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 monopolist to influence environmental policy, either with taxes or with standards, comparing two alternative policy regimes assuming that marginal damages can be constant or increasing. The first of the regimes assumes that the regulator commits to an ex-ante level of the policy instrument. The second one is the time consistent policy regime. We find that the strategic behavior of the firm is welfare improving when marginal damages are increasing only if a tax is used to control pollution. However, with constant marginal damages, the strategic behavior of the firm has a detrimental effect on welfare regardless of the instrument used by the regulator. The result is that the optimal policy consists of applying a tax without commitment when marginal damages are increasing but when they are constant, the optimal policy is commitment regardless of the policy instrument since a tax and a standard are equivalent in welfare terms.

Keywords: monopoly, commitment, innovation, taxes, standards.

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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 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. Interestingly, Petrakis and Xepapadeas (2001) find for a polluting monopoly, that profits and total welfare are always higher when the regulator is unable to commit to a specific *tax* level. In other words, they show that the strategic behavior of the firm has a beneficial effect on social welfare noting that it may induce more environmental innovation than under regulatory commitment. This result 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.

We show that this policy prescription depends on the environmental policy instrument selected by the regulator as well as on the nature of the environmental damage function. The analysis considers two policy instruments, emission taxes and emission standards, and distinguishes whether the regulator has the ability to commit or not to a specific level of the policy instrument. Under commitment the regulator can credibly choose the emission tax or standard before the monopolist decides on innovation effort. When the regulator's policy is non-credible, the monopolist anticipates that it can use innovation to influence the regulator's choice of the time-consistent (or ex-post) emission tax or standard. Our findings show that for increasing marginal damages the regulator's ability to commit to an emission *standard* level 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 intuition is given by the fact that the strategic relationship between the policy instrument and the innovation for the monopolist changes with the instrument so that 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 Petrakis and Xepapadeas' (2001) result is sensitive to the specification of the environmental damage function. With constant marginal damages, instead of increasing marginal damages as these authors assume, the tax cannot be influenced by the monopolist because it is independent of innovation. In other words, because of the linearity of environmental damages, the model predicts a dominant strategy for the regulator. Then, the monopolist *cannot* strategically use innovation to influence the environmental policy although the regulator is not able to commit to the emission tax rate. In this case, the committed regulator achieves a larger welfare level. The same occurs for a standard if environmental policy should be in place, i.e. if environmental damages are large enough to yield an unregulated monopolist equilibrium where the distortion caused by the pollution externality dominates the distortion caused by market power. Large enough marginal damages push the monopolist not to undertake any innovation effort to obtain the maximum standard the regulator is available to set. The result is that the reduction in investment costs and the increase in consumer surplus because of the increase in output is compensated by the increase in environmental damages. The strategic behavior of the firm has a detrimental effect on welfare. Summarizing, our analysis shows that the strategic behavior of the monopolist is welfare improving *only* when the tax can be influenced, which occurs for increasing marginal damages.

Thus, policy prescriptions will depend on marginal damages. If they are increasing with emissions, the optimal policy is to apply an emission tax without commitment. Commitment is better than no commitment when a standard is used but the welfare level achieved is lower than that achieved with a time-consistent emission tax. If marginal damages are constant, the optimal policy is commitment regardless of the instrument since a tax and a standard are equivalent in welfare terms.

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).[1] Gersbach and Glazer (1999) consider an oligopoly where the regulator allocates tradable emission permits after firms have decided whether to make an irreversible investment that reduces the cost of compliance. They thus examine equilibria in which firms make investment decisions strategically: they take into account how other firms decide on their investments and how environmental policy is influenced by the firms' investment decisions. 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. Petrakis and Xepapadeas (1999) study as well the case of a monopolist albeit assuming that the firm can reduce the unit emissions coefficient through the introduction of cleaner technology and that marginal damages are constant. They find that in spite of this assumption on marginal damages, the tax can be influenced by environmental innovation but strategic behavior is not welfare improving. Welfare is always larger when the regulator is able to commit to the emission tax rate. The effects of time consistent emission tax on location decisions of a monopoly have been examined by Petrakis and Xepapadeas (2003). Instead marginal damages are assumed to be increasing. The result is that domestic welfare is lower under commitment whenever the monopolist stays in the home country. Thus, the possibility of acting strategically is again welfare improving. Petrakis and Xepapadeas (2003) derive these results for an emissions function that is additively separable in output and abatement effort although in the second part of the paper they demonstrate that their main results turn out to be robust when emissions are proportional to output and the unit emissions coefficient can be reduced through the introduction of cleaner technology as in Petrakis and Xepapadeas (1999). The results obtained by Petrakis and Xepapadeas in both papers are difficult to compare because of the difference in marginal damages and because of the possibility of relocation that the monopolist is given in the latter paper. Nevertheless, their analyses show the importance of the structure of the marginal damage function to get one type of results or another, as we also emphasize in this paper. Moreover, our research also signifies the importance of the policy instrument, a point not dealt with by these authors. Our results are also 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. In his model, the reduction of the performance standard increases the marginal cost of production but

[1] 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).

investment can mitigate this effect. With linear environmental damages, under no commitment the monopolist does not invest, the performance standard is larger and welfare is lower. Puller (2006) also investigates the effects of regulation through performance standards for a Cournot duopoly with spillovers. Poyago-Theotoky and Teerasuwannajak (2002) examine a Cournot differentiated duopoly to show that the effects of an emission tax on innovation and welfare depend on the degree of product differentiation. Finally, Petrakis and Xepapadeas (2001) also study the case of a polluting oligopoly and illustrate that the monopoly results extend to the small numbers oligopoly, but they are reversed for the large numbers oligopoly case. Competition plays for regulatory commitment.

Another strand of the literature has investigated the interplay between environmental policy, the incentives to adopt new technology, and the repercussions on R&D in a setting where a monopolistic upstream firm engages in R&D and sells advanced abatement technology to polluting downstream firms that could sell their output in a competitive market. See, among others, the contributions by Laffont and Tirole (1996), Denicolò (1999), Requate (2005b), Montero (2011) and more recently Wirl (2014).[2] All these papers highlight the importance of commitment of environmental policy on the incentives to make investments in R&D to reduce pollution. Schoonbeek and de Vries (2009) and Espínola-Arredondo and Muñoz-García (2013) consider a market with an incumbent monopolistic firm and a potential entrant. Both papers evaluate the welfare benefits of introducing an emission tax but they focus on entry-deterring practices and do not take into account the possibility that firms invest in R&D. Other papers have addressed the effects of environmental policy on innovation assuming that the regulator is unable to commit credibly. 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 where firms are subject to research spillovers in emission reduction. Ulph and Ulph (2013) study optimal climate change policies when governments cannot commit but they abstract from any competition issues arising from the potential exercise of monopoly power by the single firm that is regulated by the government. Jakob and Brunner (2014) analyze the optimal type and degree of commitment to a future climate policy when damages from climate change are uncertain. However, as Ulph and Ulph (2013), they abstract from any competition issues between polluting firms.[3]

[2] David and Sinclair-Desgagné (2005) extend the analysis assuming that abatement technologies are provided by an imperfectly competitive eco-industry.

[3] Another paper where damages are uncertain is Tarui and Polasky (2005). They solve a model with endogenous technology adoption and learning involving a regulator and a single polluting firm. They compare environmental policy under commitment and no commitment, in which policy is updated after the firm has

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 standard when marginal damages are increasing and compares the results obtained with those derived by Petrakis and Xepapadeas (2001) for an emission tax. Section 4 takes up the same comparison between a tax and a standard under the assumption of constant marginal damages. Section 5 offers some concluding remarks and points out lines for future research.

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 $a > c > 0$. Following Petrakis and Xepapadeas (2001), Poyago-Theotoky (2007) and Ulph (1996), 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.[4] 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: $D(e) = de^2/2$, where $d > 0$ captures how important are damages.

In what follows we shall consider two alternative policy regimes, each featuring a multi-stage game of complete and perfect information between a welfare maximizing regulator and a profit maximizing firm, to examine the properties and desirability of having either a committed or non-committed regulator regarding environmental policy. To be more precise, in the first regime, which will be labelled 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

invested in R&D and uncertainty has been resolved but as the previous authors they do not take into account the firm's production decision.

[4] 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, as was pointed out in the Introduction, 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.

given, chooses the level of environmental innovation and output. In the second regime, 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. 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, 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 two 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. 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 Quadratic environmental damages

We address first the case of quadratic damages analyzed by Petrakis and Xepapadeas (2001) for an emission tax to highlight the importance of the policy instrument when the desirability of having either a committed or non-committed regulator is examined. We leave the study of linear environmental damages for the next section.

3.1 Emission standard

We shall begin by considering an emission standard $\bar{e}$, sometimes referred to as *command and control policy.* We first analyze the policy game where the regulator moves first.

3.1.1 The committed regulator game

Under emission standards regulation, $q = \bar{e} + w$, where $\bar{e}$ is the emission standard imposed on the monopolist. Then in the second stage, the monopolist chooses innovation effort to maximize profits taking as given the emission standard, $\bar{e}$. That is

$$\max_{\{w\}} \pi = (a-q)q - cq - \frac{\gamma}{2}w^2 \tag{1}$$
$$s.t.\ q = \bar{e} + w$$

From the first-order condition $a-c-2(\bar{e}+w)-\gamma w = 0$, we get the monopolist's best response in terms of the regulator's first-stage choice

$$w = \frac{A-2\bar{e}}{2+\gamma} \tag{2}$$

where $A = a - c$, with A being a measure of market size. Notice that there is an inverse relation between w and $\bar{e}$ and so the firm reduces innovation when the regulator increases the emission standard. Of course, the effect on production is the opposite

$$q = \frac{A+\gamma\bar{e}}{2+\gamma}. \tag{3}$$

An increase of the emission standard leads the monopolist to choose a larger production level.

In the first stage, the regulator chooses the emission standard taking into account how the monopolist is going to respond. The regulator maximizes welfare, which is defined as the sum of consumer surplus and monopoly profits minus environmental damages, that is

$$\max_{\{\bar{e}\}} W = \int_0^{q(\bar{e})} (a-c-x)dx - \frac{\gamma}{2}w(\bar{e})^2 - \frac{d}{2}\bar{e}^2,$$
$$= Aq(\bar{e}) - \frac{1}{2}q(\bar{e})^2 - \frac{\gamma}{2}w(\bar{e})^2 - \frac{d}{2}\bar{e}^2 \tag{4}$$

where $q(\bar{e})$ is given by (3) and $w(\bar{e})$ by (2). Thus, the regulator selects the welfare maximizing level of $\bar{e}$

$$\bar{e}_s^c = \frac{A\gamma(\gamma+3)}{d(\gamma+2)^2+\gamma(\gamma+4)} > 0. \tag{5}$$

It is straightforward that the emission standard decreases with environmental damages.[5] Then we can calculate the equilibrium innovation and production levels, which are given by

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

$$q_s^c = \frac{A(\gamma+d)(\gamma+2)}{d(\gamma+2)^2+\gamma(\gamma+4)} > 0. \tag{7}$$

[5] In the expressions that follow, superscript c is used to denote the commitment case and subscript s stands for emission standards.

It is sufficient to assume that $d > 1$ to have a positive innovation level. Finally, equilibrium profits and welfare are provided below

$$\pi_s^c = (A - q_s^c)q_s^c - \frac{\gamma}{2}(w_s^c)^2, \tag{8}$$

$$W_s^c = Aq_s^c - \frac{1}{2}(q_s^c)^2 - \frac{\gamma}{2}(w_s^c)^2 - \frac{d}{2}(\bar{e}_s^c)^2. \tag{9}$$

This completes the analysis of this policy game.

3.1.2 The non-committed regulator game

In this subsection we solve for the two stage game where the monopolist plays before the regulator does. When there is no commitment, in the second stage, the regulator chooses the emission standard that maximizes welfare taking as given the innovation effort, w. Welfare is defined as in the previous subsection and the first-order condition is given by $A-(\bar{e}+w)-d\bar{e} = 0$ from where the emission standard is obtained:

$$\bar{e} = \frac{A - w}{d + 1}. \tag{10}$$

There is an inverse relation between w and $\bar{e}$, that is, the regulator increases the emission standard in response to a reduction in the monopolist's innovation level. This means that the monopolist can strategically use its choice of innovation to influence the standard on its emissions: by decreasing investment in emission-reducing activities the firm can expect a larger emission standard. Of course, this strategic aspect is missing in the case of commitment to the environmental policy studied above.

In the first stage, the monopolist chooses the innovation effort taking into account how the regulator is going to respond and that then production increases with the innovation level according to the following expression:

$$q = \bar{e} + w = \frac{A + dw}{d + 1}. \tag{11}$$

Thus, the monopolist solves

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

where $q(w)$ is given by (11). The maximization problem yields the optimal innovation effort[6]

$$w_s^{nc} = \frac{Ad(d-1)}{(\gamma + 2)d^2 + 2\gamma d + \gamma} \tag{12}$$

[6]We employ superscript nc to denote the equilibrium in the no commitment game.

which is positive for $d > 1$. Then we can substitute for the equilibrium values of emission standard and production levels, which are given by

$$\bar{e}_s^{nc} = \frac{A((\gamma+1)d+\gamma)}{(\gamma+2)d^2+2\gamma d+\gamma} > 0 \tag{13}$$

$$q_s^{nc} = \frac{A((\gamma+d)d+\gamma)}{(\gamma+2)d^2+2\gamma d+\gamma} > 0. \tag{14}$$

Finally, equilibrium profits and welfare are:

$$\pi_s^{nc} = (A - q_s^{nc})q_s^{nc} - \frac{\gamma}{2}(w_s^{nc})^2, \tag{15}$$

$$W_s^{nc} = Aq_s^{nc} - \frac{1}{2}(q_s^{nc})^2 - \frac{\gamma}{2}(w_s^{nc})^2 - \frac{d}{2}(\bar{e}_s^{nc})^2. \tag{16}$$

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

3.1.3 Comparing policy games

In this subsection we draw comparisons between the committed and non-committed regulator games. Subtracting (5) from (13) 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 (6) and (12) 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 1. *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., $w_s^{nc} < w_s^{c}$, provided that $d > 1$.*

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. In this sense the monopolist enjoys a first-mover advantage in influencing the environmental policy through its choice. This strategic effect is not present when the government can commit to a specific emission standard in advance. Consequently, the optimal commitment emission standard is lower than the optimal no commitment emission standard and innovation is larger. 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 (7) and (14) 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 2. *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 $\gamma(d) = 2d/(d^2-3d-2)$ with $\lim_{d\to\infty} \gamma(d) = 0$, such that for all $\gamma < \gamma(d)$ the optimal commitment production is lower than the optimal no commitment production, i.e. $q_s^c < q_s^{nc}$ but if $\gamma > \gamma(d)$ 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.

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. The comparison yields the following result:

Proposition 3. *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., $\pi_s^c < \pi_s^{nc}$, provided that $d > 1$.*

Proof. See Appendix A. □

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. For $d > 1$, welfare is larger when there is commitment regardless of whether the production is larger or lower. What happens when a standard is used to control pollution 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.

3.2 Taxes versus standards

To conduct the comparisons, we employ the results obtained by Petrakis and Xepapadeas (2001) and those obtained in the previous subsections. 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 expressions (14) and (15) in Petrakis and Xepapadeas' (2001) paper with expressions (6) and (7) above is:

Proposition 4. *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.*

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. 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 Proposition 3 in Petrakis and Xepapadeas' (2001) paper and Propositions 3 and 4 in this paper the following corollary is established:[7]

[7] Subscript t stands for the emission tax.

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 $\pi_t^c = \pi_s^c < \pi_s^{nc}$ according to Propositions 3 and 4, but on the other hand the relationship between π_t^{nc} and π_t^c depends on the relative convexity of the damage function according to the results obtained by Petrakis and Xepapadeas (2001).[8] Thus, when $\pi_t^{nc} < \pi_t^c$ it is straightforward that $\pi_t^{nc} < \pi_t^c = \pi_s^c < \pi_s^{nc}$ but when $\pi_t^c < \pi_t^{nc}$ we need to compare first π_s^{nc} and π_t^{nc} to rank profits. Using (15) and (43) in Appendix B we obtain that

$$\pi_s^{nc} - \pi_t^{nc} = \frac{(a-c)^2 \left((2+3\gamma)d^2 + 2\gamma d - \gamma\right)^2}{2((\gamma+2)d^2 + 2(\gamma+2)d + \gamma)^2((\gamma+2)d^2 + 2\gamma d + \gamma)} > 0.$$

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 equation (44) in Appendix B such that if* $d < \hat{d}(\gamma)$ *then* $\pi_t^{nc} < \pi_t^c = \pi_s^c < \pi_s^{nc}$. *However, if* $d > \hat{d}(\gamma)$ *then* $\pi_s^c = \pi_t^c < \pi_t^{nc} < \pi_s^{nc}$.

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 Petrakis and Xepapadeas (2001) in which in the first stage the monopolist and the regulator select *simultaneously* the innovation and the emission tax level, respectively, and in the second stage the monopolist decides its output. 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

[8] In Appendix B we calculate profits before taxation and show that the sign of the difference between π_t^c and π_t^c depends on the values of parameters γ and d take. See Proposition 12 in Appendix B.

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 game in which the monopolist and the regulator select *simultaneously* the innovation and the emission standard level. The reaction functions of this simultaneous game are given by (2) and (10). 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. Table 1 displays 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, emissions, innovation, output, 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.

⇒ Table 1 ⇐

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.[9] 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 (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

[9] $w(t)$ is the firm's best response function. $t(w)$ is the regulator's best response 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.

monopolist's reaction function that maximizes welfare. In equilibrium, the regulator sets up a tax of 41.70 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.

$\Rightarrow$ Fig. 1 $\Leftarrow$

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.[10] Again, 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 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 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 provided that environmental damages are quadratic.

[10] $w(\bar{e})$ is the firm's best response function. $\bar{e}(w)$ is the regulator's best response 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.

$\Rightarrow$ Fig. 2 $\Leftarrow$

4 Linear environmental damages

4.1 Emission standard

In this section we provide the analysis when the environmental damage function is linear in net emissions and is given by $D(e) = de$. As shall be seen the policy recommendation changes drastically. We begin by examining the policy game with a committed regulator that uses emission standards to control pollution.

4.1.1 The committed regulator game

Since the monopolist does not care about pollution damages, there are no changes in the second stage of the game. In the first stage, the regulator selects $\hat{e}$ to maximize welfare. We employ the hat notation to denote the equilibrium variables under linear environmental damages. The maximization problem yields the optimal emission standard as follows:

$$\hat{e}_s^c = \frac{A\gamma(3+\gamma) - (2+\gamma)^2 d}{\gamma(4+\gamma)}. \tag{17}$$

It is immediate that the standard decreases with marginal environmental damages, d. Using (17) we calculate the equilibrium innovation and production levels, which are given by

$$\hat{w}_s^c = \frac{2(2+\gamma)d - A\gamma}{\gamma(4+\gamma)} \tag{18}$$

$$\hat{q}_s^c = \frac{(2+\gamma)(A-d)}{4+\gamma} \tag{19}$$

with positive values for all variables provided that

$$d \in \left(\frac{A\gamma}{2(2+\gamma)}, \frac{\gamma(3+\gamma)A}{(2+\gamma)^2} \right). \tag{20}$$

Finally, equilibrium profits and welfare are provided bellow

$$\hat{\pi}_s^c = \frac{\gamma(3\gamma+8)A^2 + 2\gamma(2+\gamma)^2 Ad - 2(2+\gamma)^3 d^2}{2\gamma(4+\gamma)^2} \tag{21}$$

$$\hat{W}_s^c = \frac{\gamma(3+\gamma)A^2 - 2\gamma(3+\gamma)Ad + (2+\gamma)^2 d^2}{2\gamma(4+\gamma)}. \tag{22}$$

This completes the analysis of this policy game.

4.1.2 The non-committed regulator game

When the regulator is not able to commit, in the second stage, it chooses the emission standard that maximizes welfare taking as given the innovation effort, w. In this case the first-order condition is given by $A - (\hat{e} + w) - d = 0$ from where we get the regulator's best response in terms of the monopolist's first-stage decision

$$\hat{e} = A - d - w. \tag{23}$$

Note that the first-order condition directly characterizes the equilibrium level of production $\hat{q}_s^{nc} = A - d$.[11] Then, the monopolist maximizes profits by choosing an equilibrium innovation equal to zero, $\hat{w}_s^{nc} = 0$, and therefore $\hat{e}_s^{nc} = \hat{q}_s^{nc}$.[12] Equilibrium profits and welfare are given by

$$\hat{\pi}_s^{nc} = d(A - d), \tag{24}$$

$$\hat{W}_s^{nc} = \frac{1}{2}(A - d)^2. \tag{25}$$

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

4.1.3 Comparing policy games

In drawing comparisons we shall focus on interior solutions, which requires that marginal damages belong to the interval (20).[13] It is immediate that $\hat{w}_s^{nc} = 0 < \hat{w}_s^c$. On the other hand, using (17) the difference between the equilibrium emission standards is given by the following expression:

$$\hat{e}_s^{nc} - \hat{e}_s^c = \frac{A\gamma + 4d}{\gamma(4 + \gamma)} > 0.$$

And using (19) the difference in equilibrium output is given by

$$\hat{q}_s^{nc} - \hat{q}_s^c = \frac{2(A - d)}{4 + \gamma} > 0 \text{ for } d < A.$$

Thus, the following proposition can be established:

[11] Notice as well that this quantity corresponds to the efficient level of production because of constant marginal damages. In this case, the first-order condition coincides with the condition that characterizes the efficient outcome: price equal to marginal cost plus marginal damages with production as the only variable.

[12] Gersbach and Glazer (1999) and Puller (2006) also obtain that the monopoly's innovation is zero as was noted in the Introduction.

[13] Since $\gamma(3+\gamma)A/(2+\gamma)^2 < A$, if d belongs to the interval (20) then $d < A$ and we have an interior solution for both policy games except for the innovation in the non-committed regulator game that is zero.

Proposition 5. *The optimal commitment emission standard and production are lower than the optimal no commitment emission standard and production, i.e.* $\hat{e}_s^c < \hat{e}_s^{nc}$ *and* $\hat{q}_s^c < \hat{q}_s^{nc}$*. However, the optimal commitment environmental innovation is larger than the optimal no commitment environmental innovation that is zero, i.e.,* $\hat{w}_s^{nc} = 0 < \hat{w}_s^c$*.*

The results are similar to those derived when damages are quadratic except that now production is always larger when the regulator is not able to commit, regardless of the decreasing returns in innovation effort. The strategic incentive of the monopolist to lower innovation in order to induce a larger emission standard is maximal because a decrease of one unit in the amount of innovation is exactly compensated by an increase of one unit in the emission standard. The result is that the monopolist does not devote any resources to abate emissions.

Next we compare welfare under both regimes getting the following result:

Proposition 6. *For all* $\gamma \in (0, 0.38)$, *the optimal commitment welfare is lower than the optimal no commitment welfare, i.e.,* $\hat{W}_s^c < \hat{W}_s^{nc}$*. However for all* $\gamma > 0.38$ *there exists an increasing concave function* $d_W(\gamma) = A((\gamma^2 + 4\gamma)^{1/2} - \gamma)/4$ *that belongs to interval (20) with* $\lim_{\gamma \to \infty} d_W(\gamma) = A/2$ *such that if* $d < d_W(\gamma)$ *then the optimal commitment welfare is lower than the optimal no commitment welfare, i.e.* $\hat{W}_s^c < \hat{W}_s^{nc}$ *but if* $d > d_W(\gamma)$ *the contrary occurs, i.e.* $\hat{W}_s^{nc} < \hat{W}_s^c$*.*

Proof. See Appendix A. □

It is easy to check, see Appendix C, that if $d > A/2$ and $\gamma > 1$ then the efficient production and emissions are positive and lower than those corresponding to the unregulated monopolist. In that eventuality, the distortion caused by the pollution externality dominates the distortion coming from the exercise of market power, which tends to reduce production and emissions. Hence the environmental problem is the main problem to solve by the regulator. Under these conditions the regulation policy is basically an environmental policy. Thus, it is immediate from the proposition that

Corollary 3. *If the efficient production and emissions are positive and lower than those corresponding to the unregulated monopolist then the optimal commitment welfare is larger than the optimal no commitment welfare when the regulator uses a standard to control pollution.*

Finally, we compare profits to establish that

Proposition 7. *For all* $\gamma \in (0, 0.49)$, *the optimal commitment profits are larger than the optimal no commitment profits, i .e.,* $\hat{\pi}_s^{nc} < \hat{\pi}_s^c$*. However, for all* $\gamma > 0.49$*, there exists* *an increasing concave function* $d_\pi(\gamma) = A(2\gamma(\gamma+3) - (\gamma+4)(\gamma(\gamma+2))^{1/2})/2(\gamma^2+2\gamma-4)$ *that belongs to interval (20) with* $\lim_{\gamma\to\infty} d_\pi(\gamma) = A/2$ *such that if* $d < d_\pi(\gamma)$ *the optimal commitment profits are larger than the optimal no commitment profits, i.e.* $\hat{\pi}_s^{nc} < \hat{\pi}_s^{c}$ *but if* $d > d_\pi(\gamma)$ *the contrary occurs, i.e.* $\hat{\pi}_s^{c} < \hat{\pi}_s^{nc}$.

Proof. See Appendix A. □

It is immediate from the proposition that

Corollary 4. *If the efficient production and emissions are positive and lower than those corresponding to the unregulated monopolist then the optimal commitment profits are lower than the optimal no commitment profits when the regulator uses a standard to control pollution.*

These results show that if environmental policy should be in place, then the regulator's *ability* to commit to an emission standard promotes environmental innovation relative to the no commitment case and guarantees a larger welfare level. The chance for strategic firm behavior to be welfare improving only arises when marginal damages are low enough. Note however that then the efficient level of production and emissions exceed those under the unregulated monopoly, just as would happen in the standard monopoly case where only the market power distortion is present. We understand that this setting becomes more of a competition policy issue. A proper environmental policy would be applied by the regulator when production and emissions exceed the efficient outcome. If this is so the monopolist's profits are always larger under no commitment policies. The monopolist's first-mover advantage allows it to increase profits by manipulating its environmental innovation to influence the regulator's choice of emission standard.

In order to graphically illustrate the results and give some intuition as we did in the previous section, we draw Figure 3 resorting to a numerical example. Table 2 displays the equilibrium outcomes under regulatory commitment and lack of commitment when marginal damages are large enough according to Corollary 3 and 4. As in the previous numerical example, we also include the unregulated monopoly equilibrium and the efficient solution. Notice that in this case, the efficient production and emissions are below those corresponding to the market equilibrium without regulation.

$\Rightarrow$ Table 2 $\Leftarrow$

A monopolist facing a regulator without commitment is going to reduce innovation to zero to obtain the maximum amount of emission standards the regulator is available to deliver (point NC in Figure 3). In equilibrium, it places on the vertical axis so that the regulator sets up a standard of 38.[14] For this standard, the regulator achieves a welfare level equal to 50.01% of the maximum welfare corresponding to the efficient outcome. If instead the regulator is able to commit then it obtains a larger welfare level, which is 92.23% of the efficient outcome. In equilibrium, (point C in Figure 3), the regulator sets up a standard of 8.15 and it induces the monopolist to choose a level of innovation equal to 18.15. The point is that the reduction in environmental damages more than compensates the increment in investment costs and the reduction of the consumer surplus. Commitment leads to a larger welfare and lower profits. Thus, when emission standards are used to control pollution, the regulator would prefer to act as the leader of the game but the same occurs for the monopolist.

$\Rightarrow$ Figure 3 $\Leftarrow$

4.2 Emission tax

We now examine whether the strategic use of innovation can be welfare improving when the regulator selects an emission tax to control pollution. When a tax is the policy instrument the game has three stages. In the first stage, the regulator sets up the emission tax, then the monopolist chooses its investment in innovation conditional on the emission tax and, finally, given the tax and innovation it decides its output which yields the level of emissions.

4.2.1 The committed regulator game

In the third stage, the monopolist chooses its output to maximize profits

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

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

$$\hat{q}(t) = \frac{A - t}{2}. \tag{26}$$

In the second stage, the monopolist chooses innovation, w, to maximize profits

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

[14] Notice that although the monopolist selects an extreme of the regulator's reaction function, this extreme is a tangency point between the regulator's reaction function and the isoprofits curve that represents the profits the monopolist gets as a Stackelberg leader.

where $q(t)$ is given by (26). The equilibrium innovation is given by

$$\hat{w}(t) = \frac{t}{\gamma}. \tag{27}$$

Note that innovation increases with the emission tax.

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

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

where $q(t)$ is given by (26) and $w(t)$ by (27). This maximization problem yields the optimal emission tax as follows:

$$\hat{t}^c = \frac{2(2+\gamma)d - A\gamma}{4+\gamma}. \tag{28}$$

It is straightforward that the equilibrium tax increases with marginal environmental damages, d. Using (28) we can calculate the equilibrium values for the remaining variables. Then we check that all of them take the same values than for the committed regulator game when a standard is used to control emissions. In other words, as could be expected, Proposition 4 also applies when marginal environmental damages are constant. Moreover, as long as (20) is satisfied, the optimal policy according to (28) is to set up a tax instead of a subsidy.

4.2.2 The non-committed regulator game

The last stage is the same as in the previous game. In the second stage, the regulator chooses the welfare maximizing emission tax taking as given the innovation level, w. In this case, the first-order condition is $A - (A - t)/2 - d = 0$ from where the regulator's best response is obtained as

$$\hat{t}^{nc} = 2d - A. \tag{29}$$

Again, the tax increases with marginal damages. Moreover, the tax is lower than marginal damages, as established by Barnett (1980) and it is *independent* of the innovation effort. In other words, because of the linearity of the environmental damages, the model predicts a dominant strategy for the regulator defined by (29). In this case, the monopolist *cannot* strategically use its innovation to influence the environmental policy in its own benefit even though the regulator cannot commit to the emission tax rate. Thus, the equilibrium innovation level and production can be calculated using (26) and (27) to get:

$$\hat{w}_t^{nc} = \frac{t^{nc}}{\gamma} = \frac{2d - A}{\gamma} \tag{30}$$

$$\hat{q}_t^{nc} = \frac{A - t^{nc}}{2} = A - d. \tag{31}$$

Equilibrium emissions are equal to the difference between production and innovation, that is,

$$\hat{e}_t^{nc} = \frac{A(1+\gamma) - (2+\gamma)d}{\gamma} \tag{32}$$

with positive values for all variables provided that

$$d \in \left(\frac{A}{2}, \frac{(1+\gamma)A}{2+\gamma} \right). \tag{33}$$

Observe that $\hat{t}^{nc}$ is positive for $d > A/2$, the same condition under which the efficient production is lower than the unregulated monopolist production, i.e. marginal damages are so large that environmental policy should be in place. Finally, equilibrium profits before taxation and welfare are

$$\hat{\pi}_t^{nc} = -\frac{1}{2\gamma}(2(2+\gamma)d^2 - 2(2+\gamma)Ad + A^2), \tag{34}$$

$$\hat{W}_t^{nc} = \frac{1}{2\gamma}\left(\gamma d^2 - 2(\gamma-1)Ad + (\gamma-1)A^2\right). \tag{35}$$

This completes the analysis of the policy game. Notice that for this game the first-mover advantage cannot be exploited by the monopolist so that the (subgame perfect) equilibrium outcome of the game where the monopolist is the Stackelberg leader coincides with the Nash equilibrium of the *simultaneous* game where the regulator chooses the tax and the monopolist selects the innovation level. This coincidence is due to the linearity of the environmental damages function.[15]

4.2.3 Comparing policy games

In this section we compare the two policy games we have just presented. To focus on interior solutions and draw coherent comparisons we must consider the intersection of intervals (20) and (33). The intersection is not empty provided that $\gamma > 1.24$ and it is given by the following interval:[16]

$$d \in \left(\frac{A}{2}, \frac{\gamma(3+\gamma)A}{(2+\gamma)^2} \right). \tag{36}$$

[15] Rubio (2006) has analyzed the conditions to get this coincidence in economic applications of differential games.

[16] Notice that these conditions are the same that guarantee that production and emissions in the two policy games analyzed in Section 4.1 and also in the efficient outcome and unregulated monopolist equilibrium are positive. See condition (45) in Appendix C.

First, we compare the equilibrium emission taxes

$$\hat{t}^c - \hat{t}^{nc} = \frac{4(A-d)}{4+\gamma} > 0.$$

It is straightforward that $\hat{w}_t^{nc} < \hat{w}_t^c$ and that $\hat{q}_t^c < \hat{q}_t^{nc}$; consequently we have that $\hat{e}_t^c < \hat{e}_t^{nc}$.

Thus, the following proposition can be established:

Proposition 8. *The optimal commitment emission tax and environmental innovation are larger than the optimal no commitment emission tax and environmental innovation, i.e., $\hat{t}^{nc} < \hat{t}^c$ and $\hat{w}_t^{nc} < \hat{w}_t^c$. However, the optimal commitment production and emissions are lower than the optimal no commitment production and emissions, i.e., $\hat{q}_t^c < \hat{q}_t^{nc}$ and $\hat{e}_t^c < \hat{e}_t^{nc}$.*

The results are qualitatively similar to those obtained when the regulator uses an emission standard except that now environmental innovation is positive when the regulator cannot commit to its environmental policy. Notice that the optimal no commitment tax is lower than the optimal commitment tax even though the monopolist cannot strategically use innovation to get a reduction in the tax.

Next, we compare the monopolist's profits and welfare. The following proposition summarizes the results of the comparison.

Proposition 9. *For all $\gamma > 1.24$, the optimal commitment welfare is larger than the optimal no commitment welfare, i.e., $\hat{W}_t^{nc} < \hat{W}_t^c$. However, the optimal commitment profits are lower than the optimal no commitment profits, i.e. $\hat{\pi}_t^c < \hat{\pi}_t^{nc}$.*

Proof. See Appendix A. □

In order to illustrate these results and complete the graphical analysis we presented in the previous sections, we have solved a numerical example using the parameter values in Table 2. The example provides graphical support to Figure 4. As happened with quadratic environmental damages, the monopolist's reaction function is upward sloping and the interpretation of the isoprofit curves is the same. In contrast, the regulator's reaction function is a horizontal line at $t = \hat{t}^{nc}$; the isowelfare curves are C-shaped and welfare levels increases as we move rightwards toward point E that represents the efficient level of innovation. Table 3 displays the equilibrium outcomes under regulatory commitment and lack of commitment. We also include the unregulated monopoly equilibrium and the efficient solution, that coincide with those in Table 2 in order to facilitate the comparison of the different solutions.

⇒ Table 3 ⇐

As can be seen in Figure 4, when the monopolist is the leader of the game it chooses a level of innovation equal to 8.80 and the regulator selects a dominant strategy defined by a tax rate equal to 22 (point NC in Figure 4). For these equilibrium values, the regulator reaches 79.96% of the welfare associated to the efficient outcome. However, when the regulator is able to commit to the tax rate, it achieves a larger welfare level, which is 92.23% of the maximum welfare that can be achieved. In equilibrium, the regulator chooses a tax of 45.38 that drives the monopolist to select a level of innovation equal to 18.15 (point C in Figure 4). It follows, by simple inspection of the isopayoff contours, that commitment leads to larger welfare and lower profits. Thus, in this setting, the regulator would prefer to act as a leader but the same occurs for the monopolist.

$\Rightarrow$ Figure 4 $\Leftarrow$

It is fair to compare Figures 1 and 4 to note some qualitative differences. In Figure 1 one observes that the no commitment innovation level lies to the right of the commitment innovation level and this will occur, according to Proposition 2 in Petrakis and Xepapadeas' (2001) paper, provided that investment costs are large enough. On the other hand, according to our Proposition 8, the contrary occurs in Figure 4. This explains the difference in the welfare ordering. With increasing marginal damages, the reduction in welfare due to the decrease in output is not compensated by the increase in welfare coming from lower innovation and emissions. The conclusion is that welfare is larger under no commitment. However, with constant marginal damages, the reduction in welfare because of the reduction in output and the increase in environmental innovation is more than compensated by the reduction in emissions so that welfare is larger under commitment.

4.3 Taxes versus standards

Next, we use the results obtained in the previous subsections to rank welfare levels. We have already established the equivalence between the instruments when the regulator can credibly commit to its environmental policy.

As above, we restrict comparisons for values of d in (36) and $\gamma > 1.24$. For these values, Corollary 3 establishes that $\hat{W}_s^{nc} < \hat{W}_s^{c}$. On the other hand, Proposition 9 establishes that $\hat{W}_t^{nc} < \hat{W}_t^{c}$. Thus, to complete the welfare ordering we need only calculate the difference between $\hat{W}_s^{nc}$ and $\hat{W}_t^{nc}$. Using (25) and (35) we get:

$$\hat{W}_s^{nc} - \hat{W}_t^{nc} = \frac{A}{2\gamma}(A - 2d) < 0 \text{ for } d > \frac{A}{2}.$$

Then it can be concluded that

Proposition 10. *The highest welfare is achieved when the regulator is able to commit to its environmental policy and the lowest welfare is achieved when the regulator is not able to commit and chooses an emissions standard to control pollution. When the regulator is not able to commit and chooses an emission tax, the welfare level lies between these two values, i.e.* $\hat{W}_s^{nc} < \hat{W}_t^{nc} < \hat{W}_s^c = \hat{W}_t^c$.

On the other hand, according to Corollary 4 $\hat{\pi}_s^c < \hat{\pi}_s^{nc}$ and according to Proposition 9 $\hat{\pi}_t^c < \hat{\pi}_t^{nc}$. In order to close the comparison we calculate the difference between $\hat{\pi}_s^{nc}$ and $\hat{\pi}_t^{nc}$ using (24) and (34)

$$\hat{\pi}_s^{nc} - \hat{\pi}_t^{nc} = \frac{1}{2\gamma}\left(4d^2 - 4Ad + A^2\right) > 0 \text{ for } d > \frac{A}{2}.$$

Thus, given the positive sign of this difference the following proposition can be established:

Proposition 11. *The highest profits are achieved when the regulator is not able to commit and selects an emission standard to control pollution and the lowest profits are achieved when the regulator is able to commit to its environmental policy. When the regulator is not able to commit and chooses an emission tax, the profits level lies between these two values, i.e.* $\hat{\pi}_s^c = \hat{\pi}_t^c < \hat{\pi}_t^{nc} < \hat{\pi}_s^{nc}$.

These results are in contrast with those obtained for quadratic environmental damages. Now, the lack of regulatory commitment, regardless of the instrument selected by the regulator, cannot yield larger welfare as compared with commitment. Strategic firm behavior can by no means be socially beneficial. Nevertheless, without commitment the choice of the instrument becomes relevant since each delivers a different welfare level. In this case taxation is a better option than the use of an emission standard. On the other hand, the relationship between profits shows that the larger degree of influence that the monopolist can exercise on the environmental policy appears when the regulator uses an emission standard without commitment. In this case, the optimal no commitment environmental innovation is zero just as in the unregulated monopoly equilibrium.

5 Conclusions

This paper has examined the effects that the strategic use of environmental innovation by a monopolist have on environmental policy and its welfare implications. Specifically, it has been shown that policy recommendations depend on the policy instrument and the nature of the damage function. To evaluate the strategic behavior of the monopolist, we compare two alternative policy regimes. The first of the regimes 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 regime where the regulator sets the ex-post optimal level of the instrument once the monopolist has chosen its innovation level. Production is always chosen at the end. We have considered two instruments, a tax and a standard. Moreover, for each policy instrument we have distinguished whether marginal damages are increasing or constant. In order to facilitate the presentation of the main results of the paper, we have summarized the welfare comparisons in Table 4.

$\Rightarrow$ Table 4 $\Leftarrow$

We show that the strategic behavior of the firm is welfare improving and may induce more environmental innovation than under regulatory commitment *only* when a tax is used to control pollution and marginal damages are increasing, regardless of the importance of environmental damages. In all other cases, if environmental policy should be in place, the strategic behavior of the firm has a detrimental effect on welfare. The intuition goes as follows. The regulator's best response function changes depending on the instrument. There is a positive relation between the tax and the innovation effort whereas it is negative between the standard and innovation effort. Then strategic behavior gives rise to more innovation by inducing the regulator to lower the equilibrium tax. The opposite happens with a standard and hence the superiority of a non-committed policy with a tax when marginal damages are increasing. However, the tax and the innovation effort are independent for constant marginal damages. This means that the monopolist cannot strategically use its abatement to influence the environmental policy in its own benefit. Given the linearity of environmental costs the regulator can enhance more innovation and lower emissions with a commitment policy. Moreover, we have found that the emission standard is more vulnerable to the strategic behavior of the monopolist when marginal damages are constant, i.e. the welfare level achieved without commitment when a standard is used is lower than the welfare level achieved by the application of a tax.

These findings have implications for the design of environmental policy to regulate the emissions of a monopoly. The preference of rules over discretion depends on marginal damages. When these are increasing, the optimal policy is to apply an emission tax without commitment. Rules are not better than discretion. Although commitment is preferred for the case of an emission standard, this is dominated by a time consistent tax in welfare terms. Instead, when marginal damages are constant, the optimal policy is commitment regardless of the instrument. Now, rules are better than discretion. Commitment yields higher welfare than no commitment for both instruments and, moreover, with commitment the two instruments are equivalent since they yield the same outcome. However, a tax could be preferred to a standard in the choice of the policy instrument regardless of the type of environmental damages. The reason is that without commitment a tax allows to achieve a larger welfare level than a standard and with commitment the same welfare level.

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. Another interesting 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.[17]

[17] 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.

Appendix A

Proof of Proposition 3

Using (9) and (16) we get

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

where

$$\begin{aligned} b_0(d) &= (3d+1)(d-1)(d+1)^2 \\ b_1(d) &= (d+1)(2d^4 + 19d^3 + 12d^2 - 13d - 4) \\ b_2(d) &= 4d(d+1)(3d^3 + 13d^2 + 6d - 2) \\ b_3(d) &= 4d^2(7d^3 + 24d^2 + 20d - 1) \\ b_4(d) &= 32d^2(d+2) \\ b_5(d) &= 16d^5. \end{aligned}$$

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

Next, using (8) and (15) we obtain the difference in profits

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

where

$$\begin{aligned} f_0(d) &= (5d+3)(d-1)(d+1)^2 \\ f_1(d) &= 2(2d^5 + 19d^4 + 16d^3 - 5d^2 - 12d - 4) \\ f_2(d) &= 4d(6d^4 + 23d^3 + 6d^2 - 7d - 4) \\ f_3(d) &= 8d^2(6d^3 + 8d^2 - 4d - 1) \\ f_4(d) &= 16d^2(2d-1). \end{aligned}$$

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

Proof of Proposition 6

Using (22) and (25) we get

$$\hat{W}_s^c - \hat{W}_s^{nc} = \frac{4d^2 + 2\gamma A d - \gamma A^2}{2\gamma(4+\gamma)} \tag{37}$$

that is positive for high enough values of marginal damages, d. However, we are making the comparisons for values of d in the interval (20), so that we need to check the sign of the welfare difference in that interval. To do that we substitute first the lower extreme of the interval in the numerator of (37) that yields the following expression:

$$4\left(\frac{A\gamma}{2(2+\gamma)}\right)^2+2\gamma A\frac{A\gamma}{2(2+\gamma)}-\gamma A^2=-\frac{A^2\gamma(\gamma+4)}{(2+\gamma)^2}<0$$

and afterwards the upper extreme that gives the following expression:

$$4\left(\frac{\gamma(3+\gamma)A}{(2+\gamma)^2}\right)^2+2\gamma A\left(\frac{\gamma(3+\gamma)A}{(2+\gamma)^2}\right)-\gamma A^2=\frac{\gamma A^2\left(\gamma+4\right)\left(8\gamma+6\gamma^2+\gamma^3-4\right)}{(2+\gamma)^4}.$$

This expression is zero for $\gamma = 0.38$. Thus, for $\gamma < 0.38$ the difference (37) is negative. On the other hand, for $\gamma > 0.38$ there exists a value $d(\gamma)$ given by the positive root of equation $4d^2 + 2\gamma Ad - \gamma A^2 = 0$,

$$d_W(\gamma)=\frac{A}{4}((\gamma^2+4\gamma)^{1/2}-\gamma)$$

that belongs to the interior of the interval (20) such that if $d < d_W(\gamma)$ the welfare difference given by (37) is negative and if $d > d_W(\gamma)$ is positive. It is is easy to show that $d_W(\gamma)$ is an increasing concave function that converges to $A/2$ since

$$\lim_{\gamma\to\infty}(\gamma^2+4\gamma)^{1/2}-\gamma=2.$$

Proof of Proposition 7

Using (21) and (24) we obtain the difference in profits

$$\hat{\pi}_s^c-\hat{\pi}_s^{nc}=\frac{4(\gamma^2+2\gamma-4)d^2-8A\gamma(\gamma+3)d+A^2\gamma(3\gamma+8)}{2\gamma(4+\gamma)^2}. \tag{38}$$

It is easy to check that the equation $4(\gamma^2 + 2\gamma - 4)d^2 - 8A\gamma(\gamma + 3)d + A^2\gamma(3\gamma + 8) = 0$ has two positive roots if $\gamma > 1.24$ and only one if $\gamma < 1.24$. Notice that $\gamma^2 + 2\gamma - 4 = 0$ for $\gamma = 1.24$. Then the difference (38) is negative in the interval of d defined by the two positive roots when $\gamma > 1.24$ and when d is larger than the positive root if $\gamma < 1.24$.

Next, we check the sign of (38) for the values of d that defines the interval (20). First we substitute the lower extreme in the numerator of (38) that yields the following expression:

$$4(\gamma^2+2\gamma-4)\left(\frac{A\gamma}{2(2+\gamma)}\right)^2-8A\gamma(\gamma+3)\frac{A\gamma}{2(2+\gamma)}+A^2\gamma(3\gamma+8)=\frac{2A^2\gamma\left(\gamma+4\right)^2}{(2+\gamma)^2}>0 \tag{39}$$

and afterwards the upper bound that gives the following expression:

$$4(\gamma^2+2\gamma-4)\left(\frac{\gamma(3+\gamma)A}{(2+\gamma)^2}\right)^2-8A\gamma(\gamma+3)\frac{\gamma(3+\gamma)A}{(2+\gamma)^2}+A^2\gamma(3\gamma+8)$$

$$= -\frac{A^2\gamma\left(\gamma+4\right)^2\left(\gamma^3+8\gamma^2+12\gamma-8\right)}{(2+\gamma)^4}. \tag{40}$$

This expression is negative for $\gamma > 0.49$.

Then for $\gamma > 1.24$, (40) is negative so that we can conclude that there exists a value $d_\pi(\gamma)$ given by the smaller positive root of the equation $4(\gamma^2+2\gamma-4)d^2-8A\gamma(\gamma+3)d+A^2\gamma(3\gamma+8)=0$,

$$d_\pi(\gamma) = \frac{A}{2}\frac{2\gamma(\gamma+3)-(\gamma+4)(\gamma\left(\gamma+2\right))^{1/2}}{\gamma^2+2\gamma-4} \tag{41}$$

that belongs to the interior of the interval (20) such that if $d < d_\pi(\gamma)$ the difference in profits is positive and if $d > d_\pi(\gamma)$ the difference is negative. It is easy to check that $d_\pi(\gamma)$ is an increasing concave function that converges to $A/2$ since

$$\lim_{\gamma\to\infty}\frac{2\gamma(\gamma+3)-(\gamma+4)(\gamma\left(\gamma+2\right))^{1/2}}{\gamma^2+2\gamma-4} = 1.$$

For $\gamma \in (0.49, 1.24)$, (40) is also negative so that there exists a value $d(\gamma)$ given again by (41) such that if $d < d_\pi(\gamma)$ the difference in profits is positive and if $d > d_\pi(\gamma)$ the difference is negative. Finally, for $\gamma < 0.49$, (40) is positive for all d that belongs to the interval (20) and the difference in profits is positive.

Proof of Proposition 9

Using (22) and (35) we get the difference in welfare

$$\hat{W}_t^c - \hat{W}_t^{nc} = \frac{2(A-d)^2}{\gamma(4+\gamma)} > 0.$$

Next, using (21) and (34) we obtain the difference in profits

$$\hat{\pi}_t^c - \hat{\pi}_t^{nc} = \frac{2(2+\gamma)(2(3+\gamma)d^2-(3\gamma+8)Ad+(\gamma+2)A^2)}{\gamma(4+\gamma)^2}. \tag{42}$$

It is easy to check that the equation $2(3+\gamma)d^2-(3\gamma+8)Ad+(\gamma+2)A^2=0$ has two positive roots. Then the difference (42) is negative in the interval of d defined by the two positive roots.

Now, we check the sign of (42) for the values of d that defines the interval (36). First we substitute d in the numerator of (42) by the lower extreme of the interval that yields the following expression:

$$2(3+\gamma)\left(\frac{A}{2}\right)^2-(3\gamma+8)A\frac{A}{2}+(\gamma+2)A^2 = -\frac{A^2}{2} < 0$$

and afterwards the upper extreme of the interval that gives the following expression:

$$2(3+\gamma)\left(\frac{\gamma(3+\gamma)A}{(2+\gamma)^2}\right)^2-(3\gamma+8)A\frac{\gamma(3+\gamma)A}{(2+\gamma)^2}+(\gamma+2)A^2$$

$$= -\frac{A^2(4+\gamma)^2(\gamma^2+2\gamma-2)}{(2+\gamma)^4} < 0 \text{ for } \gamma > 1.24.$$

Since the two expressions are negative, we can conclude that the difference of profits (42) is negative for values of d in the interval (36).

Appendix B

Comparison of profits before taxation with quadratic environmental damages

Using expressions in Petrakis and Xepapadeas' (2001) paper for innovation, (8), and for production, (10), we obtain the expression for profits before taxation when there is no commitment

$$\pi_t^{nc} = \frac{(a-c)^2((\gamma+2)\,d^4 + 2\,(3\gamma+\gamma^2+4)\,d^3 + 2\,(4\gamma+2\gamma^2+3)\,d^2 + 2\gamma\,(\gamma+3)\,d - \gamma)}{2((\gamma+2)d^2+2(\gamma+2)d+\gamma)^2}, \quad (43)$$

and using (14) and (15), the expression for profits before taxation when there is commitment

$$\pi_t^{c} = \frac{(a-c)^2((\gamma+2)^3\,d^2 + 2\gamma\,(\gamma+2)^3\,d + \gamma^2\,(3\gamma+8))}{2((\gamma+2)^2d+\gamma(4+\gamma))^2}.$$

Then the difference in profits is

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

where

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

Thus, for any given γ the equation

$$b_0(\gamma)d^5 - b_1(\gamma)d^4 - b_2(\gamma)d^3 - b_3(\gamma)d^2 - b_4(\gamma)d - b_5(\gamma) = 0, \quad (44)$$

gives us the critical values for d that allow us to define the intervals of marginal damages for which the difference in profits is 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 12. *For all $\gamma > 0$, there exists a value $\hat{d}(\gamma)$ given for the positive root of equation (44) 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., $\pi_t^{nc} < \pi_t^c$. However, if $d > \hat{d}(\gamma)$ the optimal commitment profits before taxation are lower than the optimal no commitment profits before taxation, i.e., $\pi_t^c < \pi_t^{nc}$.*

Appendix C

The efficient outcome and the unregulated monopolist equilibrium

The first-best or efficient outcome is given by the solution to the following maximization problem:

$$\max_{\{q,w\}} W = Aq - \frac{1}{2}q^2 - \frac{\gamma}{2}w^2 - de$$

$$s.t.\ e = q - w.$$

The solution is given by the following expressions:[18]

$$q^e = A - d,\ w^e = d/\gamma,\ e^e = A - \frac{1+\gamma}{\gamma}d.$$

On the other hand, the maximization of profits yields the well known unregulated monopoly equilibrium[19]

$$q^m = e^m = \frac{A}{2},\ w^m = 0.$$

Comparing production and emissions it is obtained

$$q^m - q^e = d - \frac{A}{2}, \quad e^m - e^e = \frac{1+\gamma}{\gamma}d - \frac{A}{2}.$$

Thus, to have $0 < q^e < q^m$ and $0 < e^e < e^m$ the parameters should satisfy the following conditions:

$$d \in \left(\frac{A}{2}, \frac{\gamma A}{1+\gamma}\right) \text{ with } \gamma > 1.$$

Comparing the extremes of this interval with those that define interval (20), we obtain the ordering

$$\frac{A\gamma}{2(2+\gamma)} < \frac{A}{2} < \frac{\gamma(3+\gamma)A}{(2+\gamma)^2} < \frac{\gamma A}{\gamma+1}.$$

Thus, if we constraint the parameters to satisfy[20]

$$d \in \left(\frac{A}{2}, \frac{\gamma(3+\gamma)A}{(2+\gamma)^2}\right) \text{ with } \gamma > 1.24, \tag{45}$$

[18] In the expressions, the superscript e stands for efficiency.

[19] In the expressions, the superscript m stands for unregulated monopoly.

[20] $\gamma > 1.24$ guarantees that the interval is not empty.

production and emissions in the two policy games analyzed in Section 4.1 and also in the efficient outcome and unregulated monopolist equilibrium are positive.

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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	1500. 6	1800. 8	
Unregulated monopoly (M)		49.00	0.00	49.00	2401.0	-2401.0	
Commitment (standard) (C)		11.47	16.68	28.15	1618.5	1685.8	93.61
Commitment (tax) (C)	41.70	11.47	16.68	28.15	1618.5	1685.8	93.61
No commitment (standard) (NC)		14.00	14.00	28.00	1715.0	1617.0	89.79
No commitment (tax) (NC)	30.62	12.87	20.82	33.69	1624.8	1778.2	98.74

a=100, c=2, d=5.0, γ=2.5

Table 2. Emission standards with constant marginal damages.

	e	w	q	π	W	$\%W^e$
Efficient outcome (E)	14.00	24.00	38.00	1560	1442	
Unregulated monopoly (M)	49.00	0.00	49.00	2401	−68429	
Commitment (C)	8.15	18.15	26.30	1474	1330	92.23
No Commitment (NC)	38.00	0.00	38.00	2280	722	50.01

a=100, c=2, d=60, γ=2.5

Table 3. Emission taxes with constant marginal damages.

	t	e	w	q	π	W	$\%W^e$
Efficient outcome (E)		14.00	24.00	38.00	1560	1442	
Unregulated monopoly (M)		49.00	0.00	49.00	2401	−68429	
Commitment (C)	45.38	8.15	18.15	26.30	1474	1330	92.23
No Commitment (NC)	22.00	29.20	8.80	38.00	2183	1153	79.96

a=100, c=2, d=60, γ=2.5

Table 4. Comparison of welfare levels.

	Marginal damages	
	Increasing	Constant
Tax	$W_t^c < W_t^{nc}$	$\hat{W}_t^c > \hat{W}_t^{nc}$
Standard	$W_s^c > W_s^{nc}$	$\hat{W}_s^c > \hat{W}_s^{nc}$
Rank	$W_s^{nc} < W_s^c = W_t^c < W_t^{nc}$	$\hat{W}_s^{nc} < \hat{W}_t^{nc} < \hat{W}_t^c = \hat{W}_s^c$

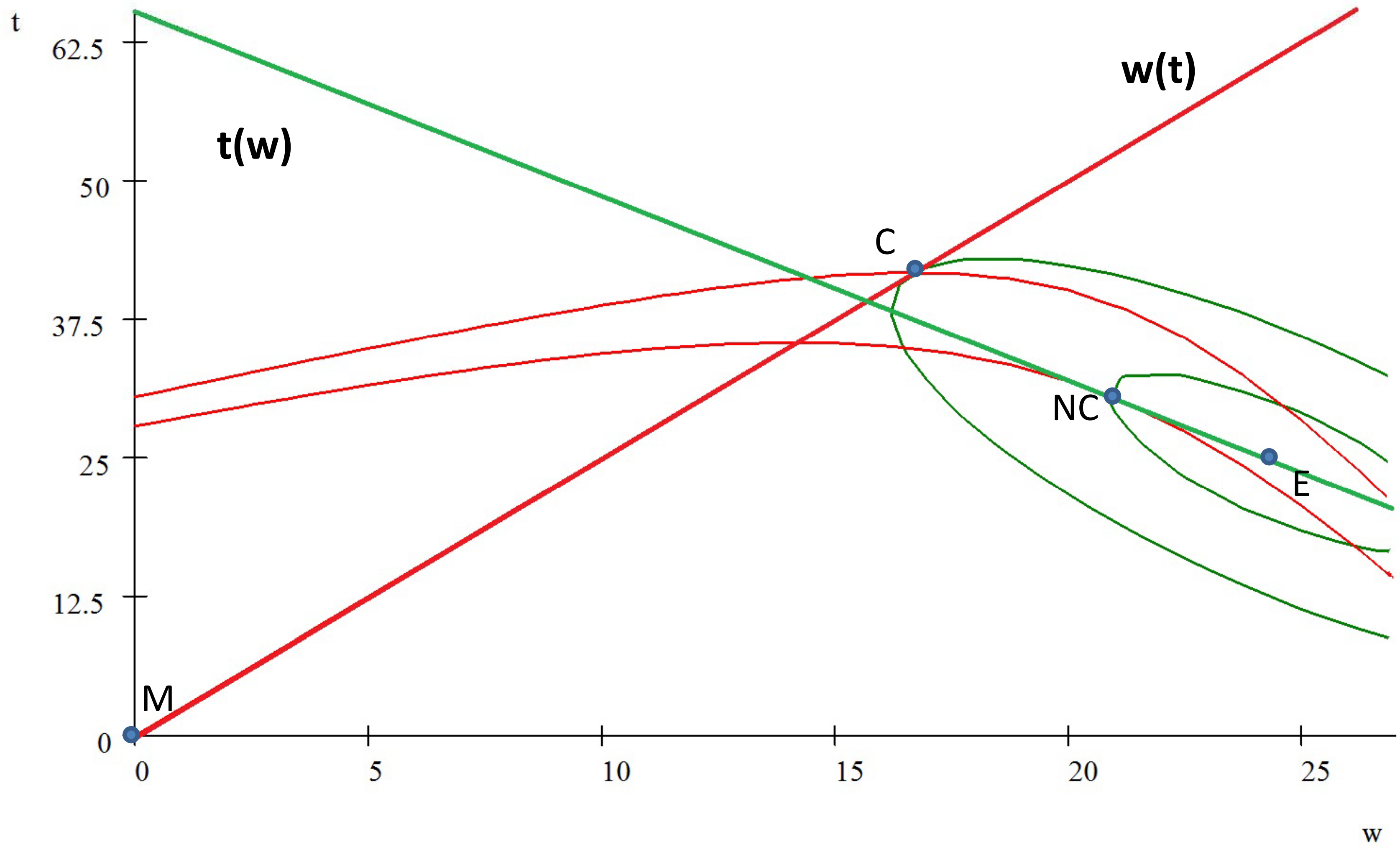

Figure 1. Equilibrium outcomes when the regulator uses a tax .

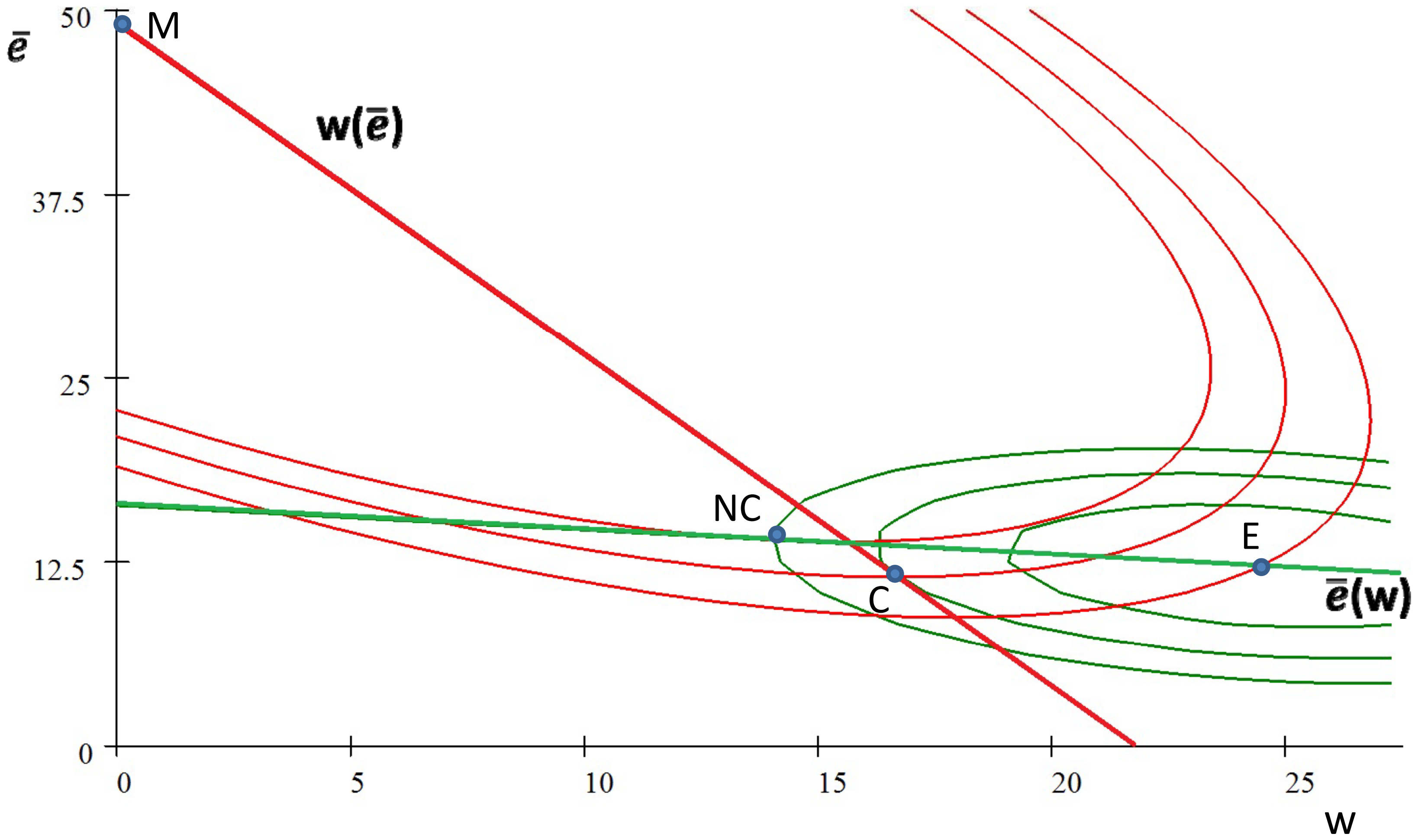

Figure 2. Equilibrium outcomes when the regulator uses a standard.

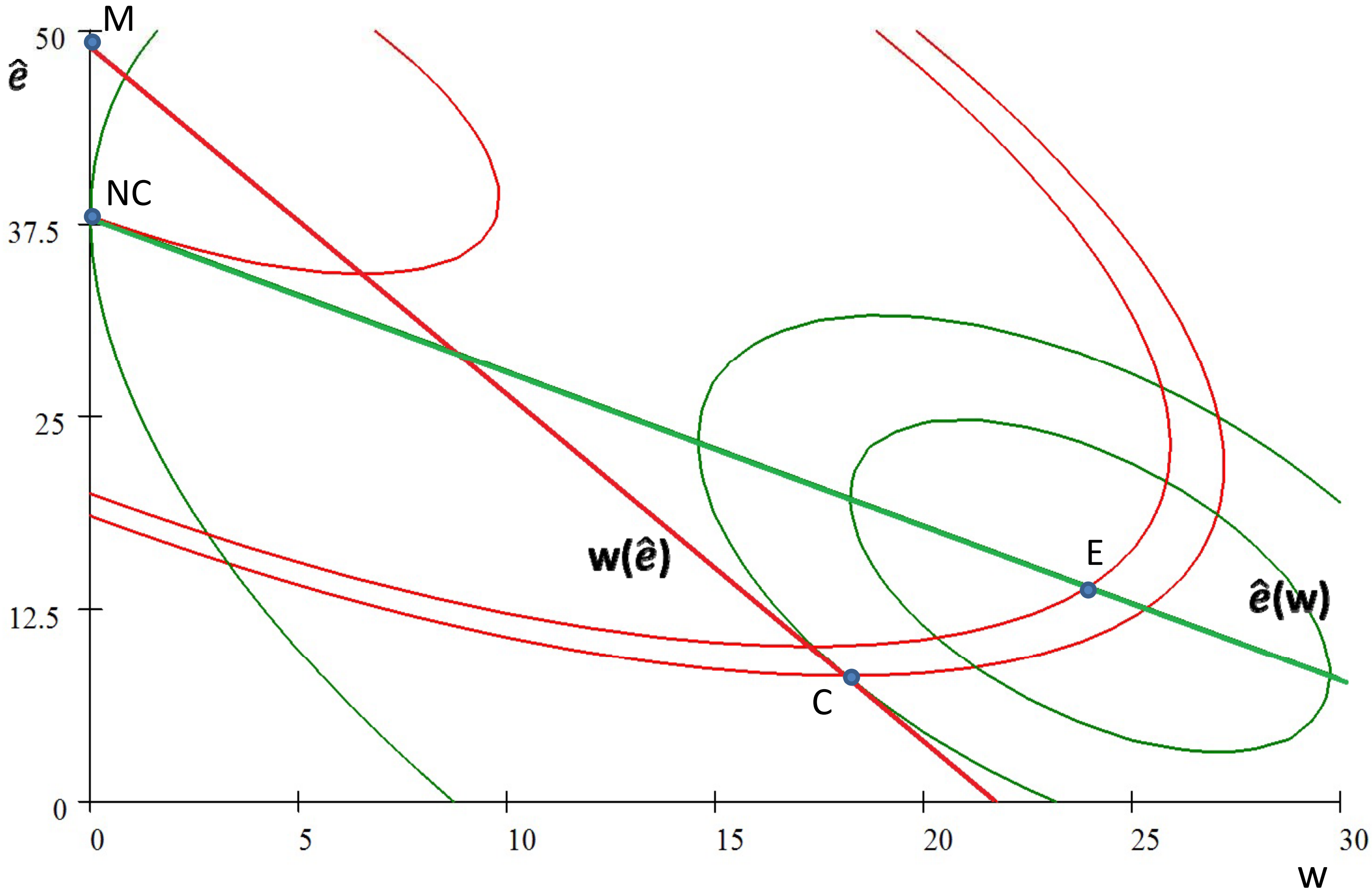

Figure 3. Constant marginal damages. Equilibrium outcomes when the regulator uses a standard.

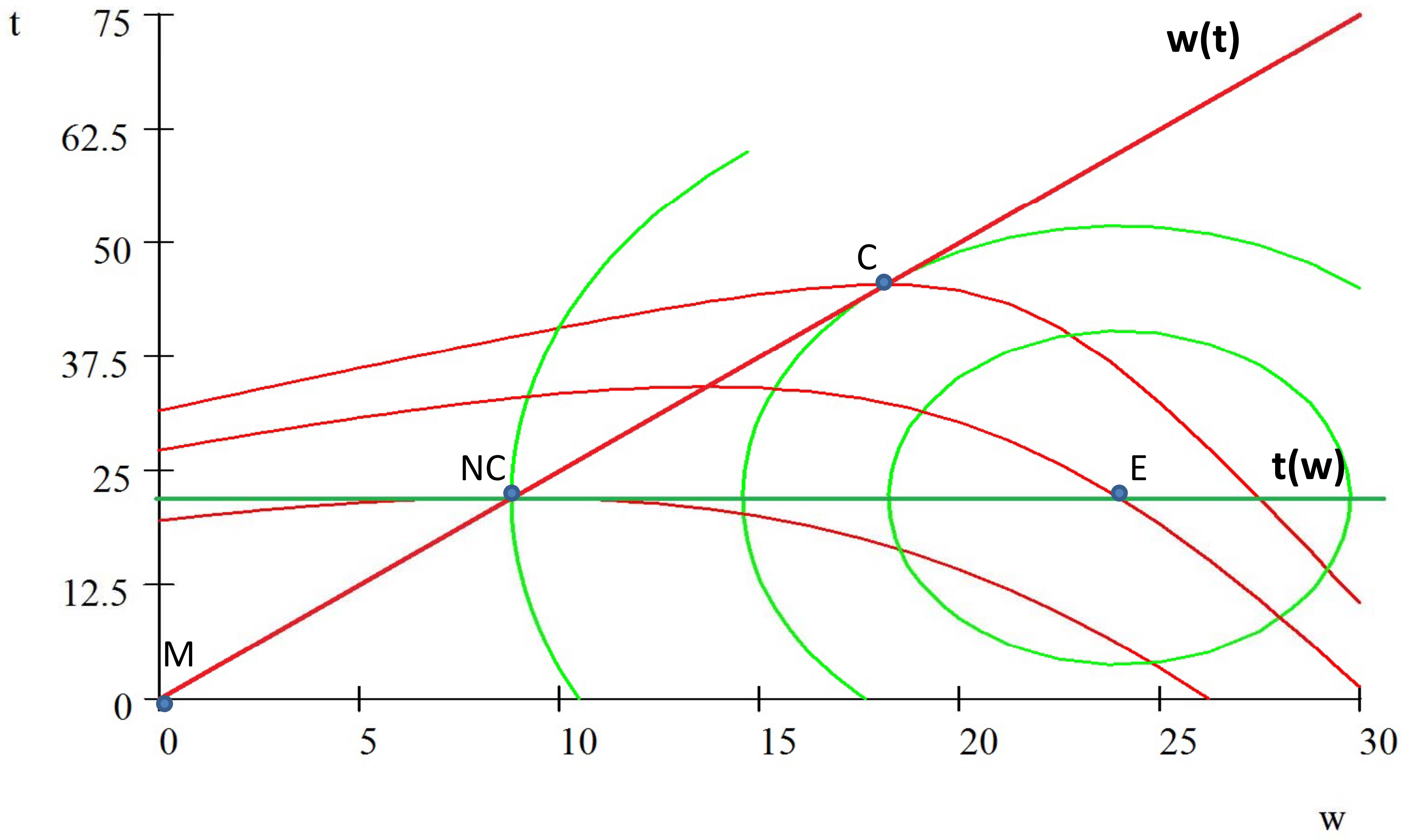

Figure 4. Constant marginal damages. Equilibrium outcomes when the regulator uses a tax.