Topics

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The Strategic Use of Innovation to Influence Environmental Policy: Taxes versus Standards

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Abstract: This paper evaluates the strategic behavior of a polluting monopolist to influence environmental policy, either with taxes or with standards, comparing two alternative policy games. The first of the games assumes that the regulator commits to an ex-ante level of the policy instrument. The second one is the time-consistent policy game. We find that the strategic behavior of the firm is welfare improving and leads to more environmental innovation than under regulatory commitment if a tax is used to control pollution. However, the contrary occurs if an emission standard is used. Under commitment, it is shown that both policy instruments are equivalent. We conclude that the optimal environmental policy is to use an emission tax since it yields the same welfare level than an emission standard for a committed regulator yet a larger welfare for a non-committed regulator.

Keywords: monopoly, commitment, innovation, taxes, standards

1 Introduction

The analysis of the incentives provided by environmental policy for both adoption and development of advanced abatement technology has been extensively addressed in the literature (see for instance the survey published by Requate (2005a)). Among the different themes studied, this paper focuses on the credibility of regulator policies when faced with the strategic behavior of a firm with market power. As noted by Gersbach and Glazer (1999), when the regulator is not able to commit to the stringency of the policy instrument, firms may

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strategically use innovation to ratchet down regulation and increase profits. One expects this behavior to have a negative effect on welfare relative to the case of regulatory commitment. The regulatory programs to reduce automobile emissions constitute a classical example, as quoted by Gersbach and Glazer (1999). The effectiveness of such programs depends critically on the regulator's credibility. If the automakers conjecture that the regulator will not implement the standards if they do not invest because of the large costs firms should support in this case, then they will not invest to comply with the standards and the regulator will have to postpone the date of compliance. A well-known case of this kind of time-inconsistency problem is the implementation of the 1970 U.S. Clean Air Act Amendments for controlling automobile emissions. The legislation mandated that new vehicles in 1975 had to reduce hydrocarbons (HC) and carbon monoxide (CO) emissions by 90% relative to the 1970 standards. A 90% reduction in nitrogen oxides (NO_x) emissions was also required for 1976 vehicles. However, the big U.S. producers, General Motors, Ford and mainly Chrysler did very little internal R&D and failed to secure external commitment from suppliers to satisfy the new standards. This circumstance along with the macroeconomic effects of the 1973 oil embargo led the Congress in June 1974 to extend standards until 1978. However, in August 1977, automakers began manufacturing 1978 model cars that did not meet the new standards. Because the law prohibited introducing cars into commerce without certification, the manufacturers could not ship them to the dealers. Thus, the Congress was forced either to delay the deadline for compliance or prohibit U.S. producers from selling automobiles. Finally, the Congress passed the 1977 amendments to the Clean Air Act and delayed the compliance of the standards until 1980 for HC and until 1981 for CO and NO_x.¹ The regulation of the power sector in Spain offers another example. In June 2012, the Spanish Government gave 2 months to the firm running the oldest nuclear power station in Spain in the town of Santa María de Garoña to apply for an extension of its activity until 2019 provided that the firm invested €120 million in security measures and around that time announced a new tax on radioactive waste. Garoña has a reactor identical to #1 reactor of Fukushima. After these two announcements the firm not only refused to apply for an extension but also stopped producing electricity on the same day the Government approved the tax at the end of December 2012. That year the nuclear power station generated 1,600 jobs, had an economic impact in

¹ A very detailed analysis of the implementation problems of the 1970 U.S. Clean Air Act Amendments can be found in Gerard and Lave (2005). Another interesting paper that reviews the recent experience concerning the role of standards in stimulating environmental innovation is Vollebergh and van der Werf (2014).

the region of €279 million and yielded fiscal revenues of €75 million. The firm claimed that the new tax made the investment unprofitable. Thus, the Spanish Government was forced either to revise its policy or to face a definitive shutdown of the nuclear power station with all its economic and political implications. At the end of October 2013 (less than one year later), the Spanish Congress passed a law that included, among other fiscal measures, a €153 million tax exemption on radioactive waste for the nuclear power station of Garoña and the Government announced that it would consider an extension of its activity until 2031 to complete a life cycle of 60 years. All these changes were proposed by the same government that implemented the tax on radioactive waste. In May 2014, the firm revised its decision and applied for an authorization to put in activity the nuclear power station until 2031. These are examples that describe the case of a non-credible policy and how in that case the firms can use strategically their investments to influence environmental policy.

Interestingly, Petrakis and Xepapadeas (2001) find for a polluting monopoly, that the strategic behavior of the firm has a beneficial effect on social welfare when the regulator is unable to commit to a specific tax rate noting that it may induce more environmental innovation than under regulatory commitment. They obtain this result comparing two three-stage policy games that differ only in the timing. In the first, that they name the “precommitment (or ex-ante) policy game”, the regulator commits to a specific emission tax rate, then the firm selects the abatement effort, and finally it chooses its output. In the second, that they call the “time-consistent (or ex-ante) policy game”, the firm first selects its abatement effort, then the government sets its emission tax level, and finally the firm chooses its output. This game emerges whenever the environmental policy is non-credible. Then, the monopoly acting as a Stackelberg leader can strategically select its abatement effort in order to influence the emission tax rate that the regulator will eventually implement. In other words, they compare a game where the regulator is the “first-mover” with a game where the firm is the “first-mover” to evaluate the effects of firm strategic behavior.² The result derived by these authors has implications for the design of environmental policy. Policy makers often believe that the inability to establish rules that limit future regulatory discretion is detrimental for implementing optimal environmental regulation. According to Petrakis and Xepapadeas’ (2001) paper rules are not necessarily better than discretion for controlling the emissions of a monopoly.

² This approach has also been applied by Poyago-Theotoky and Teerasuwannajak (2002) to examine the effects of the strategic behavior of firms in a duopoly with product differentiation when the regulator uses an emission tax for controlling pollution, and by Puller (2006) to examine the same issue in a Cournot duopoly when the regulator uses a performance standard.

In this paper, we investigate whether this result holds when the regulator uses an emission standard for controlling pollution instead of an emission tax. We follow Petrakis and Xepapadeas' approach to study the strategic behavior of the monopoly with the difference that when an emission standard is used the policy games only have two stages.³ We show that the regulator's ability to commit to an emission *standard* not only yields larger welfare relative to the no commitment case but also promotes more environmental innovation, i.e. the strategic behavior of the monopolist has a detrimental effect on social welfare – the opposite to what happens with an emission tax. The intuition for why a particular policy instrument operates differently is the following. Different policy instruments give rise to drastically different best response functions for the monopolist. Specifically, there is strategic complementarity between the investment in environmental innovation and the emission tax from the firm's point of view, whereas there is strategic substitutability between the investment in environmental innovation and the emission standard. Therefore the strategic behavior of the monopolist has different effects on output, innovation, profits and welfare. When a tax is used to control pollution, the reduction in the tax induced by the strategic behavior of the monopolist usually gives rise to an increase in environmental innovation that mitigates the increment in emissions. The result is that the increase in consumer surplus because of a larger production more than compensates the increment in investment costs and environmental damages leading to higher welfare. However, when a standard is used to control pollution, the monopolist substantially reduces innovation to obtain a larger standard which has a low impact on production. In the end the increment in environmental damages more than compensates the reduction in investment costs and the small gains in consumer surplus resulting in lower welfare.

Moreover, we also show that the two policy instruments are equivalent when there is commitment as they deliver identical investment, production, emissions and welfare. This result is the consequence that for each tax rate there exists one and only emission standard that yields the same level of welfare and vice versa. Then the substitution of the tax rate by the corresponding emission standard in the welfare function of the optimization problem that solves the regulator when a tax is used yields the welfare function of the optimization problem that solves the regulator when a standard is applied.

³ As emissions are a function of production and innovation effort, if the regulator applies an emission standard in the first stage when the firm decides its level of abatement effort in the second stage is also determining the level of output compatible with the standard. The same kind of argument applies when the timing is changed.

Thus, our results do not support that discretion (no commitment) is necessarily better than rules (commitment) because it depends on the instrument selected by the regulator. No commitment is better than commitment if a tax is used for controlling the emissions of a monopoly but the contrary occurs if the regulator applies a standard. Nevertheless, we may derive a policy recommendation from our analysis. In the case of a polluting monopoly, the optimal policy is to apply an emission tax. With commitment, a tax leads to same level of welfare than that achieved applying a standard and, without commitment, it implements a larger level of welfare.

Besides Gersbach and Glazer (1999) and Petrakis and Xepapadeas (2001), and to best of our knowledge, there are only a few papers directly addressing the research question studied in this paper: Petrakis and Xepapadeas (1999, 2003), Poyago-Theotoky and Teerasuwannajak (2002) and Puller (2006).⁴ Petrakis and Xepapadeas (1999, 2001, 2003) and Poyago-Theotoky and Teerasuwannajak (2002) analyze the strategic use of innovation to influence the environmental policy for different market structures when the regulator uses an emission tax. They find that the strategic behavior of firms may be welfare improving except when marginal damages are constant – see Petrakis and Xepapadeas (1999). In this paper, we extend their analyses to the case of a regulator that applies an emission standard to control pollution coming from a monopoly. Gersbach and Glazer (1999) consider an oligopoly where the regulator allocates tradable emission permits after firms have decided whether to make a lumpy and irreversible investment that reduces the cost of compliance. For simplicity, they assume that production capacity and output are fixed and that each firm produces one unit of the good at a fixed price. In the case of a monopoly, they show that the firm does not invest. Because the firm cannot be credibly threatened with regulation, it minimizes costs by not investing. Instead in our model, the investment is not lumpy and the monopoly can select the level of production to sell in the market. These two changes modify the result obtained by Gersbach and Glazer (1999) and the investment, when there is no commitment, is positive. Moreover, we compare this solution with that corresponding to a committed regulator, something that is not done by Gersbach and Glazer (1999) who focus only on the time-consistent policy game. Finally, we would like to point out that our results are consistent with those derived by Puller (2006) who finds that strategic behavior is not welfare improving when the regulator uses a performance standard (emissions per unit of output) to control monopolist's emissions and environmental damages are

⁴ The list of papers studying the design of the environmental policy under imperfect competition is much longer. An excellent survey is given by Requate (2006).

linear. In our paper, we focus on emission standards, assume that environmental damages are quadratic and compare the strategic effects obtained for an emission standard with those derived for an emission tax.⁵

More recently, Ulph and Ulph (2013) study optimal climate change policies when governments cannot commit. However, their approach differs in several respects from that used in this paper. In Ulph and Ulph (2013) no commitment comes from the possibility that future governments give different weights in the welfare function to environmental damages relative to economic production than current governments. Thus, the lack of commitment implies that both the firm and the current government face uncertainty about future tax rates. In their model, in period 1 the government uses a lump-sum R&D subsidy to induce the firm to make a large investment with a fixed cost, and in period 2, the government sets up a tax on emissions and the firm produces, pollutes and pays the taxes. However, in our paper, the implication of the lack of commitment is that the environmental policy cannot be credible what gives the firm the possibility to be the first-mover in the policy game with a non-committed regulator. Moreover, they abstract from any competition issues arising from the potential exercise of monopoly power by the single firm that is regulated by the government and assume that environmental damages are linear.⁶

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 analyzes the strategic use of innovation to influence an emission tax. Section 4 considers an emission standard and in Section 5 the results obtained for an emission standard are compared with those derived by Petrakis and Xepapadeas (2001) for an emission tax. Section 6 offers some concluding remarks and points out lines for future research.

⁵ Other relevant contributions have examined various aspects of environmental policy and firms' incentives to adopt cleaner technologies. Regarding the importance of commitment in a setting where a monopolistic upstream firm engages in R&D and sells abatement technology to polluting downstream firms, see, among others, Laffont and Tirole (1996), Denicolò (1999), Requate (2005b), Montero (2011) and Wirl (2014). An incumbent's strategic behavior under an emission tax has been studied by Schoonbeek and de Vries (2009) and Espnola-Arredondo and Muñoz-García (2013). Poyago-Theotoky (2007, 2010) and Ouchida and Goto (2014) examine how the organization of R&D influences the incentives that a time-consistent emission tax has on environmental innovation in a Cournot duopoly with research spillovers in emission reduction.

⁶ Other papers where damages are uncertain and environmental policy is compared under commitment and no commitment are Tarui and Polasky (2005) and Jakob and Brunner (2014). However, as Ulph and Ulph (2013), both papers abstract from any competition issues between polluting firms.

2 The Model

Following Petrakis and Xepapadeas (2001), our model considers a monopolist that faces a linear (inverse) demand function given by $P = a - q$, where P is price and q is total output. The marginal cost of production is assumed constant and equal to c , with $a > c > 0$. After an appropriate choice of measurement units such that each unit of output generates one unit of pollution, we write firm i 's (net) emissions as $e(q, w) = q - w$, where w stands for environmental innovation.⁷ Environmental innovation, w , commonly referred to as end-of-pipe pollution investment for this specification of the emission function, is costly. Investment costs are given by $c(w) = \gamma w^2/2$, $\gamma > 0$, which captures that there exist decreasing returns to scale in innovation effort, with the parameter γ measuring the extent of such decreasing returns. Finally, pollution generates environmental damages. The damage function is assumed to be quadratic in (net) emissions as follows: $D(e) = de^2/2$. To guarantee an interior solution for environmental innovation, we assume that $d > 1$, that is, environmental damages are not insignificant for the economy.

In what follows we shall consider two alternative policy games, each featuring a multi-stage game of complete and perfect information between a welfare maximizing regulator and a profit maximizing firm. To be more precise, in the first policy game, which will be labeled as the *committed (or ex-ante) regulator game*, the regulator sets the level of an environmental policy instrument, then the monopolist, taking that level as given, chooses the level of environmental innovation and output. In the second policy game, the *non-committed (or ex-post) regulator game*, it is the monopolist who first selects its environmental innovation level, then the regulator sets the level of the policy instrument and finally the monopolist chooses its output.⁸ The analysis will distinguish two instruments: a per unit tax on emissions and a standard. When the regulator chooses an emission tax, the two policy games have three stages. In both games, the firm selects output in the third stage. However, when the regulator chooses a standard, the two policy games only have two stages provided that output,

⁷ The particular choice for the specification of the pollution generation process is made for simplicity. We conjecture that for a non-linear emissions function we would obtain the same qualitative results. For instance, Petrakis and Xepapadeas (2003) show that the results derived for a linear specification of the emissions function – like the one used in this paper – turn out to be robust under a non-linear specification.

⁸ We use this terminology to emphasize the importance of the regulator's commitment to define the timing of the game.

according to the emission function, is determined once the regulator has chosen the standard (emissions) and the monopolist has chosen the innovation. The solution concept employed is subgame perfection.

Finally, we would like to point out that the focus in this paper is on *second-best policies*. As is well known, since there are two variables to adjust because of the distortions that characterize a polluting monopoly, the regulator would need two instruments to implement the first-best or efficient solution: a subsidy per unit of production could be used to correct for market power and a tax on emissions to correct for the pollution externality.⁹ In this case, it is easy to show that the tax set by the regulator equals the marginal environmental damages. As already mentioned we assume that the regulator can use only one policy instrument, a tax or a standard.

3 Emission Tax

In this section we first summarize the analysis developed by Petrakis and Xepapadeas (2001) for an emission tax. In addition to the committed regulator game and the non-committed regulator game and to facilitate the comparison of the outcomes of these two games, Petrakis and Xepapadeas (2001) present a *reference two-stage game* in which in the first stage the firm and the regulator decide simultaneously the innovation effort and the emission tax rate, respectively, and in the second stage the monopolist selects its output.

Output selection occurs in the last stage which is common to all the above games, so we begin with the analysis of this stage. The monopolist chooses its output to maximize profits:

$$\max_{\{q\}} \pi = (a - q)q - cq - \frac{\gamma}{2}w^2 - t(q - w)$$

taking as given the emission tax rate, t . From the first-order condition $a - 2q - c - t = 0$, we obtain the monopolist's optimal output:

$$q(t) = \frac{A - t}{2}, \quad [1]$$

⁹ The distortions that characterize a polluting monopoly are three: the output and abatement effort distortions due to the firm's market power and the distortion associated with the environmental externality. However, as emissions are a function of output and abatement effort, it is possible with two policy instruments to implement the efficient solution.

where $A = a - c$, with A being a measure of market size. Using this expression profits can be written as follows

$$\pi(t, w) = (A - q(t))q(t) - \frac{\gamma}{2}w^2 - t(q(t) - w) \quad [2]$$

where $q(t)$ is given by eq. [1].

Next, consider the reference game. In the first stage, the monopolist, taking as given the emission tax, chooses its innovation effort to maximize profits defined by eq. [2]. At the same time, the regulator, taking as given the firm's innovation effort, selects the welfare maximizing emission tax rate, which is defined as the sum of consumer surplus and monopoly profits minus environmental damages, that is

$$\begin{aligned} \max_{\{t\}} W(t, w) &= \int_0^{q(t)} (a - c - x) dx - \frac{\gamma}{2}w^2 - \frac{d}{2}(q(t) - w)^2 \\ &= Aq(t) - \frac{1}{2}q(t)^2 - \frac{\gamma}{2}w^2 - \frac{d}{2}(q(t) - w)^2, \end{aligned} \quad [3]$$

where $q(t)$ is given by eq. [1]. The reaction functions for the monopolist and the regulator are, respectively,

$$w(t) = \frac{t}{\gamma}, \quad \frac{dw}{dt} = \frac{1}{\gamma} > 0, \quad [4]$$

$$t(w) = \frac{(d-1)A - 2dw}{1+d}, \quad \frac{dt}{dw} = -\frac{2d}{1+d} < 0. \quad [5]$$

Note that since the slope of eq. [4] is positive, investment in innovation and emission tax are strategic *complements* from the monopolist's perspective. However, they are strategic *substitutes* from the regulator's point of view.

Once the reference game has been defined, it follows that the committed regulator game corresponds to the game where the regulator is the Stackelberg leader and the monopolist the Stackelberg follower while the non-committed regulator game corresponds to the game where their roles are reversed. In the next two subsections, the (subgame perfect) equilibrium outcome of those two policy games are characterized.

3.1 The Committed Regulator Game

In the first stage, the regulator selects the emission tax to maximize welfare, taking into account how the monopolist is going to respond to it, that is,

$$\max_{\{t\}} W(t) = Aq(t) - \frac{1}{2}q(t)^2 - \frac{\gamma}{2}w(t)^2 - \frac{d}{2}(q(t) - w(t))^2 \quad [6]$$

where $q(t)$ is given by eq. [1] and $w(t)$ by eq. [4], the monopolist's reaction function of the reference game. This maximization problem yields the optimal emission tax¹⁰

$$t^c = \frac{A\gamma(2d + (d-1)\gamma)}{4d + (1+d)(4+\gamma)\gamma}. \quad [7]$$

A sufficient condition that ensures a positive tax rate is that $d > 1$. Using eq. [7] we can calculate the equilibrium values for the remaining variables. Then the monopolist's environmental innovation and output are given by¹¹

$$w_t^c = \frac{A(2d + (d-1)\gamma)}{4d + (1+d)(4+\gamma)\gamma} > 0 \text{ for } d > 1, \quad [8]$$

$$q_t^c = \frac{A(2+\gamma)(d+\gamma)}{4d + (1+d)(4+\gamma)\gamma} > 0. \quad [9]$$

It is easy to check that $e_t^c = q_t^c - w_t^c$ is positive. Finally, equilibrium profits and welfare are obtained by developing the following expressions

$$\pi_t^c = (A - q_t^c)q_t^c - \frac{\gamma}{2}(w_t^c)^2 - t^c e_t^c, \quad [10]$$

$$W_t^c = Aq_t^c - \frac{1}{2}(q_t^c)^2 - \frac{\gamma}{2}(w_t^c)^2 - \frac{d}{2}(e_t^c)^2. \quad [11]$$

3.2 The Non-committed Regulator Game

In the first stage, the monopolist chooses the innovation effort to maximize profits, taking into account how the regulator is going to react to it, that is,

$$\max_{\{w\}} \pi(w) = (A - q(t(w)))q(t(w)) - \frac{\gamma}{2}w^2 - t(w)(q(t(w)) - w)$$

where $t(w)$ is given by eq. [5], the regulator's reaction function of the reference game. This means that the monopolist, by choosing a higher innovation level in the first stage, can strategically prompt a lower tax rate in the second stage.¹²

¹⁰ In the expressions that follow, superscript c is used to denote the commitment case.

¹¹ The subscript t stands for the emission tax.

¹² The possibility of using innovation strategically to influence the environmental policy disappears if damages are linear. In this case, the regulator's reaction function is independent of the innovation effort. In other words, because of the linearity of environmental damages, the

Plugging eq. [5] in the monopolist's profit function results in the following equilibrium innovation¹³

$$w_t^{nc} = \frac{A((1+d)^2 - 2)}{\gamma(1+d)^2 + 2d(2+d)} > 0 \text{ for } d > 1. \quad [12]$$

Then the equilibrium tax and output under no commitment are given by

$$t^{nc} = \frac{A((d^2 - 1)\gamma - 2d)}{\gamma(1+d)^2 + 2d(2+d)}, \quad [13]$$

$$q_t^{nc} = \frac{A((1+d)\gamma + d(3+d))}{\gamma(1+d)^2 + 2d(2+d)} > 0. \quad [14]$$

It is worth noting that $d > 1$ does not guarantee a positive tax.¹⁴ The reason is that if abatement is *relatively* cheap, for $\gamma < \check{\gamma}(d)$, the monopolist can find it optimal to select a large level of innovation effort to induce the regulator to apply a subsidy instead of a tax. Notice that according to eq. [12], the lower γ the bigger w_t^{nc} . Thus, with low enough γ , the increase in the spending on environmental innovation would be more than compensated by the subsidies received and the increase in revenues because of a larger level of production. Nevertheless, since $\check{\gamma}(d)$ is a decreasing function for any value of γ , there exists a critical value of d such that for d larger than the critical value, $\gamma > \check{\gamma}(d)$ and the optimal policy would be to set a tax even if the monopolist can use strategically the innovation to influence the environmental policy.

It is easy to check that $e_t^{nc} = q_t^{nc} - w_t^{nc}$ is positive. Finally, equilibrium profits and welfare are obtained by developing the following expressions

$$\pi_t^{nc} = (A - q_t^{nc})q_t^{nc} - \frac{\gamma}{2}(w_t^{nc})^2 - t^{nc}e_t^{nc}, \quad [15]$$

$$W_t^{nc} = Aq_t^{nc} - \frac{1}{2}(q_t^{nc})^2 - \frac{\gamma}{2}(w_t^{nc})^2 - \frac{d}{2}(e_t^{nc})^2. \quad [16]$$

model predicts a dominant strategy for the regulator. Thus, the monopolist *cannot* strategically use its innovation to influence the tax rate in its own benefit even though the regulator cannot commit to the emission tax rate.

13 We employ superscript *nc* to denote the equilibrium in the no commitment game.

14 t^{nc} is positive provided that $\gamma > \check{\gamma}(d) = 2d/(d^2 - 1)$ where $\check{\gamma}(d)$ is a decreasing convex function with $\check{\gamma}(1) = +\infty$. If this is not the case, then the optimal policy is to apply a subsidy in the non-commitment case.

3.3 Comparing Policy Games

In this subsection we reproduce Proposition 3 in Petrakis and Xepapadeas (2001). It summarizes the comparison of expressions [10]–[15] and [11]–[16].

Proposition 1 (Petrakis and Xepapadeas 2001): *The monopolist's profits and total welfare are always higher when the government is unable to commit to a specific emission tax level, that is, when it follows time-consistent policies.*

Therefore, when the regulator employs an emission tax the strategic behavior of the firm has a positive effect in welfare terms. It turns out that the equilibrium tax under non commitment is lower than under commitment, $t^{nc} < t^c$. Moreover, this leads to more innovation when $t^{nc} > 0$, i.e. if investment costs are large enough to guarantee that the optimal policy consists of implementing a tax on emissions when there is no commitment. In the end, the output level and so consumer surplus is higher under no commitment. On the other hand, the bigger the output the bigger the environmental damages. The welfare comparison indicates that the latter negative effect is weaker than the positive effects from the increase in consumer surplus and in monopoly profits.

Next, we calculate and compare profits before taxation. We will need the expressions of profits before taxation to compare them with the profits the monopolist gets when the regulator uses an emission standard instead of an emission tax. Profits before taxation when there is commitment, denoted by $\hat{\pi}_t^c$, are given by the following expression

$$\begin{aligned}\hat{\pi}_t^c &= (A - q_t^c)q_t^c - \frac{\gamma}{2}(w_t^c)^2 \\ &= \frac{(a-c)^2((\gamma+2)^3d^2 + 2\gamma(\gamma+2)^3d + \gamma^2(3\gamma+8))}{2((\gamma+2)^2d + \gamma(4+\gamma))^2}.\end{aligned}\quad [17]$$

and profits before taxation when there is no commitment, $\hat{\pi}_t^{nc}$, are

$$\begin{aligned}\hat{\pi}_t^{nc} &= (A - q_t^{nc})q_t^{nc} - \frac{\gamma}{2}(w_t^{nc})^2 \\ &= \frac{(a-c)^2((\gamma+2)d^4 + 2(3\gamma+\gamma^2+4)d^3 + 2(4\gamma+2\gamma^2+3)d^2 + 2\gamma(\gamma+3)d - \gamma)}{2((\gamma+2)d^2 + 2(\gamma+2)d + \gamma)^2}.\end{aligned}\quad [18]$$

Then the difference in profits is

$$\hat{\pi}_t^c - \hat{\pi}_t^{nc} = - \frac{(a-c)^2(b_0(\gamma)d^5 - b_1(\gamma)d^4 - b_2(\gamma)d^3 - b_3(\gamma)d^2 - b_4(\gamma)d - b_5(\gamma))}{2(4d + \gamma(\gamma+4)(d+1))^2(2d(d+2) + \gamma(1+d)^2)^2}$$

where

$$\begin{aligned}
 b_0(\gamma) &= 4\gamma(\gamma + 2)^3 > 0 \\
 b_1(\gamma) &= 4(\gamma + 2)(2\gamma + 5\gamma^2 + 5\gamma^3 + \gamma^4 + 4) > 0 \\
 b_2(\gamma) &= 4\gamma(28\gamma + 32\gamma^2 + 11\gamma^3 + \gamma^4 + 8) > 0 \\
 b_3(\gamma) &= 4\gamma(2\gamma + 5\gamma^2 + \gamma^3 + 4) > 0 \\
 b_4(\gamma) &= 4\gamma^2(6\gamma + 4\gamma^2 + \gamma^3 + 8) > 0 \\
 b_5(\gamma) &= 4\gamma^3(\gamma + 2)^2 > 0.
 \end{aligned}$$

Thus, for any given γ the equation

$$b_0(\gamma)d^5 - b_1(\gamma)d^4 - b_2(\gamma)d^3 - b_3(\gamma)d^2 - b_4(\gamma)d - b_5(\gamma) = 0, \quad [19]$$

gives us the critical values for d that allow us to define the intervals of marginal damages for which the difference in profits is either positive or negative. Since the independent term of the equation is negative, $b_0(\gamma)$ is positive and there is only one change of sign, according to Descartes' rule, the equation has only one positive root. Then we can conclude that

Proposition 2: *For all $\gamma > 0$, there exists a value $\hat{d}(\gamma)$ given by the positive root of eq. [19] such that if $d < \hat{d}(\gamma)$ the optimal commitment profits before taxation are larger than the optimal no commitment profits before taxation, i.e., $\hat{\pi}_t^{nc} < \hat{\pi}_t^c$. The opposite happens if $d > \hat{d}(\gamma)$, i.e., $\hat{\pi}_t^c < \hat{\pi}_t^{nc}$.*

Notice that although profits after taxation are larger without commitment for any combination (γ, d) , this is not necessarily so when profits before taxation are compared. Without commitment, the output is larger but also is the environmental innovation. The previous proposition establishes that only when damages are relatively large, the increase in revenues because of a larger output compensates the increase in costs because of higher innovation.

The analysis in the next section unveils that an emission standard produces opposite results.

4 Emission Standard

We shall continue by considering an emission standard $\bar{e}$, sometimes referred to as *command and control policy*. A first difference to highlight with respect to the analysis of emission taxation is that under emission standards regulation,

$q = \bar{e} + w$, and, consequently, the two policy games studied in the previous section only have two-stages, as pointed out in the introduction. To provide a better understanding of the results, we resort again to a reference one-stage game in which the monopolist and the regulator take their decisions simultaneously.

In the reference game, the monopolist, taking as given the emission standard, chooses its innovation effort to maximize profits defined as follows

$$\max_{\{w\}} \pi(\bar{e}, w) = (a - (\bar{e} + w))(\bar{e} + w) - c(\bar{e} + w) - \frac{\gamma}{2}w^2. \quad [20]$$

At the same time, the regulator, taking as given the firm's innovation effort, selects its emission standard to maximize social welfare,

$$\max_{\{\bar{e}\}} W(\bar{e}, w) = A(\bar{e} + w) - \frac{1}{2}(\bar{e} + w)^2 - \frac{\gamma}{2}w^2 - \frac{d}{2}\bar{e}^2. \quad [21]$$

The reaction functions for the monopolist and the regulator are, respectively,

$$w(\bar{e}) = \frac{A - 2\bar{e}}{2 + \gamma}, \quad \frac{dw}{d\bar{e}} = -\frac{2}{2 + \gamma} < 0, \quad [22]$$

$$\bar{e}(w) = \frac{A - w}{1 + d}, \quad \frac{d\bar{e}}{dw} = -\frac{1}{1 + d} < 0. \quad [23]$$

Observe that since the slope of eqs [22] and [23] are negative, the investment in innovation and the emission standard are strategic *substitutes* for both players. However, investment in abatement and emission tax were strategic *complements* from the monopolist's point of view. This is relevant a difference when conducting comparison between taxes and standards.

The next two subsections characterize the (subgame perfect) equilibrium when one of the agents plays before the other.

4.1 The Committed Regulator Game

In the first stage, the regulator selects the emission standard to maximize welfare taking into account how the monopolist is going to respond to it, that is,

$$\max_{\{\bar{e}\}} W(\bar{e}) = A(\bar{e} + w(\bar{e})) - \frac{1}{2}(\bar{e} + w(\bar{e}))^2 - \frac{\gamma}{2}w(\bar{e})^2 - \frac{d}{2}\bar{e}^2 \quad [24]$$

where $w(\bar{e})$ is given by eq. [22], the monopolist's reaction function of the reference game. Thus, the regulator selects the welfare maximizing level of $\bar{e}$

$$\bar{e}_s^c = \frac{A\gamma(3+\gamma)}{d(2+\gamma)^2 + \gamma(4+\gamma)} > 0, \quad [25]$$

where subscript s stands for emission standards. It is straightforward that the emission standard decreases with environmental damages. Then we can calculate the equilibrium innovation and production levels, which are given by

$$w_s^c = \frac{A((\gamma+2)d-\gamma)}{d(\gamma+2)^2 + \gamma(\gamma+4)} > 0 \text{ for } d > 1, \quad [26]$$

$$q_s^c = \frac{A(\gamma+d)(\gamma+2)}{d(\gamma+2)^2 + \gamma(\gamma+4)} > 0. \quad [27]$$

Finally, equilibrium profits and welfare are provided below

$$\pi_s^c = (A - q_s^c)q_s^c - \frac{\gamma}{2}(w_s^c)^2, \quad [28]$$

$$W_s^c = Aq_s^c - \frac{1}{2}(q_s^c)^2 - \frac{\gamma}{2}(w_s^c)^2 - \frac{d}{2}(\bar{e}_s^c)^2. \quad [29]$$

This completes the analysis of this policy game.

4.2 The Non-committed Regulator Game

In the first stage, the monopolist chooses the abatement effort to maximize profits taking into account how the regulator is going to respond to it.

$$\max_{\{w\}} \pi(w) = (A - (\bar{e}(w) + w))(\bar{e}(w) + w) - \frac{\gamma}{2}w^2$$

where $\bar{e}(w)$ is given by eq. [23], the regulator's reaction function of the reference game. This means that the monopolist, by choosing a lower innovation, can strategically prompt a higher emission standard in the second stage.¹⁵ The maximization problem yields the optimal innovation effort

$$w_s^{nc} = \frac{Ad(d-1)}{(\gamma+2)d^2 + 2\gamma d + \gamma} > 0 \text{ for } d > 1 \quad [30]$$

15 Conversely to what occurs with an emission tax, the possibility of using innovation strategically to influence the environmental policy when the regulator applies a standard does not disappear if damages are linear. The only difference is that the slope of the reaction function in absolute value is equal to one that gives the monopolist a strong capacity to influence the environmental policy. A complete analysis of the linear case is available from the authors upon request.

Then we can substitute for the equilibrium values of emission standard and production levels, which are given by

$$\bar{e}_s^{nc} = \frac{A((\gamma+1)d+\gamma)}{(\gamma+2)d^2+2\gamma d+\gamma} > 0, \quad [31]$$

$$q_s^{nc} = \frac{A((\gamma+d)d+\gamma)}{(\gamma+2)d^2+2\gamma d+\gamma} > 0. \quad [32]$$

Finally, equilibrium profits and welfare are:

$$\pi_s^{nc} = (A - q_s^{nc})q_s^{nc} - \frac{\gamma}{2}(w_s^{nc})^2, \quad [33]$$

$$W_s^{nc} = Aq_s^{nc} - \frac{1}{2}(q_s^{nc})^2 - \frac{\gamma}{2}(w_s^{nc})^2 - \frac{d}{2}(\bar{e}_s^{nc})^2. \quad [34]$$

This completes the analysis of the non-committed regulator game.

4.3 Comparing Policy Games

In this subsection we draw comparisons between the committed and non-committed regulator games. Subtracting eq. [25] from eq. [31] we obtain the difference between the equilibrium emission standards as follows:

$$\bar{e}_s^{nc} - \bar{e}_s^c = \frac{A(2(\gamma+2)d^2 + \gamma(3\gamma+8)d + \gamma^2)}{(d(\gamma+2)^2 + \gamma(\gamma+4))((\gamma+2)d^2 + 2\gamma d + \gamma)} > 0$$

and using eqs [26] and [30] the expression

$$w_s^{nc} - w_s^c = - \frac{A((\gamma^2 + 2\gamma + 4)d^2 + 6\gamma d - \gamma^2)}{(d(\gamma+2)^2 + \gamma(\gamma+4))((\gamma+2)d^2 + 2\gamma d + \gamma)}$$

shows the difference in innovation. This expression is negative for $d > 1$.

Thus, the following proposition can be established:

Proposition 3: *The optimal commitment emission standard is lower than the optimal no commitment emission standard, i.e. $\bar{e}_s^c < \bar{e}_s^{nc}$. However, the optimal commitment environmental innovation is larger than the optimal no commitment environmental innovation, i.e., $w_s^{nc} < w_s^c$.*

So when the government selects its policy after the monopolist's decision on environmental innovation, the monopolist has a strategic incentive to lower its innovation effort in order to induce a larger emission standard. This strategic effect is not present when the government can commit to a specific emission

standard in advance. Therefore, the regulator's *ability* to commit to an emission standard promotes environmental innovation relative to the no commitment case.

Since $q = e + w$ it is unclear what happens to production. Making use of eqs [27] and [32] we obtain the following expression:

$$q_s^c - q_s^{nc} = \frac{A\gamma(\gamma(d^2 - 3d - 2) - 2d)}{(d(\gamma + 2)^2 + \gamma(\gamma + 4))((\gamma + 2)d^2 + 2\gamma d + \gamma)}.$$

This difference in production is zero for all the combinations (γ, d) that satisfy $\gamma = 2d/(d^2 - 3d - 2)$. Analyzing this function it can be concluded that

Proposition 4: *For all $d \in (1, 3.56]$, the optimal commitment production is lower than the optimal no commitment production, i.e., $q_s^c < q_s^{nc}$, regardless of the value of γ . However, for all $d > 3.56$ there exists a decreasing convex function $\tilde{\gamma}(d) = 2d/(d^2 - 3d - 2)$ with $\lim_{d \rightarrow \infty} \tilde{\gamma}(d) = 0$, such that for all $\gamma < \tilde{\gamma}(d)$ the optimal commitment production is lower than the optimal no commitment production, i.e. $q_s^c < q_s^{nc}$ but if $\gamma > \tilde{\gamma}(d)$ the contrary occurs, i.e. $q_s^{nc} < q_s^c$.*

The above result discloses that when d and γ are sufficiently large the increase in environmental innovation when the regulator commits dominates the reduction in the emission standard yielding an increase in production. For low values of d the slope of the regulator's reaction function is steep which gives the monopolist more capacity to get a higher standard and produce more than in the case of a committed regulator, regardless of the importance of the investment costs. However, for large values of d such capacity is weaker and the relationship between the equilibrium levels of production depends on the magnitude of the investment costs as well. In this case, for a given value of d and a non-committed regulator, an increase in γ supposes that the marginal investment costs curve becomes steeper what will push the monopolist to reduce its level of environmental innovation. The regulator will react by increasing the emission standard. However, such increase will not suffice to compensate the reduction in innovation and the result will be a drop in production. Notice that production increases with innovation according to the reaction function of the regulator, eq. [23],

$$q(w) = \bar{e}(w) + w = \frac{A - w}{1 + d} + w = \frac{A + dw}{1 + d}, \quad \frac{dq}{dw} = \frac{d}{1 + d} > 0.$$

The result is that an increase in γ reduces output in the non-committed regulator game. On the other hand, for a committed regulator since the monopolist's reaction function has a negative slope, as γ increases the reduction in the

marginal investment costs *caused by an increase in the emission standard* becomes larger what will lead eventually the regulator to increase the emission standard. The monopolist will react by reducing environmental innovation. However, in this case, the increase in the emission standard more than compensates the reduction in environmental innovation yielding an increase in output. Notice that production increases with emissions standards according to the monopolist's reaction function, eq. [22],

$$q(\bar{e}) = \bar{e} + w(\bar{e}) = \bar{e} + \frac{A - 2\bar{e}}{2 + \gamma} = \frac{A + \gamma\bar{e}}{2 + \gamma}, \quad \frac{dq}{d\bar{e}} = \frac{\gamma}{2 + \gamma} > 0.$$

The result is that an increase in γ increases output in the committed regulator game. Thus, we have to expect that for large enough values of γ , in particular for $\gamma > \hat{\gamma}(d)$, the optimal commitment production will be larger than the optimal no commitment production as the above proposition establishes.

Finally, we compare monopoly profits and welfare under commitment and no commitment environmental policies. The welfare comparison is particularly important because it establishes potential welfare gains from choosing a certain policy regime. Developing welfare expressions [29] and [34] and calculating the difference we get

$$W_s^c - W_s^{nc} = \frac{A^2(b_0(d)\gamma^5 + b_1(d)\gamma^4 + b_2(d)\gamma^3 + b_3(d)\gamma^2 + b_4(d)\gamma + b_5(d))}{2(d(\gamma + 2)^2 + \gamma(\gamma + 4))^2((\gamma + 2)d^2 + 2\gamma d + \gamma)^2}$$

where

$$b_0(d) = (3d + 1)(d - 1)(d + 1)^2$$

$$b_1(d) = (d + 1)(2d^4 + 19d^3 + 12d^2 - 13d - 4)$$

$$b_2(d) = 4d(d + 1)(3d^3 + 13d^2 + 6d - 2)$$

$$b_3(d) = 4d^2(7d^3 + 24d^2 + 20d - 1)$$

$$b_4(d) = 32d^2(d + 2)$$

$$b_5(d) = 16d^5.$$

It is easy to check that all these coefficients are positive for $d > 1$ which implies that $W_s^{nc} < W_s^c$.

Next, using eqs [28] and [33] we obtain the difference in profits

$$\pi_s^c - \pi_s^{nc} = - \frac{A^2\gamma(f_0(d)\gamma^4 + f_1(d)\gamma^3 + f_2(d)\gamma^2 + f_3(d)\gamma + f_4(d))}{2(d(\gamma + 2)^2 + \gamma(\gamma + 4))^2((\gamma + 2)d^2 + 2\gamma d + \gamma)^2}$$

where

$$f_0(d) = (5d + 3)(d - 1)(d + 1)^2$$

$$f_1(d) = 2(2d^5 + 19d^4 + 16d^3 - 5d^2 - 12d - 4)$$

$$f_2(d) = 4d(6d^4 + 23d^3 + 6d^2 - 7d - 4)$$

$$f_3(d) = 8d^2(6d^3 + 8d^2 - 4d - 1)$$

$$f_4(d) = 16d^2(2d - 1).$$

It is easy to check as well that all these coefficients are positive for $d > 1$ and so $\pi_s^c < \pi_s^{nc}$.

The above comparisons lead to the following result:

Proposition 5: *The optimal commitment welfare is larger than the optimal no commitment welfare, i.e. $W_s^{nc} < W_s^c$. However, the optimal commitment profits are lower than the optimal no commitment profits, i.e., $\pi_s^c < \pi_s^{nc}$.*

Notice that the relationship between welfare and profits for the two policy games is unequivocal and does not depend on the ordering of the equilibrium production levels. Welfare is larger when there is commitment regardless of whether the production is larger or lower. What happens when a standard is used is that the reduction in environmental damages more than compensates the increase in investment costs and the reduction in consumer surplus when production is lower under regulatory commitment and, when production is larger, the increase in investment costs is more than compensated by the reduction in environmental damages plus the increment in consumer surplus.

The monopolist can certainly take advantage of his earlier choice when the regulator is unable to commit to a specific emission standard. Under this lack of regulatory commitment, the monopolist increases its profits by appropriately choosing its innovation effort. Thus, the monopolist's profits are always larger under no commitment policies. However, commitment dominates no commitment from a social point of view when the instrument of the environmental policy is an emission standard. This finding is in contrast with the one obtained by Petrakis and Xepapadeas (2001), where the regulator's inability to commit to an emission tax promotes environmental innovation and results in larger welfare. Our analysis uncovers the relevance of the policy instrument in establishing the superiority of either a commitment or a time-consistent policy. This motivates the analysis that follows.

5 Taxes versus Standards

We wish to order welfare levels according to the policy instrument used to control pollution and to the commitment the regulator has with the stringency of the policy instrument in order to determine which is the environmental policy that yields the largest welfare level.

A first result that is straightforward to establish by comparing environmental innovation and output when a committed regulator uses a tax, given by expressions [8] and [9], with environmental innovation and output when it uses a standard, given by expressions [26] and [27] is:

Proposition 6: *If the regulator is able to commit to its environmental policy the two instruments are equivalent in the sense that they yield the same outcome.*

The equivalence implies that both instruments lead the firm to select the same levels of production and environmental innovation yielding also the same level of emissions. Thus, consumers are going to pay the same price under the two instruments and the society is going to enjoy the same welfare level. Profits are identical before taxation and they could be identical after taxation too in case the regulator reimburses the tax revenues using, in the Pigouvian tradition, a lump-sum subsidy that in practice could be implemented for example as an exemption in corporate rates. The equivalence result is based on the fact that, for each emission standard, there exists a tax rate that yields the same level of welfare and vice versa, so that a change of the emission standard by the corresponding tax rate in the welfare function of the optimization problem [24] yields the welfare function of the optimization problem [6] and vice versa. This explains why both instruments deliver the same solution for production and environmental innovation. To be more precise, the relationship between the standard and the tax is defined using eqs [1] and [4]:

$$e(t) = q(t) - w(t) = \frac{A-t}{2} - \frac{t}{\gamma} = \frac{\gamma A - (2+\gamma)t}{2\gamma}. \quad [35]$$

It is easy to check that doing $\bar{e} = e(t)$ in eq. [24], the welfare function that faces the regulator when a tax is used to control pollution, eq. [6], is obtained. Thus, the level of emissions associated to maximum welfare when a tax is used defines the emission standard that gives the maximum welfare when an emission standard is used. On the other hand, the emission standard that maximizes welfare defines, according to eq. [35], the tax that gives the maximum welfare when a tax is used by the regulator. In fact, both optimization problems can be

rewritten as a unique optimization problem in terms of production and innovation. Using the first-order conditions that characterize stage two and three of the committed regulator game when a tax is applied, eqs [1] and [4], we obtain the following condition

$$a - 2q = c + \gamma w,$$

that establishes that when the monopolist is a follower it selects the levels of production and investment to satisfy that marginal revenue, $a - 2q$, is equal to marginal cost of production, c , plus marginal cost of investment, γw . The same condition is obtained directly from the maximization of profits when a standard is used to control pollution. Taking into account this condition that characterizes the committed regulator game for both instruments, the equilibrium of both games is given by the solution of the following optimization problem

$$\begin{aligned} \max_{\{q, w\}} W &= Aq - \frac{1}{2}q^2 - \frac{\gamma}{2}w^2 - \frac{d}{2}(q - w)^2 \\ \text{s.t. } a - 2q &= c + \gamma w. \end{aligned}$$

Without the constraint, the solution to this problem is the efficient outcome. This means that the problem we have just presented defines the outcome that can be implemented when a committed regulator is constrained to use a second-best policy regardless of whether a tax or a standard is applied.

Thus, when the monopolist cannot use innovation to influence the environmental policy, the choice of the instrument is not an issue since the same welfare is achieved regardless of the instrument selected by the regulator.

Then using Propositions 1, 5 and 6 the following corollary is established:

Corollary 1: *The highest welfare is achieved when the regulator is not able to commit and uses a tax on emissions whereas the lowest welfare is achieved when it uses an emission standard. When the regulator is able to commit, the welfare level is between these two extreme values, i.e. $W_s^{nc} < W_s^c = W_t^c < W_t^{nc}$.*

The profits comparison is not so immediate because on the one hand $\hat{\pi}_t^c = \pi_s^c < \pi_s^{nc}$ according to Propositions 5 and 6, but on the other hand the relationship between $\hat{\pi}_t^{nc}$ and $\hat{\pi}_t^c$ depends on the relative convexity of the damage function according to Proposition 2. Thus, when $\hat{\pi}_t^{nc} < \hat{\pi}_t^c$ it is straightforward that $\hat{\pi}_t^{nc} < \hat{\pi}_t^c = \pi_s^c < \pi_s^{nc}$ but when $\hat{\pi}_t^c < \hat{\pi}_t^{nc}$ we need to compare first π_s^{nc} and $\hat{\pi}_t^{nc}$ to rank profits. Using eqs [18] and [33] we obtain that

$$\pi_s^{nc} - \hat{\pi}_t^{nc} = \frac{(a - c)^2((2 + 3\gamma)d^2 + 2\gamma d - \gamma)^2}{2((\gamma + 2)d^2 + 2(\gamma + 2)d + \gamma)^2((\gamma + 2)d^2 + 2\gamma d + \gamma)} > 0.$$

Then a second corollary tells us that

Corollary 2: *For all $\gamma > 0$, there exists a function $\hat{d}(\gamma)$ defined by the positive root of eq. [19] such that if $d < \hat{d}(\gamma)$ then $\hat{\pi}_t^{nc} < \hat{\pi}_t^c = \pi_s^c < \pi_s^{nc}$. However, if $d > \hat{d}(\gamma)$ then $\pi_s^c = \hat{\pi}_t^c < \hat{\pi}_t^{nc} < \pi_s^{nc}$.*

We have shown that no commitment yields the maximum welfare if the regulator chooses an emission tax to control pollution but it gives the minimum welfare if the regulator uses an emission standard. Thus, without commitment the choice of the policy instrument is not neutral. The use of an emission standard reverses the effects that the strategic behavior of the monopolist has on welfare when the regulator uses an emission tax. Moreover, strategic behavior always yields larger profits when a standard is applied and this only occurs when the regulator uses a tax if marginal damages are large enough.

The intuition that explains this result is given by the fact that the strategic relationship between the instrument and the innovation for the monopolist changes with the instrument. When the regulator uses an emission tax, the innovation and the emission tax are strategic *complements* for the monopolist in the *reference two-stage game* defined by eqs [2] and [3]. In the same game, the innovation and the emission tax are strategic *substitutes* for the regulator. In this setting, a reduction in the emission tax increases the payoffs of both players. Then, when the monopolist uses strategically innovation to obtain a reduction in the emission tax to increase its profits, it is also causing an increase in welfare that usually comes along with an increase in innovation. However, when the regulator applies an emission standard, the innovation and the emission standard are strategic *substitutes* in the reference one-stage game defined by eqs [20] and [21]. Now, a reduction of the standard along the reaction functions of both players increases welfare in one case, the regulator, and decreases profits in the other case, the monopolist. Then when the monopolist uses strategically the innovation to obtain an increase in the emission standard, the result is a reduction in welfare that comes along with a reduction in innovation.

To graphically illustrate the results and the intuition we have just presented, we resort to a numerical example to draw Figures 1 and 2.¹⁶ Table 1 displays

¹⁶ Figure 1 also appears in Petrakis and Xepapadeas (2001) although we have completed it including the representation of the unregulated monopoly equilibrium and the efficient solution. Our discussion also follows their arguments. Nevertheless, we reproduce them to facilitate the reader the comparison with Figure 2 and the understanding of the intuition that drives the difference in the results of the environmental policy when a standard is applied instead of a tax.

Figure 1: Equilibrium outcomes when the regulator uses a tax.

Figure 2: Equilibrium outcomes when the regulator uses a standard.

Table 1: Equilibrium outcomes with increasing marginal damages.

	t	e	w	q	π	W	$\%W^E$
Efficient outcome (E)		12.25	24.50	36.75	1,500.6	1,800.8	
Unregulated monopoly (M)		49.00	0.00	49.00	2,401.0	-2,401.0	
Commitment (standard) (C)		11.47	16.68	28.15	1,618.5	1,685.8	93.61
Commitment (tax) (C)	41.70	11.47	16.68	28.15	1,618.5	1,685.8	93.61
No commitment (standard) (NC)		14.00	14.00	28.00	1,715.0	1,617.0	89.79
No commitment (tax) (NC)	30.62	12.87	20.82	33.69	1,624.8	1,778.2	98.74

Note: $a = 100$, $c = 2$, $d = 5.0$, $\gamma = 2.5$.

equilibrium outcomes under regulatory commitment and lack of commitment. In addition, we show the unregulated monopoly equilibrium and the efficient solution. In Figure 1 points E and M represent the innovation level corresponding to these solutions and in Figure 2, they represent the innovation level and emissions. Columns report the equilibrium levels for the emission tax (dollars per unit of emissions), emissions, innovation in the same units than emissions, output, and payoffs in dollars: profits and welfare. The last column displays the percentage of welfare that is achieved under a particular regime with respect to the efficient welfare level.

Let us now consider the case of an emission tax. A monopolist facing a regulator without commitment is going to use innovate to obtain a lower tax. This can be seen in Figure 1.¹⁷ Because it is the first-mover, the monopolist can choose the location on the regulator's reaction function that maximizes profits. In equilibrium, the monopolist chooses a level of innovation equal to 20.82 and the regulator selects a tax of 30.62 \$/emission (point NC in Figure 1). For this tax and the level of innovation selected by the monopolist, the regulator practically achieves the level of welfare corresponding to the efficient outcome (98.74%). However, when the regulator is able to commit to the tax it achieves a lower welfare, 93.61% of the maximum welfare that can be achieved. Now the regulator is the first-mover, it can choose the location on the monopolist's reaction function that maximizes welfare. In equilibrium, the regulator sets up a tax of 41.70 \$/emission and it induces the monopolist to choose a level of innovation equal to 16.68 (point C in Figure 1). The result is that the increase in welfare coming from the reduction in environmental damages and investment costs is more than compensated by the reduction in consumer welfare because of a lower output. Thus, in this setting, the regulator would prefer to act as a follower instead of being the leader of the policy game but the same occurs for the monopolist.

On the other hand, a monopolist facing a regulator without commitment is going to use innovation to obtain a larger standard. This can be seen in Figure 2.¹⁸ Again, because it is the first-mover, the monopolist can choose the location on the regulator's reaction function that maximizes profits. In

¹⁷ $w(t)$ is the firm's *reaction function*. $t(w)$ is the regulator's *reaction function*. Isoprofit curves are shown in red. Profit is increasing toward the origin which represents the unregulated monopoly equilibrium. Isowelfare curves are shown in green. Welfare is increasing toward point E that stands for the efficient level of innovation.

¹⁸ $w(\bar{e})$ is the firm's *reaction function*. $\bar{e}(w)$ is the regulator's *reaction function*. Isoprofit curves are shown in red. Profit is increasing toward point M that represents the unregulated monopoly equilibrium. Isowelfare curves are shown in green. Welfare is increasing toward point E that stands for the efficient levels of innovation and emissions.

equilibrium, the monopolist chooses a level of innovation equal to 14.00 and the regulator fixes a standard of 14.00 (point NC in Figure 2). For this standard and the level of innovation selected by the monopolist, the regulator achieves a level of welfare equal to 89.79% of the maximum welfare corresponding to the efficient outcome. However, when the regulator is able to commit to the standard it obtains a larger welfare, 93.61% of the maximum welfare that could be achieved implementing the efficient outcome. Notice, that is the same welfare the regulator achieved by using a tax: with commitment both policy instruments turn out to be equivalent. Now the regulator is the first-mover, it can select the location on the monopolist's reaction function that maximizes welfare. In equilibrium, the regulator sets up a standard of 11.47 and it induces the monopolist to choose a level of innovation equal to 16.68 (point C in Figure 2) and hence the equivalence. That is, either setting a standard of 11.47 or setting in advance a tax of 41.70 \$/emission lead to the same welfare result. With standards, the decrease in environmental damages and the increase in consumer surplus because of a larger production more than compensate the increase in investment costs, yielding larger welfare. Thus, for this policy game, the regulator would prefer to act as the leader but the same occurs for the monopolist. All in all, we conclude that the desirability of a committed environmental policy depends on the instrument, whether an emission tax or a standard. Once we compare them, the suggested policy prescription is a time-consistent tax.

6 Conclusions

This paper has studied the strategic use of environmental innovation by a monopolist to influence an emission standard and its welfare implications. To evaluate the strategic behavior of the monopolist, we compare two alternative policy games. The first of the games assumes that the regulator commits to an ex-ante level of the policy instrument and later the monopolist chooses its environmental innovation effort. The second one is the time-consistent policy game where the regulator sets the ex-post optimal level of the emission standard once the monopolist has chosen its innovation level. We have also compared our results with those obtained by Petrakis and Xepapadeas (2001) for an emission tax.

With an emission standard, we show that the strategic behavior of the firm has a detrimental effect on social welfare and induces less environmental innovation than under regulatory commitment – the opposite to what occurs with an emission tax. Thus, when the regulator uses an emission standard,

commitment not only yields larger welfare relative to the no commitment case but also promotes more environmental innovation. Moreover, we also find that the two policy instruments are equivalent if there is commitment. In other words, with commitment investment, production and emissions are the same regardless of the policy instrument applied by the regulator. The consequence is that both policy instruments implement the same level of social welfare.

Our findings do not give support to the idea that discretion (no commitment) is necessarily better than rules (commitment) because the sign of the comparison in terms of welfare depends on the policy instrument used by the regulator. Nevertheless, from our analysis a clear policy recommendation can be derived: in the case of a polluting monopoly, the optimal environmental policy is to use an emission tax because it yields the same welfare than an emission standard for a committed regulator and a larger welfare for a non-committed regulator. In other words, regardless of the credibility of the environmental policy, an emission tax guarantees a level of welfare that is at least as large as that achieved using an emission standard.

A limitation of our analysis is that we have assumed the simplest form of the emission function, i.e. one that is additively separable in production and innovation. We conjecture, based on the analysis by Petrakis and Xepapadeas (1999, 2003), that our results could be extended to consider that innovation can reduce the emission/production coefficient, which is an area for future research. Moreover, such an extension would allow us to consider another instrument: a performance standard regulating the unit emissions coefficient. It would be also interesting to know how the results would change if the market structure is an oligopoly. According to the first results obtained for oligopolistic firms by Petrakis and Xepapadeas (2001) when the policy instrument is an emission tax, it seems that competition plays for regulatory commitment. Nevertheless, an emission tax could still be the optimal policy if it is possible to show that this instrument minimizes the welfare losses caused by the strategic behavior of the firms when there is no commitment. A very interesting line of research to put in the agenda. To conclude, another extension would be to analyze the strategic use of innovation to influence the environmental policy when environmental damages are uncertain and also when the abatement technology is subject to stochastic innovation or this is private information.¹⁹

¹⁹ A paper where this issue is studied is Antelo and Loureiro (2009). These authors examine the effects of signaling on environmental taxation in a two-period monopoly model where the regulator can only infer the firm's technology after observing the output from the first period.

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