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Cooperation in Green R&D and Environmental Policies: Taxes versus Standards

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Abstract

This article compares taxes and standards as environmental policies in a duopoly model where production generates pollution. To lower their emissions, firms invest in upstream green R&D (in the presence of technological spillovers) either cooperatively or non-cooperatively, and then compete in quantities. The outcomes of the two policies are identical when firms do not cooperate in R&D; R&D cooperation under taxes always improves social welfare while R&D cooperation under standards pushes firms to reduce production, which is harmful for consumers but better for the environment. When the choice of the policy instrument is endogenized, R&D cooperation under an environmental standard never emerges as an equilibrium strategy of the game.

Key words: R&D Cooperation, Spillovers, taxes, standards, Cournot competition.

Code JEL: L13, 032, P48, Q55.

1 Introduction

Governments in developed countries are under increasing social pressure to improve environmental protection, which typically involves measures to reduce industrial emissions. As described by Requate (Requate, 2005a), pollution can be limited by command and control or market-based instruments. Command and control instruments, the most common, typically involve environmental standards (technological, emission or relative) and caps on firms' emissions. In contrast, market-based instruments in the form of emission taxes, subsidies for emissions abatement or tradeable permits, "provide incentives to reduce emissions through prices, and firms are free to decide how much they want to emit or to abate" (Requate (2005a), p.178). This article focuses on two widely used policy instruments: i) an emission tax, and ii) an emission standard.

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In the presence of these binding environmental policies, firms may choose to invest in green R&D and reduce emissions through end-of-pipe technologies, either to reduce the costs incurred through the emission tax or to keep emissions below a given cap in the case of an emission standard. An important question addressed in this article is how the (non-)cooperative nature of environmental R&D may condition the effectiveness of environmental policies, depending on the choice of instruments.

An established property of R&D in the literature is that it generates technological externalities (*i.e.* spillovers). These spillovers tend to discourage firms from investing in R&D because some of the knowledge generated is appropriated by their rivals (Arrow, 1962). Nevertheless, cooperative R&D is now recognized as an efficient incentive for innovation, as illustrated by the regulations adopted by the EU (Article 85 of the EEC treaty) and the United States (National Cooperative Research Act) to authorize agreements between competing firms. The seminal contribution on R&D cooperation in the presence of spillovers is d'Aspremont and Jacquemin (1988) (AJ from now on), and this article has formed the basis of a vast and expanding literature.[1] In the AJ model, two firms first choose a level of cost-reducing R&D investment, cooperatively or not, before competing in quantities. The main result is that above a certain spillover threshold, cooperative R&D investments yield a higher total surplus than non-cooperative R&D. Furthermore, R&D investments increase with the level of spillovers when firms cooperate but decrease when they do not. The crucial insight underlying this result is that cooperative firms internalize the effects of spillovers on aggregate profits while R&D rivals only consider the competitive effect of R&D flows on their respective costs. As shown by Kamien et al. (1992) (KMZ), investments in cooperative R&D are driven by two types of externalities: the 'competitive-advantage' externality, which involves free-riding and is unambiguously negative, and the 'combined-profits' externality, which can be positive or negative and accounts for the impact of each firm's R&D spending on the profits of all firms. This externality is internalized when firms cooperate in R&D and has a net positive effect when spillovers are sufficiently large.

In this paper, we investigate whether this positive effect of R&D cooperation persists when different environmental policies are implemented. In other words, does R&D cooperation still produce more innovation when an environmental policy such as a tax or an emission standard is enforced, or do these measures undermine the social welfare benefits of horizontal agreements? An additional question addressed in this article is whether these environmental policy tools really protect the environment when firms cooperate in R&D? This question is made all the more relevant by the recent trend toward coalitions in the field of green R&D. A typical example is the "Research Association of Refinery Integration for Group-Operation (RING)" in Japan [2]: this research program involving 20 firms from the oil and chemical industries developed technologies for reducing the environmental impact of production processes. Another example of an environmental R&D cooperation initiative is the Electric Power Research Institute (EPRI) in the US, whose mandate is to coordinate multi-firm collaborative R&D in the

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[1] See Marinucci (2012) for a review of the literature on R&D cooperation.

[2] For details, see Ouchida and Goto (2016a) and the RING's website (http://www.ring.or.jp/).

energy sector. Recent studies have provided partial answers, when the environmental policy instrument is a tax for instance (see the discussion below), but the combination of R&D cooperation and environmental standards has never been studied. Therefore, comparing the performance of taxes and standards allows us to shed new light on the best choice of environmental policy instrument when firms cooperate in R&D and when they do not.

Beyond the cooperative aspect of green R&D investments, it may seem questionable at first why firms invest in costly emissions reduction projects at all. There is no obvious answer to this. In a very recent paper, Buccella et al. (2021) show that when pollution is limited and R&D efficiency low, firms may choose not to reduce their emissions and instead bear the costs of environmental taxes on their entire production. In the same vein, Yong and McDonald (2018) try to identify the level of subsidy required to encourage asymmetric firms to invest in clean technologies. Assuming instead that environmental awareness is sufficient for firms to invest in green R&D, a well discussed issue in the literature is the enforcement of environmental policies and regulators' commitment to enforcing them (Requate, 2005b). Uncertainty about the importance of environmental issues for future and successive governments may of course limit their commitment to enforcing present policies (Ulph and Ulph, 2013). Most often however, it is assumed in the literature that regulators are unable to credibly commit to environmental policy instruments (*i.e.* the policies are time-consistent), allowing firms to strategically use innovation to lower regulatory constraints and increase profits (Gersbach and Glazer, 1999). This is known as the 'ratchet' effect, as seen in US automobile emissions regulations in the 1970s: manufacturers' slowness in developing emissions reduction technologies forced the Environmental Protection Agency to delay the implementation of its measures. Firms' strategies in the face of environmental policies have been widely studied by comparing alternative political games (commitment vs. non-commitment) in the context of different instruments (taxes, standards or permits). For instance, Petrakis and Xepapadeas (1998) or Petrakis et al. (2001) find that firms that strategically decide to take the lead over the regulator reduce their taxes through increased abatement efforts, which improve welfare. The result is conditional on the number of firms being limited and is not confirmed by Poyago-Theotoky and Teerasuwannajak's 2002 analysis of a duopoly with product differentiation. In contrast, when the regulator uses environmental standards rather than a tax to control a monopolist's emissions, the firm's strategic advantage associated with the regulator's non-engagement is no longer welfare improving (Puller, 2006). The performance of environmental policy instruments therefore depends on whether regulators are committed or not (D'Amato and Dijkstra, 2018; Martín-Herrán and Rubio, 2016; Moner-Colonques and Rubio, 2016; Montero, 2011; Wirl, 2014). However, these comparisons were conducted in the absence of spillovers and do not consider R&D cooperation.

Elsewhere, Lambertini et al. (2017) build on the innovation literature and focus on firms' incentives to undertake green R&D in a competitive market (see also McDonald and Poyago-Theotoky (2017)). They show that there is an inverted U-shaped relationship between green innovation and competition, explained by the presence of spillovers. In line with AJ (1988) and KMZ (1992), other theoretical studies have considered environmental R&D joint ventures (ERJVs); however, the only environmental policy considered in these models is an emission tax. Basically, Chiou and Hu's 2001 model allows several forms of cooperation to be compared, but without endogenizing the tax. They emphasize the superiority of RJV cartelization (abatement technology spillovers maximize firms' joint profits). The endogenization of cooperative choices is addressed by Ouchida and Goto (2016a) in the context of an emission tax set endogenously by a non-committed regulator. Their results confirm those of Poyago-Theotoky (2007) that in ERJVs, cartelization is welfare-improving when environmental damage is low, but also when emissions are highly damaging provided R&D is sufficiently efficient.

Our contribution complements existing results and addresses the joint issues of the most appropriate environmental policy instrument and the effectiveness of R&D cooperation in the provision of end-of-pipe technologies. Emissions regulations are assumed to be credible on the basis that regulators are compelled to enforce their policies by international environmental agreements. In line with Ouchida and Goto (2016b), we compare social welfare under an emission tax when firms cooperate or not in R&D. Since R&D cooperation has so far never been studied in the case of command and control instruments, we repeat the analysis when the environmental policy tool is an emission standard. Further, we endogenize the choice of policy instruments and of the firms' R&D strategies.

The benchmark model presented here is based on regulator choosing policy a tax or a standard as policy instrument in the first stage. Once the regulator has optimally chosen the level of taxation on emissions, firms invest cooperatively or non-cooperatively in green R&D before competing in quantities. If the regulator instead chooses to set an optimal emission standard, production levels depend on the equilibrium levels of (cooperative or non-cooperative) R&D. This framework allows us to identify the optimal environmental policy instrument depending on whether firms cooperate or not in green R&D. When firms conduct R&D independently, we reproduce the results obtained elsewhere that the tax and the standard both lead to the same outcomes at equilibrium, for any level of spillovers. Now, if we compare the performance of R&D cooperation under the two instruments, the outcomes are socially more favorable under the emission tax: innovation and consumer surplus are both boosted. Interestingly however, under an emission standard, since R&D collusion reduces production, the overall level of pollution is lower. Therefore R&D cooperation entails a trade-off between social and environmental outcomes. Finally, we find that R&D cooperation is welfare improving – over non-cooperation – if the chosen policy instrument is a tax but that the opposite holds in the case of an emission standard, where cooperation in R&D leads firms to reduce their production through an anti-competitive effect. More precisely, the R&D cartel acts as a production cartel aiming to reduce output and increase prices, to the detriment of consumer welfare. This result supports the view of critics of R&D cooperation that less competition necessarily leads to less R&D (Scott, 2008). Nevertheless, if we introduce an additional stage to the benchmark game where the regulator's and the firms' choices are endogenized, we show that cartel behavior never ensues at the equilibrium, our results suggesting rather that the environmental tax is the most socially preferable instrument.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 analyses the emission tax policy (ETP) and the firms' R&D behavior (non-cooperative vs non-cooperative). Section 4 considers an emission standard policy (ESP) and in Section 5 the results obtained for the ESP and ETP are compared by considering exogenous environmental policy choices and then endogenizing them. Section 6 concludes.

2 The model

Let us consider a duopoly where two identical competing firms, i, j, produce a homogeneous good with the same polluting production technology. Demand is described by a simple linear function:

$$p(Q) = a - Q$$

where Q is the total level of production, $Q \leq a$. Firm i's output is denoted q_i, such that $Q = q_i + q_j$. The marginal cost of production is constant and equal to c with $a > c > 0$.

Following Ulph (1996) or Poyago-Theotoky (2007) among others, the production process, in both firms, is environmentally degrading such that each unit of output generates exactly one unit of pollution. However, the firms can reduce their emissions by investing in green R&D, ζ_i. For instance, the firms may develop end-of-pipe technologies, current examples of which include flue gas desulfurization and activated carbon adsorption. Moreover, we assume the presence of green R&D spillovers in that the firms benefit from their rival's pollution mitigation efforts in a proportion $\beta \in (0, 1]$, at no cost. The parameter β is exogenously given and is not affected by the firms' R&D behavior. Therefore, by investing in green R&D, firm i can reduce its gross polluting emissions by between $\zeta_i + \beta\zeta_j$ and $\zeta_i + \zeta_j$. Accordingly, firm i's net emissions after R&D investment can be expressed as:

$$e_i = e(q_i, \zeta_i) = q_i - \zeta_i - \beta\zeta_j \tag{1}$$

Following d'Aspremont and Jacquemin (1988), we assume that the R&D cost function is quadratic, leading to diminishing returns on R&D investments.[3] Firm i's cost function is additively separable and given by $C(q_i; \zeta_i) = cq_i + \gamma{\zeta_i}^2/2$. In this context, γ is usually interpreted as a measure of R&D efficiency, with firms having to spend $\gamma\zeta_i^2/2$ to reduce their emissions by ζ_i.

In what follows, we investigate the effectiveness of two environmental policies in two scenarios:

- In the first scenario ($h = nc$), the firms do not cooperate in R&D and compete during the R&D stage;

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[3] In this approach, based on d'Aspremont and Jacquemin (1988), spillovers occur in abatement technologies and firms can free ride off the abatement efforts of their competitors (*output spillover*). In Kamien et al.'s 1992 alternative approach, spillovers occur on the input side of the R&D process (*input spillover*). McDonald and Poyago-Theotoky (2017) have compared these two types of green R&D spillovers but only in the context of an ETP. They suggest the AJ model is more suitable.

- In the second scenario ($h = c$), the firms coordinate their environmental R&D investments to maximize the sum of their profits.[4]

Given the net emissions of each firm, the total level of emissions is $E^h = \sum_{i=1}^{2} e^h(q_i^h, \zeta_i^h)$, and the level of environmental damage is $D(E^h)$. The damage function is assumed to be quadratic, with $d > 0$ being the slope of the marginal environmental damage curve, *i.e.* the severity of the damage, $D(E^h) = d(E^h)^2/2$. Alternatively, following Antelo and Loureiro (2009) we could interpret d as " *the regulator's valuation of the environment, or the regulator's preferences with respect to the redistribution of environmental damage*". For ease of presentation, we will assume that $d = 1$ in the following (see Petrakis et al. (2001), Poyago-Theotoky (2007), Lambertini et al. (2017)).[5] Finally, to protect the environment, the government may implement an environmental policy, to which they commit *ex ante*. Two instruments are separately considered in the following: a per unit tax on emissions and an emission standard.

When the regulator chooses to implement an emission tax policy (ETP), the game has three stages: in stage 1, the regulator precommits to the environmental policy and thus sets the level of the emission tax so as to maximize social welfare. Firms cannot strategically modify the optimal tax rate when choosing their R&D efforts; in stage 2, firms invest, non-cooperatively or cooperatively, in green R&D; and in stage 3, firms compete in quantities. When the regulator precommits to an emission standard policy (ESP), the game has only two stages: outputs are determined once the regulator has set the emission standard (stage 1) and firms have chosen their abatement efforts, either cooperatively or non-cooperatively (stage 2). In addition, we add an extra stage 0 to the benchmark case, during which the regulator chooses which type of policy instrument, ETP or ESP, to implement. To obtain the subgame perfect Nash equilibrium (SPNE), we solve the game by backward induction for the two forms of environmental policy (ETP and ESP) and of R&D behavior (non-cooperative and cooperative).

3 Green R&D Under an Emission Tax Policy (ETP)

In this section, the regulator implements a tax, τ, on polluting emissions. Solving backward, in the last stage of this game and using equation (1), firm i chooses the level of output q_i that maximizes its profits, taking its' rival's R&D efforts as given: [6]

$$max_{q_i}[(a - Q)q_i - cq_i - \gamma\zeta_i^2/2 - \tau(q_i - \zeta_i - \beta\zeta_j)] \tag{2}$$

By symmetry and the first order condition (FOC) w.r.t. q_i, the firms' optimal output under an ETP is:

$$q(\tau) = \frac{A - \tau}{3} \tag{3}$$

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[4] This approach, referred to as an R&D cartel, is well-documented in the literature on R&D cooperation. Our analysis also covers the case in which $\beta = 1$, that is when firms form a cartelized Research Joint Venture (RJV) whereby they coordinate their R&D efforts and share all the resulting knowledge.

[5] This simplifying assumption does not alter our results. Details of the calculations, with no restriction on the value of d, are available on request.

[6] This final stage is the same under an ETP whether the firms cooperate in R&D or not.

where $A = a - c > 0$ and A is a measure of market size. As in Petrakis et al. (2001), Poyago-Theotoky (2007), Ouchida and Goto (2016b) and Lambertini et al. (2017), this optimal level of output only depends indirectly on the level of R&D, through the ETP. Firm i's profits are:

$$\pi_i(\tau, \zeta_i) = q(\tau)^2 + \tau(\zeta_i + \beta\zeta_j) - \gamma\zeta_i^2/2 \tag{4}$$

Social welfare (SW) is defined as the sum of consumer surplus and firm profits net of taxation revenue minus the environmental damage:

$$SW = \underbrace{\frac{Q^2}{2}}_{\text{Consumers surplus=CS}} + \underbrace{(\pi_i + \pi_j)}_{\text{Producers surplus=PS}} + 2\underbrace{\tau(q(\tau) - (1+\beta)\zeta(\tau))}_{\text{Tax revenue}} - \underbrace{D(E)}_{\text{Environmental damage}} \tag{5}$$

Let us now turn to the second stage of the game and calculate the equilibrium outcomes in the non-cooperative and cooperative green R&D subgames (the final production stage being non-cooperative in both cases).

3.1 Non-cooperative R&D

If, following Lambertini et al. (2017), the firms compete during the green R&D stage, they each simultaneously choose their levels of R&D spending, taking the R&D spillovers from their competitor as given. Symmetrically and for a given ETP, maximizing equation (4) with respect to ζ_i yields the firms' optimal level of green R&D:

$$\zeta^{nc}(\tau) = \frac{\tau}{\gamma} \tag{6}$$

This equilibrium level of R&D investment increases with the tax rate, leading to a reduction in polluting emissions. The level of emissions in the absence of the ETP corresponds to the optimal output with zero environmental tax burden ($= \frac{A}{3}$). The emissions generated by each firm can be deduced by substituting equations (3) and (6) into equation (1):

$$e^{nc}(\tau) = \frac{A}{3} - \frac{3(1+\beta)+\gamma}{3\gamma}\tau \tag{7}$$

As expected, emissions decrease as the environmental constraint increases. The emissions also decrease as the spillover level increases and as the R&D efficiency increases (as γ decreases). The optimal level of green R&D can also be expressed as a function of the level of emissions using equations (6) and (7):

$$\zeta^{nc}(e^{nc}) = \frac{A - 3e^{nc}}{3(1+\beta)+\gamma} \tag{8}$$

Obviously, the higher the tax, the lower the level of emissions, the more R&D is required. Also, inserting equation (6) into equation (4) yields the profits as a function of the tax rate only:

$$\pi^{nc}(\tau) = q(\tau)^2 + (1+2\beta)\frac{\tau^2}{2\gamma} \tag{9}$$

The effect of the ETP on firms' profits is non-monotonous. Nevertheless, we can see that the higher the spillovers or/and the lower the cost of R&D, the larger will be the positive impact of the tax on the profits, compared to the negative one. Now the firms' optimal behavior has been determined, let us turn to the first stage of the game. Substituting equations (1), (3) and (9) into equation (5) yields the regulator's net surplus as a function of the environmental tax rate. Notice that because taxation revenues only involve a transfer from the firms to the government, they disappear from the re-arranged welfare function:

$$SW^{nc}(\tau) = 2\left(A\left(\frac{A-\tau}{3}\right) - \left(\frac{A-\tau}{3}\right)^2 - \frac{\tau^2}{2\gamma} - \left(\frac{A-\tau}{3} - (1+\beta)\frac{\tau}{\gamma}\right)^2\right) \tag{10}$$

The optimal environmental tax is obtained from the FOC with respect to τ:[7]

$$\tau^{*,nc} = \gamma\frac{6(1+\beta)+\gamma}{X}A, \tag{11}$$

where $X = 2(3(1+\beta)+\gamma)^2 + \gamma(9+2\gamma) > 0$.

Finally, the levels of R&D effort, output and social welfare at the SPNE can be calculated using equation (11):

$$\zeta^{*,nc} = \frac{6(1+\beta)+\gamma}{X}A \tag{12}$$

$$q^{*,nc} = \frac{2(1+\beta)(3(1+\beta)+\gamma)+\gamma(3+\gamma)}{X}A \tag{13}$$

$$SW^{*,nc} = \frac{2\left(4(1+\beta)^2+\gamma\right)+4\gamma(1+\beta)+\gamma^2}{X}A^2 \tag{14}$$

The equilibrium outputs are similar to those of Ouchida and Goto (2016a) (for $\theta = 1$), Petrakis et al. (2001) and Moner-Colonques and Rubio (2016) (for $\beta = 0$ in the case of pre-commitment) and Lambertini et al. (2017).

3.2 Cooperative R&D

Let us now consider the cooperative scenario, $h = c$, in which firms, instead of maximizing their individual profits during the R&D stage, choose to coordinate their efforts in green R&D and instead maximize the sum of their profits: $\Pi = \pi_i + \pi_j$. Taking the ETP as given, the FOCs require that $\frac{\partial\Pi}{\partial\zeta_i} = \frac{\partial\Pi}{\partial\zeta_j} = 0$ and the symmetric subgame equilibrium value for the individual green R&D efforts is:

$$\zeta^c(\tau) = \frac{(1+\beta)\tau}{\gamma} \tag{15}$$

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[7] The second-order condition for welfare maximization always holds, *i.e.* $\frac{\partial^2 SW}{\partial\tau^2} < 0$.

Notice that under R&D cooperation (and for a given environmental tax rate), the incentive to invest in green R&D increases with the degree of spillover, which is not the case when the firms do not cooperate. Indeed, R&D cooperation ensures that free-riding is internalized. The firms' emissions are then obtained by substituting equations (3) and (15) into (1):

$$e^c(\tau) = \frac{A}{3} - \frac{3(1+\beta)^2+\gamma}{3\gamma}\tau \tag{16}$$

Emissions under R&D cooperation are lower than under R&D competition by an amount $\frac{\beta(1+\beta)}{\gamma}\tau$. For a given tax rate therefore, the higher the spillover rate is, the less firms pollute when they cooperate in R&D and the larger the emissions gap is between the two scenarios. Moreover, as in the non-cooperative scenario, the optimal amount of R&D can be expressed as a function of the level of emissions using equations (15) and (16):

$$\zeta^c(e^c) = (1+\beta)\frac{A-3e^c}{3(1+\beta)^2+\gamma} \tag{17}$$

For a given tax rate, τ, (or for a given level of emissions, $e^{nc} = e^c = e$), it is easy to show that the level of R&D is higher in the cooperative scenario than in the non-cooperative one, for all values of γ and β:

$$\zeta^c(e) - \zeta^{nc}(e) = \frac{\beta\gamma}{(3(1+\beta)^2+\gamma)(3(1+\beta)+\gamma)} > 0 \tag{18}$$

The profit of each firm at the end of the second stage can be expressed in terms of the environmental tax using equation (15):

$$\pi^c(\tau) = q(\tau)^2 + (1+\beta)^2\frac{\tau^2}{2\gamma} \tag{19}$$

Similarly, for a given tax rate and provided $\beta > 0$, it is straightforward to show that the profit in the cooperative scenario is higher than in the non-cooperative scenario (see equation (9)).

$$\pi^c(\tau) - \pi^{nc}(\tau) = \frac{\beta^2\tau^2}{2\gamma} > 0 \tag{20}$$

Comparing the subgame equilibrium profits reveals that the difference increases with τ and β. When the firms internalize positive R&D externalities, they are more likely to invest in R&D, which is profitable for both because it further reduces the burden of the environmental tax. In agreement with Ouchida and Goto (2016a) on p. 326, we find that unless $\beta = 0$, both firms always have a private incentive to cooperate in R&D in stage 2 once the government has set the emission tax in stage 1.

Finally turning to the first stage of the game, the regulator sets the welfare-optimal environmental tax rate based on how firms will respond to it. Using equations (3), (5) and (15), the social welfare at a given tax rate can be written as follows:

$$SW^c(\tau) = 2\left(A\left(\frac{A-\tau}{3}\right) - \left(\frac{A-\tau}{3}\right)^2 - (1+\beta)^2\frac{(\tau)^2}{2\gamma} - \left(\frac{A-\tau}{3} - (1+\beta)^2\frac{\tau}{\gamma}\right)^2\right) \tag{21}$$

The optimal tax rate when the firms cooperate in R&D is obtained from the FOC w.r.t. τ:

$$\tau^{*,c} = \gamma \frac{6(1+\beta)^2 + \gamma}{Y} A, \tag{22}$$

where $Y = 2(3(1+\beta)^2 + \gamma)^2 + \gamma(9(1+\beta)^2 + 2\gamma) > 0$. Inserting equation (22) into equations (15), (3) and (21) yields the following expressions for the R&D effort, output and social welfare at the SPNE:

$$\zeta^{*,c} = (1+\beta) \frac{(6(1+\beta)^2 + \gamma)}{Y} A \tag{23}$$

$$q^{*,c} = \frac{(3(1+\beta)^2 + \gamma)(2(1+\beta)^2 + \gamma)}{Y} A \tag{24}$$

$$SW^{*,c} = \frac{(2(1+\beta)^2 + \gamma)\left(4(1+\beta)^2 + \gamma\right)}{Y} A^2 \tag{25}$$

3.3 Cooperation versus non-cooperation in R&D under an ETP

A natural question to address is which of the two approaches (cooperation or competition) generates more R&D and how the optimal ETPs compare. We can first state the following lemma:

Lemma 1. *Under an optimal ETP,* $\forall \gamma > 0$ *and* $\beta \in (0, 1]$,

1. $\tau^{*,c} < \tau^{*,nc}$,
2. $e^{*,c} < e^{*,nc}$,
3. $\zeta^{*,c} > \zeta^{*,nc}$,
4. $CS^{*,c} = 2\left(q^{*,c}\right)^2 > 2\left(q^{*,nc}\right)^2 = CS^{*,nc}$,
5. $SW^{*,c} > SW^{*,nc}$.

Proof. See Appendix A. □

The optimal tax rate is set by the regulator to match the induced marginal increase in social welfare with the marginal decrease. Indeed, the emission tax lowers consumer surplus (see equation (3)), which decreases social welfare by an equal amount no matter the scenario. However, the cost of R&D increases with the tax all the more when firms cooperate and spillovers are high:

$$\frac{\partial \zeta^c(\tau)}{\partial \tau} = \frac{1+\beta}{\gamma} > \frac{1}{\gamma} = \frac{\partial \zeta^{nc}(\tau)}{\partial \tau} \tag{26}$$

Also, emissions reduce with taxation all the more that firms cooperate. From equation (1), we can see that:

$$\frac{\partial e(\tau)}{\partial \tau} = \frac{\partial q(\tau)}{\partial \tau} - (1+\beta) \frac{\partial \zeta(\tau)}{\partial \tau} \tag{27}$$

and we deduce that:

$$\frac{\partial e^c(\tau)}{\partial \tau} = -\frac{1}{3} - \frac{(1+\beta)^2}{\gamma} < -\frac{1}{3} - \frac{(1+\beta)}{\gamma} = \frac{\partial e^{nc}(\tau)}{\partial \tau} \tag{28}$$

Since emissions tend to decrease more under R&D cooperation in absolute value, the reduction in environmental damage is also greater. Finally, taxation is more efficient when firms cooperate and the regulator implements a lower optimal tax rate, despite the higher cost of R&D.

As in Moner-Colonques and Rubio (2016) (p. 981), green R&D and the environmental tax are strategic complements from the firms' perspective, but are strategic substitutes from the regulator's point of view: cooperation in R&D allows for a less stringent optimal ETP alongside greater green R&D efforts. However, because the optimal emission tax is lower under R&D cooperation, the equilibrium outputs are higher (see equation (3)), which benefits consumers but is detrimental to the environment. Nevertheless, in the presence of spillovers, the effect of green R&D when firms cooperate outweighs the increase in emissions associated with the higher production. This is because the internalization of R&D spillovers gives producers a particularly strong incentive to reduce their environmental tax burden by investing in green technologies. Overall, emissions are lower when firms cooperate and consumer surplus is higher, which compensates for the increased cost of R&D. Under an optimal ETP in other words, R&D cooperation outperforms non-cooperation in terms of social welfare. This result is consistent with Ouchida and Goto (2016a) in a setup without product differentiation.

Let us now investigate whether these conclusions hold when the regulator uses an emission standard rather than an emission tax.

4 Green R&D Under an Emission Standard Policy (ESP)

Under the alternative instrument, the ESP, the third stage of the game vanishes as per-firm outputs are predetermined by the cap set on emissions and the R&D efforts (with variables under the ESP denoted by a superscript tilde) are: $\tilde{q}_i = \bar{e} + \tilde{\zeta}_i + \beta\tilde{\zeta}_j$, where $\bar{e}$ is the emission standard imposed on the two firms. As a result, the firms do not compete in quantities and the total level of emissions is simply: $\tilde{E} = 2\bar{e}$. Firms nevertheless use green R&D to limit their emissions during production and comply with their environmental objectives. Again, let us consider in turn the two scenarios in which the firms cooperate or not in R&D.

4.1 Non-cooperative R&D

In the last stage of this game, the two firms choose the levels of green R&D investment that maximize their respective profits, taking the emission standard $\bar{e}$ as given. The optimization program for firm i is:

$$\begin{cases} \max_{\tilde{\zeta}_i} & \tilde{\pi}_i^{nc} = & (a-Q)\tilde{q}_i - c\tilde{q}_i - \frac{\gamma\tilde{\zeta}_i^2}{2} \\ \text{s.t.} & \tilde{q}_i = & \bar{e} + \tilde{\zeta}_i + \beta\tilde{\zeta}_j \end{cases} \tag{29}$$

Maximization under constraint yields firm i's reaction function for its R&D effort:

$$\tilde{\zeta}_i^{nc}(\bar{e};\tilde{\zeta}_j^{nc}) = \frac{A - 3\bar{e} - (1+2\beta)\tilde{\zeta}_j^{nc}}{(2+\beta+\gamma)} \tag{30}$$

Recall that under an ESP, green R&D expenditures do not reduce the environmental policy's cost to the firms but rather enable them to produce beyond the cap (the R&D ensures that the extra units are pollution-free). Profit maximization implies that this marginal benefit – in the level of production – should equal the marginal cost of R&D in a competitive environment. Equation (30) shows that the best-response functions are decreasing in ζ_j, meaning that the R&D investments chosen by the firms are strategic substitutes (as under Cournot competition). The profit maximizing response to a decrease in its rival's R&D expenditure is an increase in its own R&D effort in an amount that depends on the degree of spillover. Partial appropriation of their rival's R&D allows for more production and means the firms need not invest as much in their own R&D programs. This is a typical free-riding effect and the more spillover there is, the less incentive the firms have to engage in R&D. Note also that choosing optimal R&D efforts under an ESP boils down to choosing optimal production levels.[8] Then, by symmetry, the optimal R&D output can be expressed using equation (30) as a function of the emission standard only:

$$\tilde{\zeta}_i^{nc} = \tilde{\zeta}_j^{nc} = \tilde{\zeta}^{nc}(\bar{e}) = \frac{A - 3\bar{e}}{3(1+\beta)+\gamma} \tag{31}$$

As expected, the equilibrium level of green R&D increases with the stringency of the environmental policy: firms tend to increase their R&D efforts when governments tighten their emission standards. Furthermore, the similarity of equation (31) to equation (8) means that for a given environmental objective, e, the optimal R&D effort is the same regardless of the instrument used – ETP or ESP, when firms do not cooperate in R&D. Taking the firms' R&D choices as given (see equation (31)), we can now deduce their equilibrium outputs:

$$\tilde{q}^{nc}(\bar{e}) = \frac{(1+\beta)A + \gamma\bar{e}}{3(1+\beta)+\gamma} \tag{32}$$

At equilibrium, as expected, the stricter the standard is, the less the firms produce, particularly when spillovers are high. As mentioned above, their rival's R&D efforts

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[8] The profit function used in the maximization program (see equation (29)), can be rewritten as a function of the amount produced by firm i: $\tilde{\pi}_i^{nc}(\tilde{q}_i) = \tilde{\pi}_i^{nc}(\tilde{q}_i(\tilde{\zeta}_i)) = \tilde{\pi}_i^{nc}(\tilde{\zeta}_i)$. Using the chain rule, the derivative with regards to the R&D effort can be written:

$$\frac{\partial\tilde{\pi}_i^{nc}}{\partial\tilde{\zeta}_i} = \underbrace{\frac{\partial\tilde{q}_i}{\partial\tilde{\zeta}_i}}_{=1} \cdot \frac{\partial\tilde{\pi}_i^{nc}}{\partial\tilde{q}_i}$$

.

allow both firms to produce more. Equation (31), assuming it is positive,[9] indicates that spillovers boost production, despite their disincentive effect on green R&D investment. This means that the positive direct effect of spillovers on the level of production outweighs their negative indirect effect (free riding) on green R&D.

The profit of each firm at the end of the second stage can be expressed using equations (31) and (32) as a function of the emission standard:

$$\tilde{\pi}^{nc}(\bar{e}) = (A - 2\tilde{q}^{nc}(\bar{e}))\tilde{q}^{nc}(\bar{e}) - \frac{\gamma}{2}\tilde{\zeta}_i^{nc}(\bar{e})^2 \tag{33}$$

Let us turn now to the first stage of the game, when the government chooses the welfare-optimal emission standard. Social welfare is defined as before by equation (5), but with the tax revenues set to zero. The total surplus can be expressed as a function of the emission standard using equations (31) and (32):

$$\tilde{SW}^{nc}(\bar{e}) = 2\left(A\left(\frac{(1+\beta)A+\gamma\bar{e}}{3(1+\beta)+\gamma}\right) - \left(\frac{(1+\beta)A+\gamma\bar{e}}{3(1+\beta)+\gamma}\right)^2 - \frac{\gamma}{2}\left(\frac{A-3\bar{e}}{(3(1+\beta)+\gamma)}\right)^2 - \bar{e}^2\right) \tag{34}$$

The optimal cap in the non-cooperative case can be deduced from the FOC w.r.t. $\bar{e}$:

$$\bar{e}^{*,nc} = \gamma\frac{4+\beta+\gamma}{X}A \tag{35}$$

Inserting equation (35) into equation (31) yields the equilibrium level of green R&D investment:

$$\tilde{\zeta}^{*,nc} = \frac{6(1+\beta)+\gamma}{X}A \tag{36}$$

Interestingly, the optimal level of R&D investment under the optimal ESP in the non-cooperative scenario is closely related to the optimal tax under the ETP (see equation (11)), specifically $\tilde{\zeta}^{*,nc} = \frac{\tau^{*,nc}}{\gamma}$. This means that the R&D costs of the firms are similar in both cases and thus $\tilde{\zeta}^{*,nc} = \zeta^{*,nc}$. According to equation (1) indeed, the optimization program (29) is the same as under an emission tax (equation 2) when the strategic variable is ζ_i. Under an ETP therefore, the FOC w.r.t. ζ_i leads to the same R&D effort in the subgame equilibrium as the one obtained under an ESP for a given $\bar{e}$. In other words, the two instruments create the same incentives for firms, albeit through different mechanisms. The optimal output and social welfare at the SPNE follow from the optimal ESP and R&D effort:

$$\tilde{q}^{*,nc} = \frac{2(1+\beta)(3(1+\beta)+\gamma)+\gamma(3+\gamma)}{X}A \tag{37}$$

$$\tilde{SW}^{*,nc} = \frac{2\left(4(1+\beta)^2+\gamma\right)+4\gamma(1+\beta)+\gamma^2}{X}A^2 \tag{38}$$

As expected, when firms do not cooperate in R&D, the equilibrium levels of production and social welfare under the optimal ESP are similar to those under the optimal ETP. Further interpretation is provided below in the comparison of all the different settings considered, particularly with respect to the scenario in which firms do cooperate in green R&D.

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[9] If not, R&D investments would fall to zero and, by definition, there would be no spillovers.

4.2 Cooperative R&D

In this subsection, we solve the two-stage game where firms cooperate in R&D under an ESP. In the second stage therefore, the firms choose the level of green R&D that maximizes their aggregate profit – as spillovers are internalized – under the constraint of the ESP, and in the first stage, the regulator maximizes the social welfare function to determine the optimal standard to impose. The program is now:

$$\begin{cases} \max_{\tilde{\zeta}_i} & \sum \tilde{\pi}_i^c = & (A-Q)(\tilde{q}_i+\tilde{q}_j) - \frac{\gamma\tilde{\zeta}_i^2}{2} - \frac{\gamma\tilde{\zeta}_j^2}{2} \\ \text{s.t.} & \tilde{q}_i = & \bar{e} + \tilde{\zeta}_i + \beta\tilde{\zeta}_j \\ & \tilde{q}_j = & \bar{e} + \tilde{\zeta}_j + \beta\tilde{\zeta}_i \end{cases} \tag{39}$$

The symmetric solution of this program, $\tilde{\zeta}^c = \tilde{\zeta}_i^c = \tilde{\zeta}_j^c$, and the FOCs w.r.t. $\tilde{\zeta}$ yield the firms' optimal level of R&D as a function of the emission standard:

$$\tilde{\zeta}^c(\bar{e}) = \frac{(1+\beta)(A-4\bar{e})}{4(1+\beta)^2+\gamma} \tag{40}$$

The outcomes of cooperative and non-cooperative R&D strategies can now be compared for a given limit on emissions, $\bar{e}$. In particular, subtracting equation (31) from (40) yields:

$$\tilde{\zeta}^c(\bar{e}) - \tilde{\zeta}^{nc}(\bar{e}) = -\frac{((1+\beta)^2-\beta\gamma)A + (1+4\beta)\gamma\bar{e}}{(4(1+\beta)^2+\gamma)(3(1+\beta)+\gamma)} \tag{41}$$

Contrary to the standard result in the literature, we find that provided the abatement technology is very efficient (γ is low), levels of innovation are not necessarily higher in the cooperative scenario, even when spillovers are high. In this case, R&D cooperation under ESP encourages firms to form a production cartel, reducing both production and R&D efforts. A cartel ensues even when spillovers are zero.[10]

For larger values of γ however, we obtain the "expected" results that for sufficiently large spillovers, R&D investments are higher when firms cooperate and increase with the level of spillover, whereas under non-cooperative R&D they decrease (d'Aspremont and Jacquemin, 1988; Kamien et al., 1992). Taking the firms' optimal levels of green R&D as given (see equation (40)), the level of production per firm for a given emission standard is:

$$\tilde{q}^c(\bar{e}) = \frac{(1+\beta)^2A+\gamma\bar{e}}{4(1+\beta)^2+\gamma} \tag{42}$$

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[10] Under an ESP, the joint profit to be maximized, given by equation (39), can be expressed as follows: $\sum \tilde{\pi}_i(\tilde{q}_i, \tilde{q}_j, \tilde{\zeta}_i) = \tilde{\pi}_i(\tilde{q}_i(\tilde{\zeta}_i); \tilde{q}_j(\tilde{\zeta}_i); \tilde{\zeta}_i) + \tilde{\pi}_j(\tilde{q}_i(\tilde{\zeta}_i); \tilde{q}_j(\tilde{\zeta}_i); \tilde{\zeta}_j)$. Then, the FOC w.r.t ζ_i, can be written:

$$\frac{\partial \sum \tilde{\pi}_i}{\partial \tilde{\zeta}_i} = \underbrace{\frac{\partial \tilde{q}_i}{\partial \tilde{\zeta}_i}}_{=1}\left(\frac{\partial \tilde{\pi}_i}{\partial \tilde{q}_i} + \frac{\partial \tilde{\pi}_j}{\partial \tilde{q}_i}\right) + \underbrace{\frac{\partial \tilde{q}_j}{\partial \tilde{\zeta}_i}}_{=\beta}\left(\frac{\partial \tilde{\pi}_j}{\partial \tilde{q}_j} + \frac{\partial \tilde{\pi}_i}{\partial \tilde{q}_j}\right) + \underbrace{\frac{\partial \tilde{\pi}_i}{\partial \tilde{\zeta}_i}}_{=-\gamma\tilde{\zeta}_i} = 0$$

Notice that when $\beta = 0$, we obtain the FOC of a production cartel for i: $\frac{\partial \tilde{\pi}_i}{\partial \tilde{q}_i} + \frac{\partial \tilde{\pi}_j}{\partial \tilde{q}_i} = \gamma\tilde{\zeta}_i$

Each firm's profit at the end of the second stage can be expressed using equations (40) and (42) as a function of the emission standard:

$$\tilde{\pi}^c(\bar{e}) = (A - 2\tilde{q}^c(\bar{e}))\tilde{q}^c(\bar{e}) - \frac{\gamma}{2}\tilde{\zeta}_i^c(\bar{e})^2 \tag{43}$$

Using equations (33) and (43), we can derive the difference between the subgame equilibrium profits for a given $\bar{e}$:

$$\tilde{\pi}^c(\bar{e}) - \tilde{\pi}^{nc}(\bar{e}) = \left(\frac{4(1+\beta)^2 + \gamma}{2}\right)\left(\tilde{\zeta}^c(\bar{e}) - \tilde{\zeta}^{nc}(\bar{e})\right)^2 \tag{44}$$

which is always positive.

Therefore, the firms always have a private incentive to cooperate in R&D in stage 2 for a given emission standard, $\bar{e}$. Note that the marginal incentive to cooperate increases with the environmental constraint, just as in the ETP case (from equation (41), $\frac{\partial(\tilde{\zeta}^c(\bar{e}) - \tilde{\zeta}^{nc}(\bar{e}))}{\partial \bar{e}} < 0$).

Finally, in the first stage of the game, the social welfare function can be expressed as a function of the emission standard only using equations (40) and (42):

$$S\tilde{W}^c(\bar{e}) = 2\left(A\left(\frac{(1+\beta)^2 A + \gamma\bar{e}}{4(1+\beta)^2 + \gamma}\right) - \left(\frac{(1+\beta)^2 A + \gamma\bar{e}}{4(1+\beta)^2 + \gamma}\right)^2 - \gamma\frac{\left(\frac{(1+\beta)(A-4\bar{e})}{4(1+\beta)^2+\gamma}\right)^2}{2} - (\bar{e})^2\right) \tag{45}$$

Formally, the regulator selects the optimal emission standard by maximizing equation (45) with respect to $\bar{e}$:

$$\bar{e}^{*,c} = \gamma\frac{6(1+\beta)^2 + \gamma}{W}A, \tag{46}$$

with $W = 2(4(1+\beta)^2 + \gamma)^2 + 2\gamma(8(1+\beta)^2 + \gamma) > 0$.

Inserting equation (46) into equations (40),(42) and (45) yields the levels of R&D, output and social welfare at the SPNE:

$$\tilde{\zeta}^{*,c} = \frac{8(1+\beta)^3}{W}A \tag{47}$$

$$\tilde{q}^{*,c} = \frac{(2(1+\beta)^2 + \gamma)(4(1+\beta)^2 + \gamma)}{W}A \tag{48}$$

$$S\tilde{W}^{*,c} = \frac{(2(1+\beta)^2 + \gamma)\,(6(1+\beta)^2 + \gamma)}{W}A^2 \tag{49}$$

4.3 Cooperation versus non-cooperation in R&D under an ESP

As in Section 3, we can now compare the outcomes of the two scenarios under the optimal ESP.

Lemma 2. *Under an optimal ESP,* $\forall\ \gamma > 0$ *and* $\beta \in (0, 1]$

1. $\bar{e}^{*,c} < \bar{e}^{*,nc}$,

2. $\tilde{\zeta}^{*,c} < \tilde{\zeta}^{*,nc}$ *iff* $(\beta, \gamma) \in \Omega$ *and* $\tilde{\zeta}^{*,c} > \tilde{\zeta}^{*,nc}$ *iff* $(\beta, \gamma) \in \bar{\Omega}$

3. $\tilde{CS}^{*,c} = 2\left(\tilde{q}^{*,c}\right)^2 < 2\left(\tilde{q}^{*,nc}\right)^2 = \tilde{CS}^{*,nc}$,

4. $\tilde{SW}^{*,c} < \tilde{SW}^{*,nc}$.

with $\Omega = \{\beta \in (0,1], \gamma \in \mathbb{R}^+ | f(\beta,\gamma) = -48(1+\beta)^5 + 8(1+\beta)^3(-7+8\beta)\gamma] + 8(-3+\beta+4\beta^2(2+\beta))\gamma^2 - 4\gamma^3\} < 0$ *and with* $\bar{\Omega} = \{\beta \in (0,1], \gamma \in \mathbb{R}^+ | f(\beta,\gamma) = -48(1+\beta)^5 + 8(1+\beta)^3(-7+8\beta)\gamma] + 8(-3+\beta+4\beta^2(2+\beta))\gamma^2 - 4\gamma^3\} > 0$

Proof. See Appendix B. ☐

Lemma 2 highlights the channels through which an ESP affects economic outputs. The ranking in Lemma 2 is reversed compared with Lemma 1, except for optimal emissions and, in some cases, R&D efforts. Moreover, the mechanisms differ from those under an ETP when the firms cooperate in green R&D. Under an ESP, in the cooperative scenario, firms are likely to circumvent the environmental constraint by forming a cartel, choosing to produce less rather than invest in R&D, regardless of the efficiency of the green technology and spillovers. The decrease in production leads to an increase in prices, which has a negative effect on consumer surplus. Regulators are therefore inclined to enforce a tighter emission standard to reduce environmental damage and thereby mitigate the decrease in consumer surplus. At the equilibrium however, social welfare is lower in the cooperative scenario. Nevertheless, despite the lower social welfare and lower consumer surplus in the cooperative scenario, green R&D efforts may be larger for a limited set of (β, γ) combinations. Following equation (1), this holds when at the equilibrium, the production differential is lower than the emission differential:

$$\tilde{\zeta}^{*,c} > \tilde{\zeta}^{*,nc} > 0 \Rightarrow \tilde{q}^{*,nc} - \tilde{q}^{*,c} < \bar{e}^{*,nc} - \bar{e}^{*,c} \tag{50}$$

Finally, under an ETP, cooperation in R&D stimulates innovation, increases welfare and reduces emissions compared with non-cooperation, despite a less stringent environmental policy. Under an ESP however, cooperation does not necessarily stimulate innovation and welfare is lower than under non-cooperation, although environmental performance is better.

5 ETP versus ESP

In this section, we first compare the two environmental policy instruments when the firms cooperate in R&D and when they do not. In a final subsection, we endogenize the regulator's environmental policy choice by adding an extra stage to the benchmark game.

5.1 Non-cooperation in R&D

Let us first establish the similarity of the two policy instruments when firms do not cooperate in green R&D.

Proposition 1. *In the non-cooperative R&D scenario, the two instruments, taxes and standards, are equivalent in the sense that they have the same outcome for all spillover levels* $\beta \in (0, 1]$.

Proof. See Appendix C. □

This result has already been reported in the literature (see for instance Petrakis et al. (2001) or Moner-Colonques and Rubio (2016)). However, in our setup, it is obtained in a duopoly game rather than a monopoly, and in the presence of R&D spillovers. In this context, the similarity between the two types of instruments is driven by the binding target on emissions given by equation (1). At the R&D/production stage, the firms compete in the same way under the two instruments. Under an ETP, the tax burden vanishes when firms compete in R&D: any marginal increase in the cost of taxation—due to additional units of polluting production—is exactly compensated by the marginal benefit – reduced taxation – afforded by the firm's R&D efforts. Then, the firms' only consideration when choosing their R&D investments is the trade-off between the direct cost of R&D and its benefit in terms of increased production. This is the same trade-off as under an ESP. The competition conditions are therefore exactly the same way whether the policy instrument is an emission tax or an emission standard. Formally, for the same level of emissions $\bar{e} = e(\tau) = \frac{A}{3} - \frac{3(1+\beta)+\gamma}{3\gamma}\tau$, we have identical green R&D efforts ($\zeta^{nc}(\tau) = \tilde{\zeta}^{nc}(e(\tau))$) and consequently, identical levels of production ($q^{nc}(\tau) = \tilde{q}^{nc}(e(\tau))$). Therefore, whether the government chooses an optimal tax or an optimal standard, its objective function is:

$$SW^{nc}(\tau) = \tilde{SW}^{nc}(e(\tau))$$

This directly implies that for a given optimal ETP, there is one and only one optimal ESP that yields the same level of welfare. Interestingly, this correspondence vanishes when firms cooperate in R&D.

5.2 Cooperation in R&D

Proposition 2. *In the cooperative R&D scenario, the two instruments, the emission tax and the emission standard, are not equivalent:*
$\forall \gamma > 0$ *and* $\beta \in (0, 1]$,

1. $e^{*,c} > \bar{e}^{*,c}$,
2. $\zeta^{*,c} > \tilde{\zeta}^{*,c}$,
3. $CS^{*,c} > \tilde{CS}^{*,c}$,
4. $SW^{*,c} > \tilde{SW}^{*,c}$.

Proof. See Appendix D. □

The two environmental policy instruments perform differently when firms cooperate in R&D, contrary to what happens when they choose their R&D efforts separately (proposition (1)). In the setup considered here, the ETP offers firms an additional degree of freedom. Under an optimal ETP, firms choose their R&D expenditures and their levels of production separately (which allows them to endogenize the level of emissions). If firms choose their R&D efforts cooperatively, it turns out that production levels are (still) chosen competitively. Under an optimal ESP on the other hand, firms simultaneously choose their levels of production and R&D investment, since polluting emissions are constrained. Therefore, under an optimal ESP, when firms cooperate in R&D, they can adopt a cartel behavior. As a result, R&D efforts and production are lower.

Although an optimal ETP under R&D cooperation is economically more efficient, an optimal ESP is better for the environment. Furthermore, the great the social benefit from optimal taxation is, the greater the loss is from an environmental point of view $(e^{*,c} - \bar{e}^{*,c}) > 0$:

$$SW^{*,c} - \tilde{SW}^{*,c} = (e^{*,c} - \bar{e}^{*,c}) \left(\frac{2(1+\beta)^2 + \gamma}{\gamma} A \right) > 0$$

Therefore R&D cooperation entails a trade-off between social and environmental outcomes.

5.3 Endogenous choice of environmental policy instrument

We can go a step further and study the regulator's choice depending on whether firms cooperate or not in R&D.[11] The game therefore has a new time structure, with an extra stage (stage 0): the choice of policy instrument can emerge as an equilibrium of the whole of this new game. We consider two possibilities: stage 0a) the regulator chooses the environment policy instrument, Stage 0b) the regulator chooses the environment policy instrument and the firms endogenize their strategic R&D behavior (cooperation or non-cooperation). These endogenous choices lead to further environmental policy recommendations.

5.3.1 Stage 0a: Environmental policy instrument

The new time structure of the game is as follows:

- Stage 0a: The regulator chooses the socially preferable environmental policy instrument given the firms' strategic R&D behavior;
- Stage 1: The regulator sets the optimal environmental policy (*i.e.* the regulator precommits to an emission tax or an emission standard);
- Stage 2: Firms simultaneously choose to cooperate or not in R&D and how much to invest based on the expected policy instrument;

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[11] We assume that R&D cooperation is authorized by national or supranational regulators, as illustrated in the introduction.

- Stage 3: Firms compete in quantities.[12]

We solve this game by backward induction and claim the following:

Corollary 1. *At the SPNE, the regulator implements an environmental tax policy and the firms cooperate in green R&D.*

In the two subgames, ETP and ESP, green R&D cooperation leads to higher profits (see equations (20) and (44)). Thus, in stage 0a, the regulator compares the social welfare levels at the SPNE for each environmental policy tool, given cooperating firms. Proposition 2 shows that that the environmental tax is the most socially desirable policy instrument. Let us now investigate whether this holds when firms do not anticipate which type environmental policy will be enacted.

5.3.2 Stage 0b: Simultaneous choice of R&D behavior and environmental policy

The time structure, in this game, becomes:

- Stage 0b: The regulator chooses the socially preferable environmental policy instrument and simultaneously, the firms choose the most profitable strategic behavior between cooperation and competition in green R&D (see Table 1);

		Environmental Policy Tool	
		ETP	ESP
Firm's behavior	Cooperation (C)	$(\pi^{*,c}, SW^{*,c})$	$(\tilde{\pi}^{*,c}, \tilde{SW}^{*,c})$
	Non Cooperation (NC)	$(\pi^{*,nc}, SW^{*,nc})$	$(\tilde{\pi}^{*,nc}, \tilde{SW}^{*,nc})$

Table 1: Gains matrix

- Stage 1: The regulator sets the optimal environmental policy (*i.e.* the regulator precommits to an emissions tax rate or emission standard);
- Stage 2: Firms decide how much to invest in green R&D;
- Stage 3: Firms may compete in quantities.

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[12] Under an ESP, stage 3 of the game vanishes.

We solve this game by backward induction and claim the following corollary, illustrated in Figure 1

Corollary 2. *Different equilibrium strategies arise in stage 0 from the SPNE outcomes, depending on the values of $\beta \in (0, 1]$ and $\gamma > 0$:*

- *The regulator adopts an optimal ETP and the firms strategically choose not to cooperate in R&D (Region A);*
- *The regulator adopts an optimal ETP and the firms strategically choose to cooperate in R&D or the regulator adopts an optimal ESP and the firms strategically choose not to cooperate in R&D (Region B);*
- *The regulator adopts an optimal ETP and the firms strategically choose to cooperate in R&D (Region C).*

Proof. From Lemma 1 and 2 and Proposition 1, it is straightforward to show that: $SW^{*,c} > SW^{*,nc} = \tilde{SW}^{*,nc} > \tilde{SW}^{*,c}$. Let us now investigate the equilibrium profits. Substituting the optimal ETPs into equations (9) and (19) respectively, we can state that: $\pi^{*,c} > (<) \pi^{*,nc}$ for any value of $\beta \in (0, 1]$ with γ sufficiently large (low). Similarly, for the two optimal ESPs, we can compare equations (33) and (43) and claim that: $\tilde{\pi}^{*,c} > \tilde{\pi}^{*,nc}$ for $\Phi = \{(\beta, \gamma) \in \text{Region A} \cup \text{Region C}\}$; otherwise the reverse is true. In the non-cooperative scenario, the burden of the tax (see equation (2)) leads to lower profits, given similar production and R&D efforts: $\tilde{\pi}^{*,nc} > \pi^{*,nc}$, $\forall\ \beta \in (0, 1]$ and $\gamma > 0$. Also, in the cooperative scenario, the difference $\tilde{\pi}^{*,c} - \pi^{*,c}$ always turns out positive. ☐

This time structure is representative of situations in which firms need to plan R&D partnerships in advance (signing agreements, a potentially lengthy process) without certainty regarding what environmental policy will be chosen. The environmental policy and strategic R&D behaviors are then adopted simultaneously in stage 0. Several equilibria can emerge depending on the values of γ and β. The equilibrium strategies in Region C are similar to those of the regulator when the firms choose to cooperate in the R&D stage (see Corollary 1): In stage 0b), the firms choose to cooperate in R&D and the regulator implements the optimal tax. This equilibrium solution is also obtained in Region B, for larger values of γ and β. However, as R&D becomes more efficient – for lower values of γ – the firms' equilibrium strategies change. In Region A, the regulator still chooses the tax but the firms choose not to cooperate in R&D. In conclusion, the environmental tax always emerges as the socially preferable policy instrument while the firms only choose to cooperate in green R&D when R&D is relatively inefficient.

Nonetheless, in Region B, ESP can also emerge as an equilibrium of the multistage game but only when the firms choose not to cooperate in R&D, leading to higher profits, i.e. $\tilde{\pi}^{*,nc} > \tilde{\pi}^{*,c}$ for high spillovers and inefficient R&D. [13] Finally, ESP with R&D cooperation is never an equilibrium of the game.

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[13] In this framework, we ignore coordination issues and focus on the policy implications.

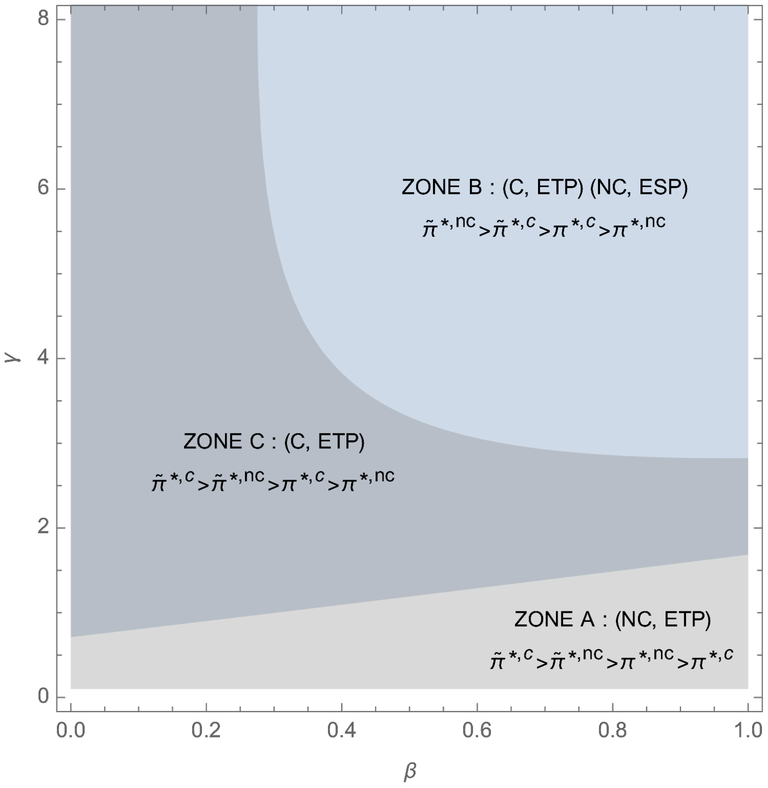

Figure 1: Equilibrium strategies for the firms and the regulator at stage 0.

6 Conclusion

This paper addresses the crucial issue of how green R&D should be organized and which environmental policy tool should be chosen for the best environmental and social welfare outcomes. Our study offers a comparison of the induced effects of a given environmental policy on the strategic behavior of firms depending on whether they cooperate or not in R&D and makes two interesting contributions.

First, we obtain a result that contradicts the conventional wisdom in the field: R&D cooperation is not necessarily more efficient than non-cooperation, even when spillovers are high, under an optimal ESP. Second, our results provide interesting insights for environmental policy recommendations. Governments aiming to maximize social welfare (consumer surplus and welfare) should adopt an ETP and encourage R&D cooperation. In terms of green R&D, consumer surplus and social welfare, R&D cooperation under an ETP outperforms R&D competition under an ETP and R&D cooperation under an ESP. Although R&D cooperation under an ESP yields lower emissions, this better environmental performance comes at the expense of consumer welfare (and ultimately total welfare). If we now consider what happens when the regulator's environmental policy choice is endogenized, an ETP is still socially preferable provided that the firms cooperate in R&D. Finally, situations in which the environmental policy and firms' green R&D strategies are chosen simultaneously remain conducive to the implementation of an environmental tax, regardless of the level of spillovers and of R&D efficiency. However, firms only choose to cooperate in R&D, for all spillover levels, when R&D is costly. Although ESP is a weakly dominated strategy, it can emerge as an equilibrium of the whole game, but only when firms compete in R&D; a production cartel (as encouraged by green R&D cooperation under an ESP) never emerges as a stable strategy. We argue on this basis that antitrust policies to control cooperative green R&D are unnecessary.

Furthermore, our results echo the literature on the effects of decision timing on the performance of environmental policy tools. For example, Moner-Colonques and Rubio (2016) show that when governments precommit to environmental regulations, outcomes do not depend on the policy instrument adopted; however, if governments do not commit (*i.e.* the environmental policy is implemented after green R&D investment choices are made), the environmental policy instruments have different outcomes. In our model, when firms cooperate in R&D, outcomes depend on the choice of instrument even if the government credibly commits to its environmental policy. It would be worthwhile to compare the effects of the two instruments when authorities cannot commit and firms can cooperate in R&D in the presence of spillovers. Note also that these results were obtained for a duopolistic market and need in principle to be confirmed for an oligopolistic market. Finally, our setup and results pave the way for future studies, for instance involving an extra instrument such as an R&D subsidy.

Appendices

A Proof of Lemma 1

Subtracting equation (22) from (11), the difference between the optimal environmental taxes can be expressed as:

$$\tau^{*,nc} - \tau^{*,c} = \frac{3\beta\gamma(\gamma^2(2-\beta) + 6(1+\beta)^2(6(1+\beta)^2 + \gamma((1+\beta)+4))}{X.Y}A, \tag{A.1}$$

which is always positive.

Emission levels at the equilibrium can be compared by substituting equation (11) into (7) and equation (22) into (16):

$$e^{*,nc} - e^{*,c} = \frac{A\beta\gamma\left(9(1+\beta)^2(2\beta+1+2(1+\beta)^2) + 5\beta + 2\right)}{XY} \tag{A.2}$$

which is always positive.

The two optimal levels of green R&D efforts can be compared using equations (12) and (23). Notice that it depends on the sign of the numerator:

$$sign\{\zeta^{*,c}(e^{*,c}) - \zeta^{*,nc}(e^{*,nc})\} = sign\{\gamma\beta(A - 3e^{*,c}) + 3\left(3(1+\beta)^2 + \gamma\right)(e^{*,nc} - e^{*,c})\}, \tag{A.3}$$

which is positive since R&D effort are always positive ($A - 3e^* > 0$) and being given that $(e^{*,nc} - e^{*,c}) > 0$ (See equation (A.2) above). Using equation (3) and (A.1) we can easily deduce that $CS^{*,c} > CS^{*,nc}$. Finally, using equations (25) and (14), the difference between the SPNE levels of social welfare can be written as follows:

$$SW^{*,c} - SW^{*,nc} = \frac{\beta\gamma A^2(24(1+\beta(4+6\beta+4\beta^2+\beta^3)) + \gamma\beta(46\beta+43\beta+14\beta^2+4\gamma) + 2\gamma(8+\gamma))}{X.Y} \tag{A.4}$$

which is always positive.

B Proof of Lemma 2

Using equations (35) and (46), the difference between optimal emission standards is given by the following expression:

$$\bar{e}^{*,nc} - \bar{e}^{*,c} = \frac{A\gamma(4(1+\beta)(5+\gamma(4-\gamma) + \beta(23+39\beta+29\beta^2+8\beta^3+\gamma(10+2\gamma+\beta(8+14\beta)))) + \gamma^2(7+4\beta))}{XW} \tag{B.5}$$

The numerator is increasing in β and for $\beta = 0$, it is positive, so that $\bar{e}^{*,nc} - \bar{e}^{*,c} > 0$ for all values of $\beta \in (0,1]$.

Using equations (36) and (47), the difference between optimal R&D efforts is given by:

$$\tilde{\zeta}^{*,c} - \tilde{\zeta}^{*,nc} = \frac{Af(\gamma,\beta)}{XW}, \tag{B.6}$$

with $f(\gamma,\beta) = -48(1+\beta)^5 + 8(1+\beta)^3(-7+8\beta)\gamma] + 8(-3+\beta+4\beta^2(2+\beta))\gamma^2 - 4\gamma^3$. We know that $f(\gamma,0) < 0$ while the sign of $f(\gamma,1)$ is unclear and depends on a combination between γ and β. Thus, we deduce that there exists a frontier $f(\gamma,\beta)$ such that $\tilde{\zeta}^{*,c} - \tilde{\zeta}^{*,nc} < 0 (> 0)$ for $(\beta,\gamma) < (>) f(\gamma,\beta)$. Figure 2 illustrates our results:

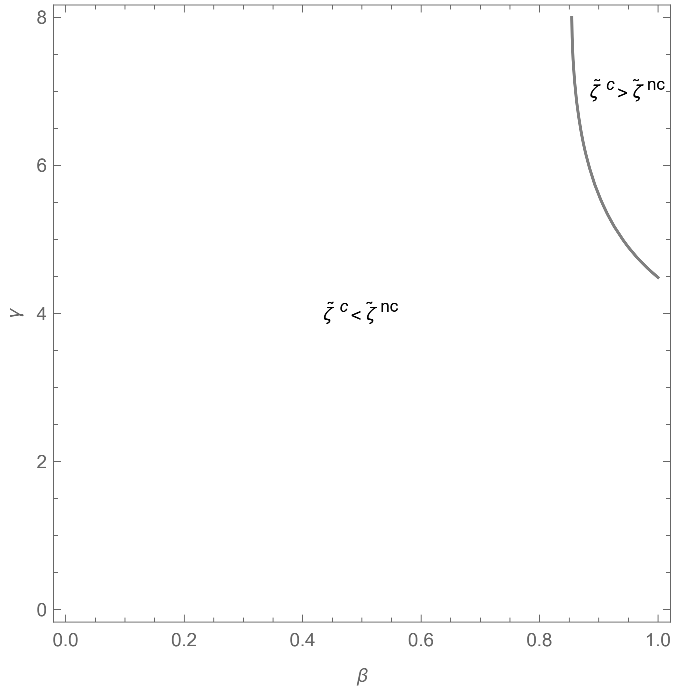

Figure 2: Comparison of green R&D efforts under an optimal ESP.

Similarly, using equations (37) and (48), the difference in optimal levels of output is given by:

$$\tilde{q}^{*,nc} - \tilde{q}^{*,c} = \frac{A}{XW}[(12(1+\beta)^4 + 8(2-\beta)(1+\beta)^2\gamma + 9\gamma^2 + 2\gamma^3)] \tag{B.7}$$

From equations (38) and (49) we obtain the difference between the two equilibrium levels of social welfare:

$$S\tilde{W}^{*,nc} - S\tilde{W}^{*,c} = \frac{2\gamma^4 + 3(5+4\beta)\gamma^3 + 2(1+\beta)^2(19-8\beta^2)\gamma^2 + 4(1+\beta)^4(13-4\beta)\gamma + 40(1+\beta)^6}{X.W}A^2 \tag{B.8}$$

which is always positive.

C Proof of Proposition 1

The proof can be sketched out as follows. First, we show that the social welfare functions (10) and (34) are identical and then we claim that optimization yields only one possible relationship between the two environmental policy instruments.
From equations (1), (3) and (6), we can write that $\bar{e} = e(\tau) = q(\tau) - (1+\beta)\zeta(\tau) = \frac{A}{3} - \frac{3(1+\beta)+\gamma}{3\gamma}\tau$. We then deduce that $S\tilde{W}^{nc}(\bar{e}) = S\tilde{W}^{nc}(\bar{e}(\tau))$.

Using equation (10),

$$\begin{cases} \frac{\partial SW^{nc}(\tau)}{\partial \tau} = \frac{2}{9\gamma^2}\left(\gamma A(6(1+\beta)+\gamma) - \tau(2(3(1+\beta)+\gamma)^2 + \gamma(9+2\gamma))\right) \\ \text{cst}(SW^{nc}(0)) = \frac{3)}{9}A^2 \end{cases}$$

and using equation (34),

$$\begin{cases} \frac{\partial \tilde{SW}^{nc}(\bar{e}(\tau))}{\partial \tau} = \frac{\partial \tilde{SW}^{nc}(\bar{e}(\tau))}{\partial e} . \frac{\partial e}{\partial \tau} = \frac{2}{9\gamma^2} \left(\gamma A(6(1+\beta)+\gamma) - \tau(2(3(1+\beta)+\gamma)^2 + \gamma(9+2\gamma))\right) \\ \text{cst}(\tilde{SW}^{nc}(e(0))) = \frac{3}{9} A^2 \end{cases}$$

then $SW^{nc}(\tau) = \tilde{SW}^{nc}(e(\tau)) \quad \forall \tau$.

2) If $SW^{nc}(\tau) = \tilde{SW}^{nc}(e(\tau)) = \tilde{SW}^{nc}(\bar{e})$, then the maximum values of $\tilde{SW}^{nc}$ and SW^{nc} are the same and obtained for the same $\tau = \tau^{nc,*}$.

D Proof of Proposition 2

Plugging equation (22) into (16) and using equation (46), the difference in emission levels is given by the following expression:

$$e^{*,c} - \bar{e}^{*,c} = \frac{A\gamma}{YW}(1+\beta)^2(2(1+\beta)^2+\gamma)(10(1+\beta)^2+3\gamma) \tag{D.9}$$

which is always positive.

In addition, from equations (23) and (47), the difference in optimal R&D efforts is given by

$$\zeta^{*,c} - \tilde{\zeta}^{*,c} = \frac{A\gamma(1+\beta)}{YW}(2(1+\beta)^2+\gamma)\left(12(1+\beta)^4 + 8(1+\beta)^2\gamma + 2\gamma^2\right) \tag{D.10}$$

which is always positive. Finally, from Lemma 1 and 2 and Proposition 1, it is straightforward that:

- $q^{*,c} > q^{*,nc} = \tilde{q}^{*,nc} > \tilde{q}^{*,c} \Rightarrow CS^{*,c} > CS^{*,nc} = \tilde{CS}^{*,nc} > \tilde{CS}^{*,c}$;
- $SW^{*,c} > SW^{*,nc} = \tilde{SW}^{*,nc} > \tilde{SW}^{*,c}$.

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