left[(x_s)^2\alpha - (x_n)^2\alpha \right]}{3(1-\mu)(x_n)^2\alpha^2 + \mu(x_s)^2\alpha^2 + \frac{1}{4c}}}_{\substack{PriceEffect \\ NormalDays}} \right].$$

Let γ_0 denote the "net abatement effect" and $\gamma_1 = (x_n)^2\alpha$ and $\gamma_2 = (x_S)^2\alpha$ the adoption savings during normal days and during environmental emergencies, respectively. Then $\frac{\partial \lambda 2^{TPP}}{\partial \mu}$ can be re-written as:

(C5) $$\frac{\partial \lambda^{2TTP}}{\partial \mu} = \gamma_0 \left[1 - \frac{2\alpha\gamma_2}{3\alpha\gamma_2 + \frac{1}{\mu}\left[(1-\mu)\alpha\gamma_1 + \frac{1}{4c} \right]} - \frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{(1-\mu)}\left[\mu\alpha\gamma_2 + \frac{1}{4c} \right]} \right].$$

Computing (C5) when $\mu \to 0$ yields:

(C6) $$\frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu=0} \to \gamma_0 \left[1 - \frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{4c}} \right].$$

Let us compare (C3) and (C6). Since $\beta_1 > \gamma_1$, the absolute value of the price effect under a mix of tradable permits and emission standards is higher:

(C7) $$\left| \frac{2\beta_1\alpha}{3\beta_1\alpha + \frac{1}{4c}} \right| > \left| \frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{4c}} \right|.$$

On the other hand, $\gamma_0 > \beta_0$ since $(x_c) \geq (x_n)$ and $(c - \tilde{c})(\overline{q_c})^2 < (x_s)^2$. Then:

(C8) $$\beta_0 \left[1 - \frac{2\beta_1\alpha}{3\beta_1\alpha + \frac{1}{4c}} \right] < \gamma_0 \left[1 - \frac{2\alpha\gamma_1}{3\alpha\gamma_1 + \frac{1}{4c}} \right].$$

In other words, the effect of changes in the incidence of environmental emergencies on the rate of adoption is higher under the mixed system of tradable permits when $\mu \to 0$; i.e., $\frac{\partial \lambda^{c}}{\partial \mu}|_{\mu \to 0} < \frac{\partial \lambda^{2TPP}}{\partial \mu}|_{\mu \to 0}$.

Appendix D

Social welfare is given by the following expression:

$$\text{(D1)}\quad \begin{aligned} W = {} & \mu\Big[\gamma_0[\lambda q_c^A + (1-\lambda)q_c^{NA}] - \gamma_1[\lambda q_c^A + (1-\lambda)q_c^{NA}]^2 - \lambda\tilde{c}(q_c^A)^2 - (1-\lambda)c(q_c^{NA})^2\Big] \\ & + [1-\mu]\Big[\beta_0[\lambda q_n^A + (1-\lambda)q_n^{NA}] - \beta_1[\lambda q_n^A + (1-\lambda)q_n^{NA}]^2 - \lambda\tilde{c}(q_n^A)^2 - (1-\lambda)c(q_n^{NA})^2\Big] - \int_0^{\lambda} k dk \end{aligned} .$$

Maximizing (D1) with respect to $[q_c^A, q_c^{NA}, q_n^A, q_n^{NA}\lambda]$, we obtain the following FOCs:

$$\text{(D2)}\quad q_c^A : \gamma_0 - 2\gamma_1\left[\lambda q_c^A + (1-\lambda)q_c^{NA}\right] = 2\tilde{c}(q_c^A) ,$$

$$\text{(D3)}\quad q_c^{NA} : \gamma_0 - 2\gamma_1\left[\lambda q_c^A + (1-\lambda)q_c^{NA}\right] = 2c(q_c^{NA}) ,$$

$$\text{(D4)}\quad q_n^A : \beta_0 - 2\beta_1\left[\lambda q_n^A + (1-\lambda)q_n^{NA}\right] = 2\tilde{c}(q_n^A) ,$$

$$\text{(D5)}\quad q_n^{NA} : \beta_0 - 2\beta_1\left[\lambda q_n^A + (1-\lambda)q_n^{NA}\right] = 2c(q_n^{NA}) ,$$

$$\text{(D6)}\quad \begin{aligned} & \lambda : \lambda = \mu\Big[\gamma_0[q_c^A - q_c^{NA}] - 2\gamma_1 A[q_c^A - q_c^{NA}] + c(q_c^{NA})^2 - \tilde{c}(q_c^A)^2\Big] \\ & + [1-\mu]\Big[\beta_0[q_n^A - q_n^{NA}] - 2\beta_1 B[q_n^A - q_n^{NA}] + c(q_n^{NA})^2 - \tilde{c}(q_n^A)^2\Big] \end{aligned} ,$$

where $A = \left[\lambda q_c^A + (1-\lambda)q_c^{NA}\right]$ and $B = \left[\lambda q_n^A + (1-\lambda)q_n^{NA}\right]$ are the total level of abatement during environmental emergencies and normal days, respectively.

From (D2) and (D3) we have that:

$$\text{(D7)}\quad 2\tilde{c}(q_c^A) = 2c(q_c^{NA}) = \delta_c .$$

Substituting (C7) into (C2) we have that:

(D8) $\gamma_0 - 2\gamma_1 A = \delta_c$.

From (D4) and (D5) we have that:

(D9) $2\tilde{c}(q_n^A) = 2c(q_n^{NA}) = \delta_n$.

Substituting (D9) into (D4) we have that:

(D10) $\beta_0 - 2\beta_1 B = \delta_n$.

Substituting (D8) and (D10) into (D6) we have that:

(D11) $\lambda = \mu\left[\delta_c[q_c^A - q_c^{NA}] + c(q_c^{NA})^2 - \tilde{c}(q_c^A)^2\right] + [1-\mu]\left[\delta_n[q_n^A - q_n^{NA}] + c(q_n^{NA})^2 - \tilde{c}(q_n^A)^2\right]$.

Finally, substituting (D7) and (D9) into (D11) we have that:

(D12) $\lambda = \left[\mu(\delta_c)^2 + (1-\mu)(\delta_n)^2\right]\alpha$,

and since $\delta_c = x_c$ and $\delta_n = x_n$,

(D13) $\lambda = \left[\mu(x_c)^2 + (1-\mu)(x_n)^2\right]\alpha$ as it is stated in equation (24).