Economía Agraria y Recursos Naturales. ISSN: 1578-0732. e-ISSN: 2174-7350. Vol. 15,1. (2015). pp. 11-40

The timing of environmental policy in a duopolistic market

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ABSTRACT: In this paper the strategic use of innovation by two polluting firms to influence environmental policy is evaluated. The analysis is carried out by comparing two alternative policy regimes for two policy instruments: Taxes and standards. The first of the regimes assumes that the regulator commits to an ex-ante level of the policy instrument. In the second one, there is no commitment. The results show that when there is no commitment and a tax is used to control emissions, the strategic behavior of firms can be welfare improving if the efficiency of the clean technology is relatively low. If this is not the case, the strategic behavior of the duopolists has a detrimental effect on welfare regardless of the policy instrument used to control emissions.

KEYWORDS: Commitment, duopoly, innovation, standards, taxes.

JEL classification: H23, L13, L51, Q55.

DOI: 10.7201/earn.2015.01.02.

La elección del momento oportuno de la política ambiental en un mercado duopolístico

RESUMEN: En este trabajo se evalúa el uso estratégico de la innovación por dos empresas contaminantes para influir en la política ambiental. El análisis se desarrolla comparando dos regímenes de política alternativos para dos instrumentos: impuestos y estándares. El primero de los regímenes supone que el regulador se compromete con un nivel ex-ante del instrumento de política. En el segundo, no hay compromiso. Los resultados muestran que cuando no hay compromiso y se utiliza un impuesto para controlar las emisiones, el comportamiento estratégico de las empresas mejora el bienestar si la eficiencia de las tecnologías limpias es relativamente baja. Si este no es el caso, el comportamiento estratégico de los duopolistas tiene un efecto perjudicial sobre el bienestar independientemente del instrumento de política utilizado para controlar las emisiones.

PALABRAS CLAVE: Compromiso, duopolio, estándares, impuestos, innovación.

JEL classification: H23, L13, L51, Q55.

DOI: 10.7201/earn.2015.01.02.

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Acknowledgements: The authors would like to thank two anonymous referees and Francisco André for their comments. The usual disclaimer applies. We gratefully acknowledge financial support from the Spanish Ministry of Economics and Competitiveness under project ECO2013-45045-R, and Generalitat Valenciana under project PROMETEO/2014 /Fase II.

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Received on October 2014. Accepted on April 2015.

1. Introduction

It is well understood by now that the ability of a government or regulator to commit to a particular policy in a credible manner has significant consequences for various aspects of economic activity. In the context of environmental regulation in imperfectly competitive markets, if the regulator cannot commit to the stringency of the policy instrument, firms have lower incentives to innovate because the regulator has an ex-post possibility to ratchet up regulation and expropriate gains from investment in clean technologies. In anticipation of expropriation, firms may reduce their innovation effort. On the other hand, if the regulator is not able to commit, firms may also strategically use innovation to ratchet down regulation and increase profits as noted by Gersbach and Glazer (1999). Besides, oligopoly firms care about their competitive position against rivals. For instance, if a firm increases innovation to obtain a reduction of the emission tax from the regulator, it will have to consider that such tax reduction will induce rivals to increase production and, therefore, that the increase in innovation will finally lead to a price lower than expected by the increase of its own production. In other words, the increase in innovation will have a negative effect on the firm's marginal revenue because its rival will raise production to adjust to a lower tax. These strategic considerations are present in many sectors such as the automobile industry and agriculture, where the introduction and adoption of new technologies has become a key feature. For instance, modern biotechnology provides breakthrough products and technologies that improve crop herbicide tolerance, ultimately increasing crop yields. In 2014, the global area of biotech crops reached 181.5 million hectares and their global market value was US$15.7 billion (James, 2014). These figures show the importance of an industry where the top three seed firms (Monsanto, Dupont and Syngenta) control almost 50 % of all seeds, and each spends more than US$1.5 billion in R&D. There are many genetically modified (GM) products ready to be commercialized yet they require approval of regulatory agencies. These are concerned with the possible toxicity of GM food and products, as well as about environmental risks such as the impact of gene flow, the evolution of pest resistance and loss of biodiversity. Whether there is consumer resistance to GM products depends on the message perceived about their quality. In many countries it is mandatory to label products that use GM ingredients as these products must comply with certain standards. In the end, the regulatory regime that should govern the industry is the outcome of competition and bargaining between pressure groups, legislators and the bureaucracy[1].

The aim of this paper is to investigate the effect of the timing of environmental policy on environmental innovation and welfare in imperfectly competitive markets. This issue can conveniently be addressed in a model that features a polluting duopoly

[1] The reader might like to see Bonroy and Constantatos (2015) for an excellent survey on the implications of labels both from a theoretical and a policy perspective. In particular, these authors identify that regulators must consider the distortions associated with market structure, the label's standard and lobbying activities in favor of, or opposed to the imposition of the label. To illustrate, Monsanto spent more than US$6 billion lobbying in 2012 in an effort to convince lawmakers not to label GM products (October 2013, Nation of Change Journal).

where firms can invest in clean technology. Such investments reduce emissions yet they are costly. On the other hand, a regulatory agency cares about environmental damages and may use environmental policy instruments to reduce emissions. The analysis considers two policy instruments, emission taxes and emission standards, and distinguishes whether the regulator has the ability to commit or not. Under commitment the regulator can credibly choose the emission tax or standard before firms decide on innovation effort. When the regulator's policy is non-credible, firms anticipate that they can use innovation to influence the regulator's choice of the time-consistent (or ex-post) emission tax or standard.

Our findings show that the regulator's inability to commit to an emission standard level not only yields a lower level of environmental innovation relative to the commitment case but also generates less welfare, i.e. the strategic behavior of firms has a detrimental effect on social welfare. If the regulator cannot commit, firms reduce innovation to prompt a larger standard. Firms use innovation to ratchet down regulation. Production can be larger or lower in the no commitment case but welfare is in any case lower. Without commitment, what happens when a standard is used to control pollution is that the increase in environmental damages because of a larger standard and the reduction in consumer surplus when production is lower more than compensates the reduction in investment costs. Instead, when the production is larger, the reduction in investment costs and the increase in consumer surplus are more than compensated by the increase in environmental damages. However, if a tax is the policy instrument selected to address pollution, the strategic behavior of firms may be welfare improving. If the regulator cannot commit, firms increase innovation to induce the regulator to set up a lower tax. Firms use innovation to ratchet down regulation but now the result may be an increase both in profits and welfare. This will occur when the convexity of investment costs is relatively more important than that of environmental damages, i.e. when the efficiency of the clean technology is low in relative terms. Then, the reduction in the tax induced by the strategic behavior of the firms comes along with an increase in environmental innovation that mitigates the increment in emissions caused by a larger production. 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. The increase in production also yields larger profits. In this case, the regulator's inability to commit to environmental policy is not a problem. However, if environmental damages are severe, i.e. if the efficiency of the clean technology is high in relative terms, the ordering between the different variables is reversed and the strategic behavior of firms has a detrimental effect on social welfare when a tax is used. Summarizing, commitment is better than no commitment for large enough environmental damages and the choice of the instrument is not an issue because with commitment both instruments are equivalent. Finally, we compare welfare for both instruments when the regulator is not able to commit and we show that for a large constellation of parameter values, the optimal policy is to apply a tax on emissions although firms would prefer a standard. Only when environmental damages are severe, the regulator should implement a standard although in this case firms would prefer a tax.

A lot of papers have studied the extent to which an environmental policy provides firms with incentives to invest in environmental innovation under imperfect competition. An excellent survey to consult is Requate (2006). The majority of them assumes that the regulator is able to commit and moves first in the policy game. See for instance the papers by Katsoulacos and Xepapadeas (1995; 1996), Damania (1996), Carlsson (2000), Innes and Bial (2002), Antelo and Loureiro (2009), Coria (2009) and more recently by McDonald and Poyago-Theotoky (2014). On the other hand, the list of papers where the regulator is not able to commit is rather short including the contributions by Poyago-Theotoky (2007; 2010) and more recently by Ouchida and Goto (2014)[2]. Other papers, such as those by Chiou and Hu (2001), Montero (2002), Gil-Moltó and Varvarigos (2013) assume that either the level of the policy instrument or the target of the environmental policy are exogenously given. Finally, there are only a few papers directly addressing the research question studied in this paper: Petrakis and Xepapadeas (1999; 2001; 2003); Poyago-Theotoky and Teerasuwannajak (2002), Puller (2006) and more recently Moner-Coloques and Rubio (2014)[3].

In Petrakis and Xepapadeas (1999; 2003) and in the first part of Petrakis and Xepapadeas (2001) the case of a polluting monopoly is studied when the regulator uses a tax to control emissions. Their analyses show that if marginal damages are increasing then the strategic behavior of the monopolist is welfare improving. Welfare is always larger when the regulator is not able to commit to the emission tax rate. Moreover, they obtain this result for two different specifications of the emission function, one that is additively separable in output and innovation and another for which emissions are proportional to output. Moner-Colonques and Rubio (2014) clarify that the former results depend on the policy instrument used by the regulator as well as on the nature of the damage function. They show that with constant marginal damages, the strategic behavior of the monopolist has a detrimental effect on welfare regardless of the instrument used by the regulator. 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. Our analysis gives support to this result and clarifies that with some competition, i.e. with two firms, the strategic behavior of firms has a detrimental effect on welfare provided that environmental damages are large enough. Moreover, our research also highlights the importance of the policy instrument, a point not dealt with by these authors. Puller (2006) investigates the effects of regulation through performance standards for a Cournot duopoly with spillovers. In his model, the reduction of the performance standard increases the marginal cost of production but investment can mitigate this effect. He finds that competition in the output market creates incentives to raise rivals' costs, which

[2] 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.

[3] 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.

induces firms to innovate into compliance cost technology. Therefore, the incentive to influence the performance standard depends on the relative size of the ratchet and raise rivals cost effects. Using numerical exercises he concludes that the raise rivals cost effect relies on the innovator's ability to appropriate the majority of the benefits of innovation efforts. This suggests that the lack of regulatory commitment in an oligopoly setting can reduce welfare in the absence of strong intellectual property rights. Poyago-Theotoky and Teerasuwannajak (2002) examine a Cournot differentiated duopoly to show that the effects of an emission tax on innovation and welfare depends on the degree of product differentiation. Our results support those obtained by these authors for a low degree of product differentiation.

Another strand of the literature has investigated the interplay between environmental policy, the incentives to adopt new technology, and 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 (2005), Montero (2011) and more recently Wirl (2014)[4]. All these papers highlight the importance of commitment versus no commitment of environmental policy on the incentives to make investments in R&D to reduce pollution.

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 and Section 4 to influence an emission tax. Section 5 summarizes the results of welfare comparisons and derives policy recommendations and Section 6 offers some concluding remarks and points out lines for future research.

2. The model

We consider a model where two firms produce a homogeneous good under a linear demand specification $P = a - Q$, where $Q = q_i + q_j$, $i, j = 1, 2$, $i \neq j$. The marginal cost of production is assumed constant and equal to c for both firms, 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 express firm *i's* (net) emissions as $e_i(q_i, w_i) = q_i - w_i$, where w_i stands for environmental innovation[5]. The investment in abatement technology, w_i commonly referred to as end-of-pipe pollution investment for this specification of the emission function, is costly. Investment costs are given by $c(w_i) = \gamma w_i^2 / 2$, $\gamma > 0$, which captures that there exist decreasing returns

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

[5] The particular choice for the specification of the pollution generation process is made for the sake of the presentation. 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 polluting monopoly with a linear specification of the emissions function (like the one used in this paper) turn out to be robust under a non-linear specification.

in innovation effort, with the parameter γ measuring the extent of such decreasing returns or the inverse of the efficiency of the emission-reducing technology. 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 marginal damages are and $E=e_i + e_j$.To guarantee an interior solution for innovation and a positive emission tax, we will assume $d \geq 1.5$ 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 two profit maximizing firms, 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 duopolists, taking that level as given, choose investment in abatement technology simultaneously and independently. In the second regime, the *non-committed (or ex-post) regulator game*, firms first select its environmental innovation level, simultaneously and independently, then the regulator sets the level of the policy instrument. 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 firms select 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 and the firms have chosen the innovation. The solution concept employed is subgame perfection. One could extend the model to include private information, but this simple game shows that the lack of commitment can have relevant welfare consequences even without private information[6].

3. Emission standard

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

3.1. The committed regulator game

Under emission standards regulation, $q_i = \overline{e}_i + w_i$, where $\overline{e}_i$ is the emission standard imposed on the firms. Then in the second stage, the firms choose innovation effort to maximize profits taking as given the emission standards

[6] A paper where this isue is studied is Antelo and Lourerio (2009). These authors examine the effects of signaling on environmental taxation in a two-period oligopoly model in which each firm privately knows whether its technology is clean or dirty while third parties have only a subjective perception about this fact.

$$\max_{\{w_i\}} \pi_i = (a-(\bar{e}_i+w_i+\bar{e}_j+w_j))(\bar{e}_i+w_i)-c(\bar{e}_i+w_i)-\frac{\gamma}{2}w_i^2, \quad i,j=1,2,\ i\neq j$$

Solving for w_i in the first-order condition yields

$$w_i = \frac{a-c-2\bar{e}_i-\bar{e}_j-w_j}{\gamma+2}.$$

Using these first-order conditions we obtain the equilibrium level of environmental innovation per firm

$$w_i = \frac{A(\gamma+1)-(2\gamma+3)\bar{e}_i-\gamma\bar{e}_j}{(\gamma+3)(\gamma+1)}, \qquad [1]$$

where $A = a - c$, with A being a measure of market size. Notice that there is an inverse relation between w_i and the standards and so the firm reduces innovation when the regulator increases the emission standards; the standard that is imposed on firm *i* has a stronger effect. The resulting level of production is the following:

$$q_i = \frac{A(\gamma+1)+(\gamma+2)\gamma\bar{e}_i-\gamma\bar{e}_j}{(\gamma+3)(\gamma+1)}.$$

An increase in firm i's emission standard leads it to choose a larger production level but the effect is the contrary if the regulator increases the standard of the rival. Adding for the output of the firms we obtain total output as follows:

$$Q = \frac{2A+\gamma(\bar{e}_i+\bar{e}_j)}{\gamma+3} = \frac{2A+\gamma\bar{E}}{\gamma+3} \qquad [2]$$

where $\bar{E} = \bar{e}_i + \bar{e}_j$. Observe that total output does not depend on the allocation of standards between the firms but on the total standard.

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

$$\max_{\{\bar{e}_i,\bar{e}_j\}} W = \int_0^{Q(\bar{E})}(a-c-x)dx - \sum_{i=1}^{2}\frac{\gamma}{2}w_i(\bar{e}_i,\bar{e}_j)^2 - \frac{d}{2}\bar{E}^2, \quad i,j=1,2,\ i\neq j,$$

or equivalently

$$\max_{\{\bar{e}_i,\bar{e}_j\}} W = AQ(\bar{E})-\frac{1}{2}Q(\bar{E})^2-\sum_{i=1}^{2}\frac{\gamma}{2}w_i(\bar{e}_i,\bar{e}_j)^2-\frac{d}{2}\bar{E}^2, \qquad [3]$$

where $Q(\overline{E})$ is given by [2] and $w_i(\overline{e}_i, \overline{e}_j)$ by [1]. This maximization yields the following condition

$$(P(\overline{E})-c)\frac{dQ}{d\overline{E}} - \gamma\sum_{i=1}^{2} w_i(\overline{e}_i, \overline{e}_j)\frac{\partial w_i}{\partial \overline{e}_j} = d\overline{E}, \quad j = 1, 2,$$

where the first term on the left-hand side measures the increase in consumer surplus coming from the increase in market output when the regulator raises the amount of standards. The second term stands for the decrease in investment costs, internalizing how individual standard affects own and rival's innovation, that is, $w_i(\overline{e}_i, \overline{e}_j)\partial w_i / \partial \overline{e}_i$, and $w_j(\overline{e}_i, \overline{e}_j)\partial w_j / \partial \overline{e}_i$. On the right-hand side, we find the increase in environmental damages coming from a raise in standards.

It is easy to show that the optimization problem [3] has a symmetric solution given by

$$\overline{e}_s^c = \frac{A\gamma(\gamma+4)}{2d(\gamma+3)^2 + \gamma(2\gamma+9)} \qquad [4]$$

where superscript c is used to denote the commitment case and 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

$$w_s^c = \frac{A(2(\gamma+3)d-\gamma)}{2d(\gamma+3)^2 + \gamma(2\gamma+9)}, \qquad [5]$$

$$q_s^c = \frac{A(\gamma+3)(\gamma+2d)}{2d(\gamma+3)^2 + \gamma(2\gamma+9)}. \qquad [6]$$

Since we have assumed that $d \geq 1.5$ the innovation level is positive. Finally, equilibrium profits and welfare are provided below:

$$\pi_s^c = (A - 2q_s^c)q_s^c - \frac{\gamma}{2}(w_s^c)^2, \qquad [7]$$

$$W_s^c = 2Aq_s^c - 2(q_s^c)^2 - \gamma(w_s^c)^2 - 2d(e_s^c)^2. \qquad [8]$$

This completes the analysis of this policy game.

3.2. The non-committed regulator game

In this subsection we solve for the two stage game where the firms plays before the regulator does. When there is no commitment, in the second stage, the regulator chooses the emission standards that maximizes welfare taking as given the firms' innovation effort. Welfare is defined as above and is given by

$$W = A\left(\overline{e}_i + w_i + \overline{e}_j + w_j\right) + \frac{1}{2}\left(\overline{e}_i + w_i + \overline{e}_j + w_j\right)^2 - \sum_{i=1}^{2}\frac{\gamma}{2}w_i^2 - \frac{d}{2}(\overline{e}_i + \overline{e}_j)^2$$

and the first-order conditions are

$$\frac{\partial W}{\partial \overline{e}_i} = A - \left(\overline{e}_i + w_i + \overline{e}_j + w_j\right) - d(\overline{e}_i + \overline{e}_j) = 0,\ i, j = 1, 2,\ i \neq j,$$

but since the two firms have the same constant marginal costs, the previous conditions only determine the total amount of standards

$$\overline{E} = \frac{A - (w_i + w_j)}{d + 1}. \qquad [9]$$

There is an inverse relation between firms' investments and the total standard, that is, the regulator increases the emission standards in response to a reduction in the firms' innovation levels. This means that firms can strategically use their choice of innovation to influence the standards: by decreasing investment in emission-reducing activities the firms 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, firms choose their innovation efforts taking into account how the regulator is going to respond to it. However, this stage cannot be solved without defining first an allocation rule of the standards between firms. Given that firms are symmetric, it seems natural to assign half of the total amount of standards to each firm, that is,

$$\overline{e}_i = \frac{A - (w_i + w_j)}{2(d + 1)}. \qquad [10]$$

Thus, firms solve

$$\max_{\{w_i\}} \pi_i = \left[A - \left(\overline{e}_i(w_i + w_j) + w_i + \overline{e}_j(w_i + w_j) + w_j\right)\right]\left(\overline{e}_i(w_i + w_j) + w_i\right) - \frac{\gamma}{2}w_i^2$$

where $\overline{e}_i(w_i + w_j)$ and $\overline{e}_j(w_i + w_j)$ are given by [10]. The maximization problem yields the following condition:

$$(a-2(\overline{e}_i(w_i+w_j)+w_i)-(\overline{e}_j(w_i+w_j)+w_j))\left(\frac{\partial \overline{e}_i}{\partial w_i}+1\right)-\left(\frac{\partial \overline{e}_j}{\partial w_i}\right)(\overline{e}_i(w_i+w_j)+w_i)$$
$$=c\left(\frac{\partial \overline{e}_i}{\partial w_i}+1\right)+\gamma w_i, \quad i,j=1,2,\ i\neq j,$$

where the left-hand side represents the marginal revenue of the firm and the right-hand side includes the marginal production and investment costs. The strategic effect, $\partial \overline{e}_i / \partial w_i$, reduces the impact that an increase of innovation has on production. The second term on the left-hand side stands for a cross strategic effect between firms that appears because when firm *i* increases its investment, given the allocation rule defined above, the regulator is going to reduce the standards for both firms. This has a positive effect on the marginal revenue of firm *i* because, ceteris paribus, its rival in the market reduces production to adjust to a lower standard which moves outwards the marginal revenue curve of firm *i*.

Solving the previous condition by assuming a symmetric equilibrium we obtain the optimal innovation effort

$$w_s^{nc}=\frac{Ad^2}{(\gamma+3)d^2+(2\gamma+1)d+\gamma}. \quad [11]$$

We employ superscript *nc* to denote the equilibrium in the no commitment game. Then we can substitute for the equilibrium values of emission standard and production levels, which are given by

$$\overline{e}_s^{nc}=\frac{A((\gamma+1)d+\gamma)}{2((\gamma+3)d^2+(2\gamma+1)d+\gamma)}, \quad [12]$$

$$q_s^{nc}=\frac{A(2d^2+(\gamma+1)d+\gamma)}{2((\gamma+3)d^2+(2\gamma+1)d+\gamma)}. \quad [13]$$

Finally, equilibrium profits and welfare are:

$$\pi_s^{nc}=(A-2q_s^{nc})q_s^{nc}-\frac{\gamma}{2}(w_s^{nc})^2, \quad [14]$$

$$W_s^{nc}=2Aq_s^{nc}-2(q_s^{nc})^2-\gamma(w_s^{nc})^2-2d(e_s^{nc})^2. \quad [15]$$

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

3.3. Comparing policy games

In this section we draw comparisons between the committed and non-committed regulator games. Subtracting [4] from [12] we obtain the difference between the equilibrium emission standards as follows:

$$\overline{e}_s^{nc} - \overline{e}_s^{c} = \frac{A(6(\gamma+3)d^2 + \gamma(5\gamma+19)d + \gamma^2)}{2((\gamma+3)d^2 + (2\gamma+1)d + \gamma)(2d(\gamma+3)^2 + \gamma(2\gamma+9))} > 0$$

and using [5] and [11] the expression

$$w_s^{nc} - w_s^{c} = -\frac{A((\gamma^2 + 2\gamma + 6)d^2 + 5\gamma d - \gamma^2)}{((\gamma+3)d^2 + (2\gamma+1)d + \gamma)(2d(\gamma+3)^2 + \gamma(2\gamma+9))} < 0 \text{ for } d > 1.5$$

shows the difference in innovation efforts.

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.* $\overline{e}_s^{c} < \overline{e}_s^{nc}$. *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 firms' decisions on environmental innovation, firms have a strategic incentive to lower its innovation effort in order to induce larger emission standards. In this sense the firms enjoy a first-mover advantage in influencing the environmental policy through its choice of innovation. This strategic effect disappears 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 [6] and [13] we obtain the following expression:

$$q_s^{nc} - q_s^{c} = \frac{A((2d+1)(3-d)\gamma^2 + d(2d+9)\gamma + 6d^2)}{2(2d(\gamma+3)^2 + \gamma(2\gamma+9))((\gamma+3)d^2 + (2\gamma+1)d + \gamma)}.$$

This difference in production is zero for all combinations (γ, d) that satisfy

$$(2d+1)(3-d)\gamma^2 + d(2d+9)\gamma + 6d^2 = 0. \qquad [16]$$

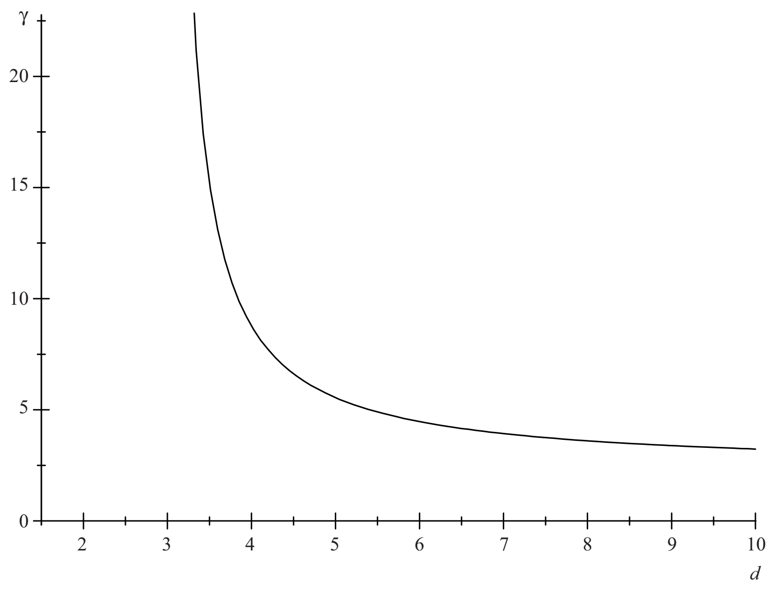
Analyzing this equation it can be concluded that

Proposition 2. *For all* $d \in [1.5, 3]$, *the optimal commitment production is lower than the optimal no commitment production, i.e.,* $q_s^c < q_s^{nc}$. *However, for all d > 3 there exists a decreasing function* $\gamma_s^q(d)$ *with* $\lim_{d\to\infty} \gamma_s^q(d) = 2.3028$ *defined by the positive root of equation [16]such that for all* $\gamma < \gamma_s^q(d)$ *the optimal commitment production is lower than the optimal no commitment production, i.e.* $q_s^c < q_s^{nc}$ *but if* $\gamma > \gamma_s^q(d)$ *the contrary occurs, i.e.* $q_s^{nc} < q_s^c$.

In Fig. 1 we represent the contour defined by [16] that divides the (γ, *d*) space in two regions. If for any *d* > 3 we have that $\gamma > \gamma_s^q(d)$ then the optimal commitment production is larger than the optimal no commitment production (region above the contour). Otherwise, the contrary occurs (region below the contour). 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.

FIGURE 1

Comparing production: $q_s^{nc} < q_s^c$ **in the region above the contour** $q_s^{nc} = q_s^c$



Finally, we compare duopoly profits and welfare under commitment and no commitment environmental policies. The welfare comparison is particularly important because it establishes potential gains in welfare from choosing a certain policy regime. The comparison yields the following result:

Proposition 3. *For all $d \geq 1.5$ there exists a decreasing function $\gamma_s^{\pi}(d)$ with* $\lim_{d\to\infty} \gamma_s^{\pi}(d) = 0.3229$, *whose value for $d = 1.5$ is equal to 0.6062 such that if $\gamma < \gamma_s^{\pi}(d)$ the optimal commitment profits are larger than the optimal no commitment profits, i.e. $\pi_s^{nc} < \pi_s^{c}$ but if $\gamma > \gamma_s^{\pi}(d)$ the contrary occurs, i.e. $\pi_s^{c} < \pi_s^{nc}$. However, the optimal commitment welfare is larger than the optimal no commitment welfare, i.e. $W_s^{nc} < W_s^{c}$, regardless of the value of* γ.

Proof. See Annex A.

Notice that the relationship between welfare 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. With commitment, when a standard is used to control pollution the reduction in environmental damages because of a lower standard more than compensates the increase in investment costs and the reduction in consumer surplus when production is lower. Instead, when the production is larger, the increase in investment costs is more than compensated by the reduction in environmental damages plus the increment in consumer surplus.

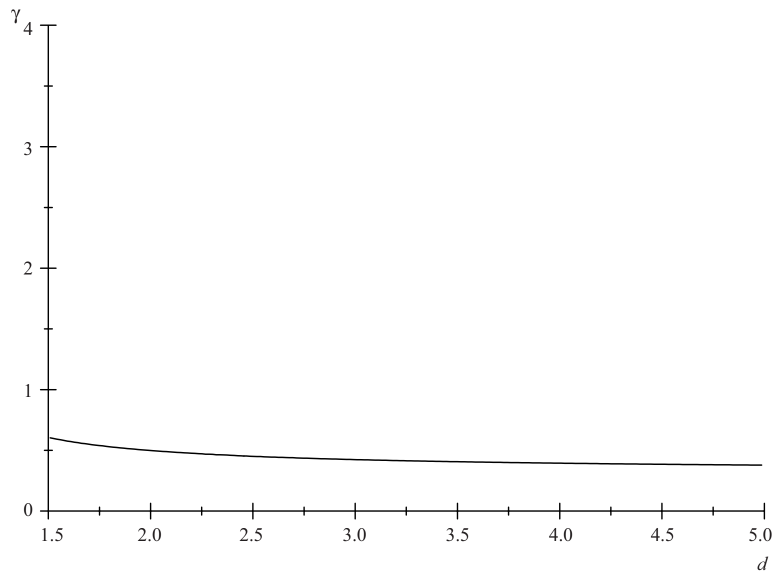
Firms can certainly take advantage of their earlier choice when the regulator is unable to commit to a specific emission standard. Under this lack of regulatory commitment, the duopolists can increase their profits by appropriately choosing their innovation effort. However, this is not possible if the efficiency of the emission-reducing technology is large enough (low decreasing returns). In this case, with low enough investment costs the reduction in revenues because of a larger production is not compensated by the reduction in investment costs yielding lower profits.

In Fig. 2 we represent the contour that divides the (γ, *d*) space in two regions such that the optimal commitment profits are lower than the optimal no commitment profits (region above the contour) when $\gamma > \gamma_s^{\pi}(d)$. Otherwise, the contrary occurs (region below the contour). A necessary condition to get that the strategic behavior of firms leads to lower profits is $\gamma < 0.6062$ what implies according to Prop. 2 that $q_s^{c} < q_s^{nc}$. Nevertheless, Fig. 2 shows that for a large constellation of parameter values we have to expect that the optimal commitment profits are lower than the optimal no commitment profits.

Summarizing, the regulator's *ability* to commit to an emission standard not only promotes environmental innovation relative to the no commitment case but also yields a larger welfare. Commitment dominates no commitment from a social point of view when the instrument of the environmental policy is an emission standard.

FIGURE 2

Comparing profits: $\pi_s^c < \pi_s^{nc}$ in the region above the contour $\pi_s^c = \pi_s^{nc}$



4. 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 the policy instrument is a tax the game has three stages. In the first stage, the regulator sets up the emission tax, then the duopolists choose their investments in innovation, simultaneously and independently, conditional on the emission tax and, finally, they decide their outputs which yield the level of emissions.

4.1. The committed regulator game

In the third stage, firms choose the profit maximizing outputs

$$\max_{\{q_i\}} \pi_i = (A-(q_i+q_j))q_i - \frac{\gamma}{2}w_i^2 - t(q_i - w_i), \quad i, j = 1, 2, \; i \neq j,$$

taking as given the emission tax rate, *t*. The first-order condition yields

$$q_i = \frac{1}{2}\left(A - t - q_j\right).$$

Using these first-order conditions we calculate the (subgame perfect) equilibrium level of production per firm and total output

$$q_i = \frac{A-t}{3}, \quad Q = \frac{2(A-t)}{3}. \qquad [17]$$

Notice that a firm's production decreases in the emission tax.

In the second stage, firms choose innovation, w_i, to maximize profits

$$\max_{\{w_i\}} \pi_i = (A - (q_i(t) + q_j(t))q_i(t) - \frac{\gamma}{2} w_i^2 - t(q_i(t) - w_i),$$

where $q_i(t),\ i = 1, 2,$ is given by [17]. The first-order conditions yield

$$w_i = \frac{t}{\gamma}, \qquad [18]$$

that defines a positive relationship between innovation and the emission tax. Now using [17] and [18], total emissions can be calculated giving the following expression

$$E = \sum_{i=1}^{2} (q_i - w_i) = \frac{2(\gamma A - (\gamma+3)t)}{3\gamma}. \qquad [19]$$

In the first stage, the regulator selects the emission tax to maximize welfare taking into account how firms are going to respond to it

$$\max_{\{t\}} W = AQ(t) - \frac{1}{2}Q(t)^2 - \sum_{i=1}^{2} \frac{\gamma}{2} w_i(t)^2 - \frac{d}{2}E(t)^2, \qquad [20]$$

where *Q(t)* is given by [17], *w(t)* by [18] and *E(t)* by [19]. This maximization problem yields the following condition

$$-dE(t)\frac{dE}{dt} = -(A - Q(t))\frac{dQ}{dt} + \sum_{i=1}^{2} \gamma w_i(t)\frac{dw_i}{dt} \qquad [21]$$

where the left-hand side measures the marginal benefit of taxation that is given by the reduction in environmental damages associated to an increase in the emission tax rate and the right-hand side the marginal cost of taxation that has two components: the decrease in consumer surplus coming from the fall in output market and the raise in investment costs both caused by an increase in the emission tax rate.

This condition yields the optimal emission tax, which is given by

$$t^c = \frac{A\gamma((2d-1)\gamma + 6d)}{2d(\gamma+3)^2 + \gamma(2\gamma+9)} > 0 \text{ for } d \geq 1.5. \qquad [22]$$

Using [22] we can calculate the equilibrium values for the remaining variables. Since the two firms face the same emission tax, both firms will select the same levels of production and innovation, and both firms will pollute by the same amount. Then we check that all variables take the same values than for the committed regulator game when a standard is used to control emissions. This allows us to conclude the following result:

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 equilibrium outcome.*

Profits are identical before taxation and they could be identical after taxation too in case the regulator reimbursed 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.

4.2. The non-committed regulator game

The last stage is the same as in the previous subsection. In the second stage, the regulator chooses the welfare maximizing emission tax taking as given the innovation levels. Welfare can be written as follows:

$$\max_{\{t\}} W = AQ(t) - \frac{1}{2}Q(t)^2 - \sum_{i=1}^{2}\frac{\gamma}{2}w_i^2 - \frac{d}{2}(Q(t) - (w_i + w_j))^2$$

where $Q(t)$ is given by [17]. The first-order condition yields

$$t = \frac{(2d-1)A - 3d(w_i + w_j)}{2(1+d)}. \qquad [23]$$

This expression defines an inverse relationship between firms' investments and the emission tax, that is, the regulator decreases the emission tax rate in response to an increase in the firms' innovation levels. Thus, firms can strategically use its choice of innovation to influence taxation: by increasing investment in emission-reducing activities the firms can expect a lower emission tax.

In the first stage, firms choose their innovation efforts taking into account how the regulator is going to respond. Firms solve the following optimization problem:

$$\max_{\{w_i\}} \pi_i = (A - (q_i(t(w_i + w_j)) + q_j(t(w_i + w_j))))q_i(t(w_i + w_j)) - \frac{\gamma}{2}w_i^2 - t(w_i + w_j)(q_i(t(w_i + w_j)) - w_i),$$

where $t(w_i + w_j)$ is given by [23] and firms' output by [17]. The first-order condition can be written as follows:

$$\frac{\partial \pi_i}{\partial w_i} = (A - 2q_i(t(w_i + w_j)) - q_j(t(w_i + w_j)) - t(w_i + w_j))\frac{dq_i}{dt}\frac{\partial t}{\partial w_i} - \frac{dq_j}{dt}\frac{\partial t}{\partial w_i}q_i(t(w_i + w_j))$$

$$-\gamma w_i - \left(\frac{\partial t}{\partial w_i} (q_i(t(w_i + w_j)) - w_i) - t(w_i + w_j) \right) = 0.$$

Taking into account that, in the third stage, marginal revenue is equal to marginal cost plus the emission tax it can be rewritten as

$$-\left(\frac{\partial t}{\partial w_i} (q_i(t(w_i + w_j)) - w_i) - t(w_i + w_j) \right) = \gamma w_i + \frac{dq_j}{dt} \frac{\partial t}{\partial w_i} q_i(t(w_i + w_j)). \quad [24]$$

This condition states that the gross reduction in fiscal expenses because of an increment in investment must be equal to the increase in investment costs plus the fall in marginal revenue coming from a *cross* strategic effect between firms, $(dq_j / dt)(\partial t / \partial w_i)$, that appears because when firm i increases its investment, the regulator is going to reduce the emission tax for both firms. This has a negative effect on the marginal revenue of firm i because its rival raises production to adjust to a lower tax which moves inwards the marginal revenue curve of firm i.

From these conditions, we obtain the reaction functions in (w_i, w_j) space

$$w_i = \frac{A(2d^2 + 2d - 1) - d(2d + 3)w_j}{(2\gamma + 5)d^2 + 2(2\gamma + 3)d + 2\gamma}, \quad i, j = 1, 2, \ i \neq j.$$

Since the slope of the reaction functions is negative, innovation efforts are strategic substitutes. This is in contrast to the commitment case where $(\partial w_i / \partial w_j) = 0$. Solving the previous system of reaction functions by assuming a symmetric equilibrium we derive the optimal innovation effort[7]

$$w_t^{nc} = \frac{A(2d^2 + 2d - 1)}{(2\gamma + 7)d^2 + (4\gamma + 9)d + 2\gamma} > 0 \text{ for } d \geq 1.5. \quad [25]$$

Then we can substitute for the equilibrium values of the emission tax and outputs, which are given by

$$t^{nc} = \frac{A(2d^2(2\gamma + 1) + (2\gamma - 3)d - 2\gamma)}{2((2\gamma + 7)d^2 + (4\gamma + 9)d + 2\gamma)} > 0 \text{ for } d \geq 1.5 \quad [26]$$

$$q_t^{nc} = \frac{A(4d^2 + (2\gamma + 7)d + 2\gamma)}{2(d^2(2\gamma + 7) + d(4\gamma + 9) + 2\gamma)}. \quad [27]$$

---

7 Subscript t stands for emission tax.

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

$$e_t^{nc} = \frac{A((2\gamma+3)d + 2(\gamma+1))}{2((2\gamma+7)d^2 + (4\gamma+9)d + 2\gamma)}. \qquad [28]$$

Finally, equilibrium profits before taxation and welfare are given by

$$\pi_t^{nc} = (A - 2q_t^{nc})q_t^{nc} - \frac{\gamma}{2}(w_t^{nc})^2, \qquad [29]$$

$$W_t^{nc} = 2Aq_t^{nc} - 2(q_t^{nc})^2 - \gamma(w_t^{nc})^2 - 2d(e_t^{nc})^2, \qquad [30]$$

which completes the analysis of this policy game.

4.3. Comparing policy games

In this subsection we compare the two policy games we have just analyzed. Subtracting [5] from [25] we obtain the difference between the equilibrium investment levels

$$w_t^{nc} - w_t^{c} = \frac{A(2d(d+1)\gamma^2 - (2d^3 - 7d^2 - 3d + 9)\gamma - 6d(d^2 + 3d + 3))}{(2d(\gamma+3)^2 + \gamma(9+2\gamma))((2\gamma+7)d^2 + (4\gamma+9)d + 2\gamma)}.$$

This difference is zero for all combinations (γ, d) that satisfy

$$2d(d+1)\gamma^2 - (2d^3 - 7d^2 - 3d + 9)\gamma - 6d(d^2 + 3d + 3) = 0. \qquad [31]$$

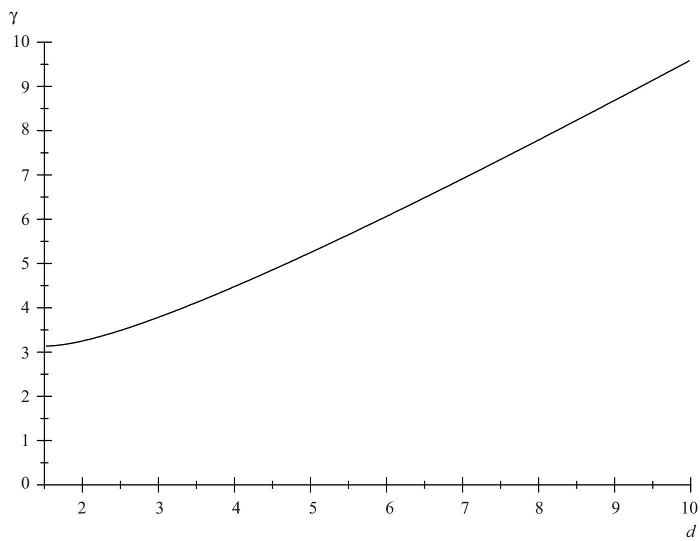
Using this equation the following result can be derived:

Proposition 5. *For all $d \geq 1.5$ there exists an increasing function $\gamma_t^w(d)$ defined by the positive root of equation [31] such that for all $\gamma < \gamma_t^w(d)$ the optimal commitment environmental innovation is larger than the optimal no commitment environmental innovation, i.e. $w_t^{nc} < w_t^c$ but if $\gamma > \gamma_t^w(d)$ the contrary occurs, i.e. $w_t^c < w_t^{nc}$.*

In Fig. 3 the contour defined by [31] that divides the (γ, d) space in two regions is drawn. Above the curve, the optimal commitment innovation is lower than the optimal no commitment innovation. However, the contrary occurs in the region below the curve. Above the curve, the efficiency of the emission-reducing technology is low enough in relative terms, or in other words, the ratio γ/d is large. In this case, the committed regulator, according to [21], will select a low tax because it is expensive to reduce pollution what will induce firms not to invest a lot. Observe that the regulator takes into account the increase in investment costs supported by the two firms. However, when there is no commitment each firm only takes into account its own investment costs, see condition [24], what will lead them to invest more in these circumstances. Matters change when the ratio γ/d is low. With large environmental damages in relative terms, the regulator will select a high tax because the reduction in pollution brings a substantial reduction in environmental damages. This incentive is absent in the no commitment case and firms will invest less than in the commitment case.

FIGURE 3

Comparing investment: $w_t^c < w_t^{nc}$ in the region above the contour $w_t^c = w_t^{nc}$



Next we compare the equilibrium emission taxes using [22] and [26]:

$$t^{nc} - t^c = -\frac{A3(2(3d + 2d^2 + 3)\gamma^2 - d(4d^2 - 30d - 21)\gamma - 6d^2(2d - 3))}{2(2d(\gamma + 3)^2 + \gamma(9 + 2\gamma))((2\gamma + 7)d^2 + (4\gamma + 9)d + 2\gamma)}.$$

This difference is zero for all combinations (γ, d) that satisfy

$$2(3d + 2d^2 + 3)\gamma^2 - d(4d^2 - 30d - 21)\gamma - 6d^2(2d - 3) = 0. \qquad [32]$$

Studying this equation and taking into account that from [17]

$$q_t^{nc} - q_t^c = \frac{1}{3}(t^c - t^{nc}),$$

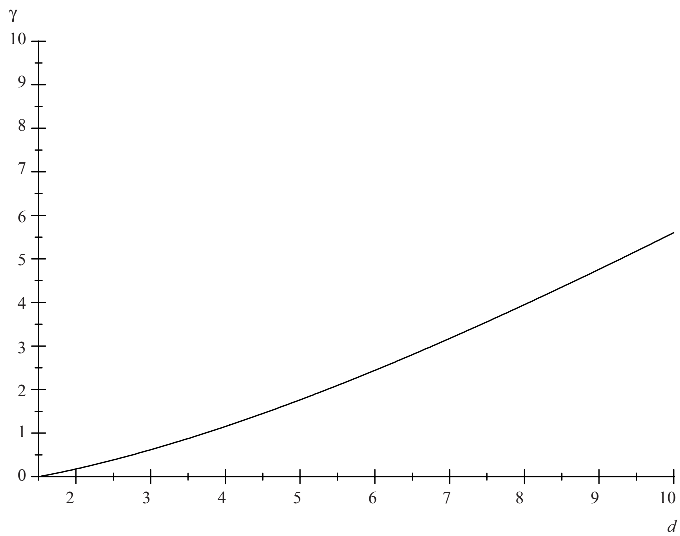
it can be concluded that

Proposition 6. *For all $d \geq 1.5$ there exists an increasing function $\gamma_t(d)$ defined by the positive root of equation [32] such that for all $\gamma < \gamma_t(d)$ the optimal commitment emission tax is lower than the optimal no commitment emission tax and the optimal commitment production is larger than the optimal no commitment production, i.e. $t^c < t^{nc}$ and $q_t^{nc} < q_t^c$ but if $\gamma > \gamma_t(d)$ the contrary occurs, i.e. $t^{nc} < t^c$ and $q_t^c < q_t^{nc}$.*

This result complements the previous one although to find an optimal commitment emission tax lower than the optimal no commitment emission tax it is necessary to have a low ratio γ/d. See Fig. 4. Notice that although a committed regulator selects a lower tax rate when γ/d is high than when this ratio is low, as the firms are investing more when γ/d is high finally the non-committed regulator will set up a tax lower than in the commitment case. This result is a consequence of the influence firms have on taxation when the regulator is not able to commit.

FIGURE 4

Comparing emission tax: $t^{nc} < t^c$ in the region above the contour $t^{nc} = t^c$



Next, we calculate the difference in emissions using [6] and [28]

$$e_t^{nc} - e_t^c = \frac{A(2(d+3)\gamma^2 + (16d^2 + 15d + 18)\gamma + 18d(3d+2))}{2(2d(\gamma+3)^2 + \gamma(9+2\gamma))((2\gamma+7)d^2 + (4\gamma+9)d + 2\gamma)} > 0.$$

Then, the following result can be established:

Proposition 7. *The optimal commitment emissions are lower than the optimal no commitment emissions, i.e.* $e_t^c < e_t^{nc}$.

Observe that regardless of the policy instrument used by the regulator to control pollution, emissions are always lower when the regulator is able to commit. Thus, we can conclude that the strategic behavior of firms to influence the environmental policy always leads to larger emissions.

Finally, we compare the firms' profits and the welfare. The following proposition summarizes the results of the comparison.

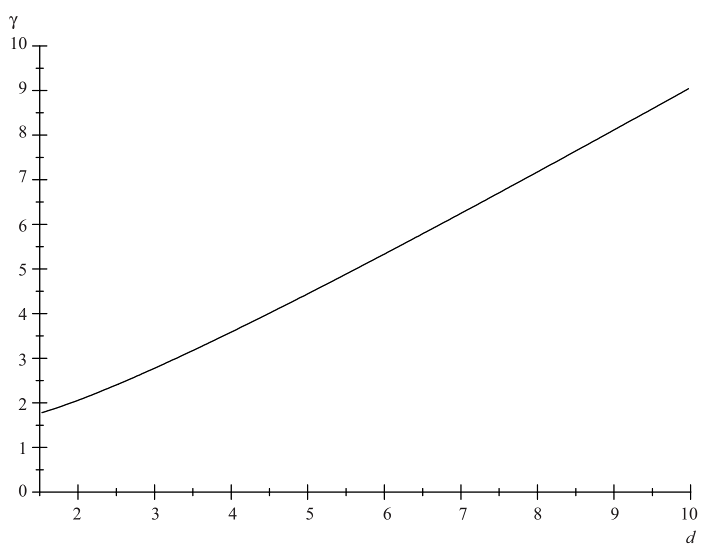
Proposition 8. *For all* $d \geq 1.5$ *there exists an increasing function* $\gamma_t^W(d)$, *whose value for* $d = 1.5$ *is equal to* 1.7677 *such that if* $\gamma < \gamma_t^W(d)$ *the optimal commitment welfare is larger than the optimal no commitment welfare, i.e.* $W_t^{nc} < W_t^c$ *but if* $\gamma > \gamma_t^W(d)$ *the contrary occurs, i.e.* $W_t^c < W_t^{nc}$. *However, the optimal commitment profits are lower than the optimal no commitment profits, i.e.* $\pi_t^c < \pi_t^{nc}$, *regardless of the value of* γ.

Proof. See Annex A.

When an emission tax is used to control pollution, the relationship between welfare for the two policy games depends on the ratio γ/*d* as is shown in Fig. 5. Welfare can be larger when there is no commitment if the efficiency of the emission-reducing technology is relatively low, or in other words, if the ratio γ/*d* is large, in particular for all combinations (γ, *d*) in the region above the contour $W_t^c = W_t^{nc}$ represented in Fig. 5.

FIGURE 5

Comparing welfare: $W_t^c < W_t^{nc}$ **in the region above the contour** $W_t^c = W_t^{nc}$



In this case, the increase in investment costs and environmental damages is more than compensated by the raise in consumer surplus. Firms bear a lower emission tax and produce more if there is a lack of regulatory commitment. This increase in production yields a larger welfare level. Under these circumstances, the strategic behavior of firms is welfare improving and can induce more environmental innovation than under regulatory commitment. On the other hand, profits before taxation are always lower under regulatory commitment. The duopolists can increase their profits by appropriately choosing its innovation effort if the regulator is unable to commit to a specific emission tax rate regardless of the efficiency of the emission-reducing technology. Thus, when the ratio γ/d is large the strategic behavior of firms improves both welfare and profits. However, when the ratio γ/d is low, i.e. environmental damages are high in relative terms, the strategic behavior of firms is detrimental for welfare and firms get more profits influencing the environmental policy but at the cost of reducing social welfare.

5. Taxes *versus* standards

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

A first result that is straightforward to establish by using Propositions 3 and 8 is:

Corollary 1. *For all $d \geq 1.5$ there exists an increasing function $\gamma_t^W(d)$, whose value for $d = 1.5$ is equal to 1.7677 such that if $\gamma < \gamma_t^W(d)$ the optimal commitment welfare is larger than the optimal no commitment welfare regardless of the policy instrument used to control pollution. However, if $\gamma > \gamma_t^W(d)$ 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 is between these two extreme values, i.e. $W_s^{nc} < W_s^c = W_t^c < W_t^{nc}$.*

This result says us that, if the efficiency of the emission-reducing technology is low enough in relative terms, the inability of the regulator to commit to environmental policy is not a problem provided that a tax is used to control emissions. The use of a tax when the regulator is unable to commit yields the maximum welfare. Thus, if the ratio γ/d is large, the optimal environmental policy is to announce a tax rate and to update it once the firms have undertaken their investments. However, if the environmental problem is serious the ratio γ/d is low and then the optimal policy is commitment regardless of the policy instrument since a tax and a standard are equivalent in welfare terms. In this case, the inability of the regulator to commit has a social cost.

In order to find the policy instrument that minimizes this cost, we compare welfare for both instruments when the regulator is not able to commit obtaining the following result.

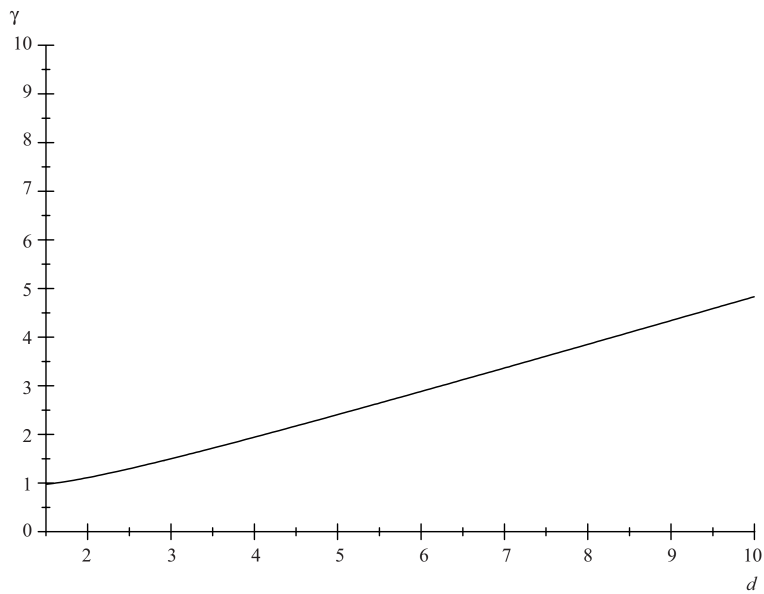
Proposition 9. *For all* $d \geq 1.5$ *there exists an increasing function* $\gamma_{st}^{nc}(d)$, *whose value for* $d = 1.5$ *is equal to* 0.9750 *such that if* $\gamma < \gamma_{st}^{nc}(d)$ *the optimal no commitment welfare when the regulator uses a tax is lower than the optimal no commitment welfare when it applies a standard but profits are larger, i.e.* $W_t^{nc} < W_s^{nc}$ *and* $\pi_s^{nc} < \pi_t^{nc}$. *However, if* $\gamma > \gamma_{st}^{nc}(d)$ *the contrary occurs, i.e.* $W_s^{nc} < W_t^{nc}$ *and* $\pi_t^{nc} < \pi_s^{nc}$.

Proof. See Annex A.

Again the sign of the comparison depends on the ratio γ/d Fig. 6 shows the function $\gamma_{st}^{nc}(d)$ implicitly defined by the condition $W_s^{nc} - W_t^{nc} = 0$. In the region above the curve, the optimal no commitment welfare when the regulator uses a tax is larger than the optimal no commitment welfare when it applies a standard and the contrary occurs for the profits.

FIGURE 6

Comparing policy instruments: $W_s^{nc} < W_t^{nc}$ **in the region above the contour** $W_s^{nc} = W_t^{nc}$



The figure shows that for a large constellation of parameter values the optimal policy when the regulator is not able to commit is to apply a tax on emissions although firms would prefer a standard. Only when environmental damages are severe, the regulator should implement a standard although in this case firms would prefer a tax.

6. Conclusions

This paper has examined the effects that the strategic use of environmental innovation has on environmental policy and its welfare implications in a duopoly. Specifically, it has been shown that the possibility that strategic behavior is welfare improving depends on the policy instrument and the severity of environmental damages. To evaluate the strategic behavior of firms, 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 duopolists choose their environmental innovation effort, simultaneously and independently. The second one is the time consistent policy regime where the regulator sets the ex-post optimal level of the instrument once the firms have chosen their innovation level. We have considered two instruments, a tax and a standard.

We have shown that the strategic behavior of firms is welfare improving and may induce more environmental innovation than under regulatory commitment *only* when a tax is used to control pollution and the convexity of investment costs is relatively more important than that of environmental damages, i.e. when the efficiency of the clean technology is relatively low. If this is not the case, the strategic behavior of firms has a detrimental effect on welfare regardless of the policy instrument used to control emissions. We also find that under regulatory commitment both policy instruments are equivalent in the sense that they yield the same outcome.

These findings have implications for the design of environmental policy to regulate the emissions of a duopoly. If the environmental damages are large enough, commitment is better than no commitment and the choice of the instrument is not a relevant issue because both policy instruments are equivalent but if the regulator is not able to commit a standard should be implemented. Otherwise, a tax yields larger welfare.

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 that, based on the analysis by Petrakis and Xepapadeas (1999; 2003), 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 damages are uncertain and also when the abatement technology is subject to stochastic innovation or this is private information. To be sure, our analysis is that it is static when in some cases environmental damages are caused by the accumulation of emissions. The study of the issue would require a dynamic approach. To conclude these words on the limitations and possible extensions of the paper, we may add that we have adopted a partial equilibrium approach so that more informed policy prescriptions would call for a general equilibrium perspective.

Annex A

Proof of Proposition 3:

Using [8] and [15] we get:

$$W_s^c - W_s^{nc} = \frac{A^2(b_0(d)\gamma^5 + b_1(d)\gamma^4 + b_2(d)\gamma^3 + b_3(d)\gamma^2 + b_4(d)\gamma + b_5(d))}{2\left((\gamma+3)d^2 + (2\gamma+1)d + \gamma\right)^2 (2d(\gamma+3)^2 + \gamma(2\gamma+9))^2}$$

where

$$b_0(d) = 2(3d+1)(d-1)(d+1)^2 = 0 \text{ for } d = 1,$$
$$b_1(d) = (d+1)(8d^4 + 52d^3 + 7d^2 - 38d - 9) = 0 \text{ for } d = 0.8512,$$
$$b_2(d) = 2d(32d^4 + 112d^3 + 63d^2 - 47d - 27) = 0 \text{ for } d = 0.6226,$$
$$b_3(d) = d^2(180d^3 + 356d^2 + 71d - 117) = 0 \text{ for } d = 0.4431,$$
$$b_4(d) = 12(18d^2 + 19d - 9) = 0 \text{ for } d = 0.3546,$$
$$b_5(d) = 36d^4(3d-1) = 0 \text{ for } d = 1/3.$$

It is easy to check that all these coefficients are positive for $d \geq 1.5$ that yields $W_s^{nc} < W_s^c$.

Next, using [7] and [14] we obtain the difference in profits

$$\pi_s^c - \pi_s^{nc} = \frac{A^2(f_0(\gamma)d^5 + f_1(\gamma)d^4 + f_2(\gamma)d^3 + f_3(\gamma)d^2 + f_4(\gamma)d + f_5(\gamma))}{2\left((\gamma+3)d^2 + (2\gamma+1)d + \gamma\right)^2 (2d(\gamma+3)^2 + \gamma(2\gamma+9))^2} \qquad [33]$$

where

$$f_0(\gamma) = -4(4\gamma^2 + 8\gamma - 3)(\gamma+3)^2 = 0 \text{ for } \gamma = 0.3229,$$
$$f_1(\gamma) = 264\gamma - 280\gamma^2 - 372\gamma^3 - 116\gamma^4 - 11\gamma^5 + 72 = 0 \text{ for } \gamma = 0.6516,$$
$$f_2(\gamma) = \gamma(315\gamma - 30\gamma^2 - 83\gamma^3 - 16\gamma^4 + 216) = 0 \text{ for } \gamma = 1.8338,$$
$$f_3(\gamma) = \gamma^2(239\gamma + 68\gamma^2 + 6\gamma^3 + 234) > 0 \text{ for } \gamma > 0,$$
$$f_4(\gamma) = \gamma^3(85\gamma + 16\gamma^2 + 108) > 0 \text{ for } \gamma > 0,$$
$$f_5(\gamma) = \gamma^4(5\gamma + 18) > 0 \text{ for } \gamma > 0.$$

All these coefficients are positive for $\gamma < 0.3229$ what implies that $\pi_s^{nc} < \pi_s^c$ in this case. Moreover, it is easy to check that for all $\gamma > 0$ there is only one change in the signs of the coefficients of polynomial form of d in the numerator of [33] so that according Descartes' rule of signs, the polynomial can have only a positive real root. In fact, as $f_5(\gamma)$ is positive and $f_0(\gamma)$ is negative for $\gamma > 0.3229$ there will exist for each value of γ one and only one positive real root for d. The set of these solutions for $\gamma \in (0.3229,\ 0.6062)$ where 0.6062 is the value of γ that corresponds to $d = 1.5$ is plotted in Fig. 2. In other words, we plot in the (d,γ) space the implicit function $\pi_s^c - \pi_s^{nc} = 0$ given by

$$f_0(\gamma)d^5 + f_1(\gamma)d^4 + f_2(\gamma)d^3 + f_3(\gamma)d^2 + f_4(\gamma)d + f_5(\gamma) = 0.$$

Finally, it is easy to check numerically that the difference in profits is negative in the region above the contour $\pi_s^c - \pi_s^{nc} = 0$.

Proof of Proposition 7

Subtracting [30] from [8] we obtain the following expression for the difference in welfare

$$W_t^c - W_t^{nc} = \frac{A^2(g_0(d)\gamma^3 + g_1(d)\gamma^2 + g_2(d)\gamma + g_3(d))}{2(2d(\gamma+3)^2 + \gamma(9+2\gamma))((2\gamma+7)d^2 + (4\gamma+9)d + 2\gamma)^2} \qquad [34]$$

where

$$\begin{aligned}
g_0(d) &= -4d(d+2)(d+1) < 0,\\
g_1(d) &= -2(6d + 28d^2 + 22d^3 + 8d^4 - 9) = 0 \text{ for } d = 0.4121\\
g_2(d) &= d(39d - 89d^2 - 44d^3 + 20d^4 + 72) = 0 \text{ for } d = 3.2746 \text{ and } d = 0.9895,\\
g_3(d) &= 2d^2(63d + 63d^2 + 32d^3 + 36) > 0.
\end{aligned}$$

Moreover, it is easy to check that for all $d \geq 1.5$ there is only one change in the signs of the coefficients of polynomial form of γ in the numerator of [34] so that according Descartes› rule of signs, the polynomial can have only a positive real root. In fact, as $g_3(d)$ is positive and $g_0(d)$ is negative, there will exist for each value of d one and only one positive real root for γ. The set of these solutions for $d \in (1.5,\ 10)$ is plotted in Fig. 5 with $\gamma = 1.7677$ for $d = 1.5$. In other words, we plot in the (γ, d) space the implicit function $W_t^c - W_t^{nc} = 0$ defined by

$$g_0(d)\gamma^3 + g_1(d)\gamma^2 + g_2(d)\gamma + g_3(d) = 0.$$

Finally, it is easy to check numerically that the difference in welfare is negative in the region above the contour $W_t^c - W_t^{nc} = 0$.

Next, using [7] and [29] we calculate the difference in profits

$$\pi_t^c - \pi_t^{nc} = \frac{A^2(h_0(d)\gamma^5 + h_1(d)\gamma^4 + h_2(d)\gamma^3 + h_3(d)\gamma^2 + h_4(d)\gamma + h_5(d))}{2(2d(\gamma+3)^2 + \gamma(9+2\gamma))^2((2\gamma+7)d^2 + (4\gamma+9)d + 2\gamma)^2}$$

where

$$h_0(d) = -4\left(-4d^2 + 4d^3 + 4d^4 - 5\right)(d+1)^2 = 0 \text{ for } d = 1.0464,$$
$$h_1(d) = -4\left(-72d - 88d^2 - 43d^3 + 116d^4 + 164d^5 + 52d^6 - 27\right) = 0 \text{ for } d = 0.8913,$$
$$h_2(d) = 576d + 1092d^2 + 660d^3 - 2388d^4 - 3356d^5 - 1024d^6 + 81 = 0 \text{ for } d = 0.6976,$$
$$h_3(d) = d\left(1044d + 1215d^2 - 5010d^3 - 7656d^4 - 2296d^5 + 324\right) = 0 \text{ for } d = 0.4955,$$
$$h_4(d) = -12d^2\left(-108d + 255d^2 + 558d^3 + 176d^4 - 27\right) = 0 \text{ for } d = 0.3714,$$
$$h_5(d) = -36d^4(5d+12)(2d-3) = 0 \text{ for } d = 1.5.$$

It is easy to check that all these coefficients are negative for $d \geq 1.5$ that yields $\pi_t^c < \pi_t^{nc}$.

Proof of Proposition 9

Subtracting [15] from [30] we obtain the difference in welfare when there is no commitment

$$W_t^{nc} - W_s^{nc} = \frac{A^2(d+1)(i_0(d)\gamma^3 + i_1(d)\gamma^2 + i_2(d)\gamma + i_3(d))}{((2\gamma+7)d^2 + (4\gamma+9)d + 2\gamma)^2((\gamma+3)d^2 + (2\gamma+1)d + \gamma)^2} \quad [35]$$

where

$$i_0(d) = (2d-1)(2d+1)(d+1)^3 = 0 \text{ for } d = 0.5,$$
$$i_1(d) = 2d(d+2)(d+1)\left(-4d + 7d^2 + 4d^3 - 1\right) = 0 \text{ for } d = 0.6018,$$
$$i_2(d) = -d^2\left(37d + 16d^2 - 26d^3 - 13d^4 + 5d^5 + 5\right) = 0 \text{ for } d = 1.3442 \text{ and } d = 3.6293,$$
$$i_3(d) = -2d^3(8d+1)(d+1)(d^2+1) < 0.$$

There is only one change in the signs of the coefficients of polynomial form of γ in the numerator of [35] for all $d \geq 1.5$ so that according Descartes' rule of signs, the polynomial can have only a positive real root. In fact, as $i_3(d)$ is negative and $i_0(d)$ is positive, there will exist for each value of d one and only one positive real root for γ. The set of these solutions for $d \in (1.5, 10)$ is plotted in Fig. 6 with $\gamma = 0.9750$ for $d = 1.5$. In other words, we plot in the (γ, d) space the implicit function $W_t^{nc} - W_s^{nc} = 0$ defined by

$$i_0(d)\gamma^3 + i_1(d)\gamma^2 + i_2(d)\gamma + i_3(d) = 0.$$

Finally, it is easy to check numerically that the difference in welfare is positive in the region above the contour $W_t^{nc} - W_s^{nc} = 0$.

Next, we derive the difference in profits from [14] and [29]

$$\pi_t^{nc} - \pi_s^{nc} = \frac{A^2(j_0(d)\gamma^3 + j_1(d)\gamma^2 + j_2(d)\gamma + j_3(d))}{2(d^2(\gamma+3)+d(2\gamma+1)+\gamma)^2(d^2(2\gamma+7)+d(4\gamma+9)+2\gamma)^2} \quad [36]$$

where

$j_0(d) = -(6d-1)(2d-1)(d+1)^4 = 0$ for $d = 1/6$ and $d = 1/2$,
$j_1(d) = -2d(-10d - 23d^2 + 13d^3 + 50d^4 + 50d^5 + 1) = 0$ for $d = 0.60120$ and $d = 8.4603\times10^{-2}$,
$j_2(d) = d^2(d+1)(31d + 32d^2 - 34d^3 + 9d^4 + 3d^5 - 1) = 0$ for $d = 3.1281\times10^{-2}$,
$j_3(d) = 2d^4(16d + 5d^2 + 7)(d^2+1) > 0$.

Again the coefficients of polynomial form of γ in the numerator of [36] only change their sign once for all $d \geq 1.5$ so that according Descartes' rule of signs, the polynomial can have only a positive real root. In fact, as $j_3(d)$ is positive and $j_0(d)$ is negative, there will exist for each value of d one and only one positive real root for γ. When the set of these solutions for $d \in (1.5, 10)$ is plotted in a graph, the resulting curve coincides with the one represented in Fig. 6 with $\gamma = 0.9750$ for $d = 1.5$. In other words, the implicit function $\pi_t^{nc} - \pi_s^{nc} = 0$ coincides with the implicit function $W_t^{nc} - W_s^{nc} = 0$ for γ, $d > 0$. Finally, it is easy to check numerically that the difference in profits is negative in the region above the contour $\pi_t^{nc} - \pi_s^{nc} = 0$.

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