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► **To cite this version:**

Marie-Laure Cabon-Dhersin, Natacha Raffin. Cooperation in Green R&D and Environmental Policies: Taxes versus Standards. 2022. hal-03610541v1

HAL Id: hal-03610541

<https://normandie-univ.hal.science/hal-03610541v1>

Preprint submitted on 16 Mar 2022 (v1), last revised 12 Dec 2023 (v3)

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

Marie-Laure Cabon-Dhersin*, Natacha Raffin†

March 16, 2022

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 by increasing abatement efforts and increasing consumer surplus. Conversely, R&D cooperation under standards pushes firms to reduce production, which is harmful for consumers but better for the environment.

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.

*Université Rouen Normandie, LERN, 3 avenue Pasteur, 76100 Rouen, France. (marie-laure.cabon-dhersin@univ-rouen.fr)

† *Corresponding author*, Université Rouen Normandie, LERN, 3 avenue Pasteur, 76100 Rouen, France. (natacha.raffin@univ-rouen.fr)

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

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

²For details, see Ouchida and Goto (2016b) 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 con-

sidered 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 (2016b) 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 (2016a), 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.

The model presented here is based on the regulator's choice of policy instrument (a tax or a standard) 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. We find that R&D cooperation is welfare improving – over non-cooperation – if the chosen policy instrument is a tax but that the opposite may hold in the case of an emission standard, where cooperation in R&D can lead 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). Now, if we compare the performance of R&D cooperation under the two instruments, the outcomes are socially more favorable under the emission tax because of higher abatement efforts and higher consumer surplus. Interestingly however, under an emission standard, since R&D collusion reduces production, the overall level of pollution is lower. Based on environmental considerations alone therefore, emission standards appear to outperform taxes when firms cooperate in R&D. Finally, 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 levels of spillovers.

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. 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:

$$e_i = e(q_i, \zeta_i) = q_i - \zeta_i - \beta\zeta_j \quad (1)$$

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

³In 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.

⁴This 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.

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*”. To guarantee relevant solutions in the following analysis, we assume $d \geq 1$, meaning that the environmental damage is substantial (see Petrakis et al. (2001), Poyago-Theotoky (2007), Lambertini et al. (2017)). 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 i), the regulator sets the level of the emission tax so as to maximize social welfare; in stage ii), firms invest, non-cooperatively or cooperatively, in green R&D; and in stage iii), firms compete in quantities. When the regulator chooses to implement an emission standard policy (ESP), the game has only two stages: outputs are determined once the regulator has chosen the emission standard (stage i) and firms have chosen, non-cooperatively or cooperatively, their abatement efforts (stage ii).

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 two types 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. 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:⁵

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

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

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

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 (2016a) 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:

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

Social welfare (SW) is defined as the sum of consumer surplus and firm profits net of

⁵This final stage is the same under an ETP whether the firms cooperate in R&D or not.

taxation revenue minus the environmental damage:

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

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:

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

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):

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

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):

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

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:

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

It can easily be shown that for a given tax rate, the profits decrease (increase) if $\gamma > \hat{\gamma}$ ⁶ ($\gamma < \hat{\gamma}$). When R&D spending is inefficient (or, alternatively, more expensive), the ETP weighs more heavily on firms' profits. Now the firms' optimal behavior has been determined, let us turn to the first stage of the game. Substituting equations (1), (3) and

⁶ $\hat{\gamma}$ is defined as $\frac{\partial \pi^{nc}(\tau; \hat{\gamma})}{\partial \tau} = 0$ with $\hat{\gamma} = \frac{-\tau(1+2\beta)}{2q(\tau)q'(\tau)} > 0$.

(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:

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

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

$$\tau^{*,nc} = \gamma \frac{2d(3(1 + \beta) + \gamma) - \gamma A}{X}, \quad (11)$$

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

As mentioned above, $\tau^{*,nc}$ is always positive if $d > d_1 = \frac{\gamma}{2(3(1 + \beta) + \gamma)} < 1/2$.⁸ Finally, the level of social welfare at the SPNE can be calculated using equation (11):

$$SW^{*,nc} = \frac{2d(4(1 + \beta)^2 + \gamma(2\beta + 1)) + 4\gamma + \gamma^2}{X} A^2 \quad (12)$$

The equilibrium outputs are similar to those of Ouchida and Goto (2016b) (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) and are presented in Table (1) (see Appendix G).

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:

$$\zeta^c(\tau) = \frac{(1 + \beta)\tau}{\gamma} \quad (13)$$

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 (13) into (1):

$$e^c(\tau) = \frac{A}{3} - \frac{3(1 + \beta)^2 + \gamma}{3\gamma} \tau \quad (14)$$

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

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

⁸Note that $d > d_1$ also guarantees that $\zeta^{nc} > 0$.

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 (13) and (14):

$$\zeta^c(e^c) = (1 + \beta) \frac{A - 3e^c}{3(1 + \beta)^2 + \gamma} \quad (15)$$

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 :

$$\zeta^c(e) - \zeta^{nc}(e) = \frac{\beta\gamma}{(3(1 + \beta)^2 + \gamma)(3(1 + \beta) + \gamma)} > 0 \quad (16)$$

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 (13), the social welfare at a given tax rate can be written as follows:

$$SW^c(\tau) = 2 \left(A \left(\frac{A - \tau}{3} \right) - \left(\frac{A - \tau}{3} \right)^2 - (1 + \beta)^2 \frac{(\tau)^2}{2\gamma} - d \left(\frac{A - \tau}{3} - (1 + \beta)^2 \frac{\tau}{\gamma} \right)^2 \right) \quad (17)$$

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

$$\tau^{*,c} = \gamma \frac{2d(3(1 + \beta)^2 + \gamma) - \gamma}{2d(3(1 + \beta)^2 + \gamma)^2 + \gamma(9(1 + \beta)^2 + 2\gamma)} A, \quad (18)$$

which is always positive if $d > d_2 = \frac{\gamma}{2(3(1 + \beta)^2 + \gamma)} < 1/2$. Inserting equation (18) into the above equation yields the following expression for the social welfare at the SPNE:

$$SW^{*,c} = \frac{2d(1 + \beta)^2 (4(1 + \beta)^2 + \gamma) + 4\gamma(1 + \beta)^2 + \gamma^2}{Y} A^2, \quad (19)$$

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

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, $\forall d \geq 1, \gamma > 0, \beta \in (0, 1]$,*

1. $\zeta^{*,c} > \zeta^{*,nc}$,
2. $\tau^{*,c} < \tau^{*,nc}$.

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. On the one hand indeed, the emission tax lowers consumer surplus and profits – if γ is large enough – and increases the cost of R&D, all of which decrease social welfare. On the other hand though, the emission tax limits environmental damage, which increases social welfare. The firms' incentive to invest in green R&D increases with the tax rate and are larger at a given tax rate when the firms cooperate in R&D (see equation (13)). Since emissions tend to be lower under R&D cooperation, this automatically reduces the amount of environmental damage. The marginal increase in social welfare due to an increase in the environmental tax is therefore smaller under R&D cooperation, leading the regulator to set a lower optimal emission tax. Finally, 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 in combination with 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. The two following lemmas describe the effects of cooperation in green R&D on the environment and on social welfare.

Lemma 2. *Under the optimal ETP,*

1. for $\beta \geq 0.5$,

$$e^{*,c} < e^{*,nc}, \forall d \geq 1, \gamma > 0$$

2. for $\beta < 0.5$,

•

$$e^{*,c} < e^{*,nc} \text{ if } \begin{cases} d \leq d_e, \\ d > d_e \end{cases} \text{ and } \gamma < \gamma_e^-$$

• $e^{*,c} > e^{*,nc}$, otherwise, that is for $d > d_e$ and $\gamma > \gamma_e^-$,

with γ_e^\pm and d_e provided in Appendix B.

Proof. See Appendix B. □

As shown in Figure 1, when spillovers are large enough ($\beta \geq 0.5$), pollution is reduced, since R&D efforts are boosted when firms cooperate. On the contrary, when spillovers are relatively small, the incentive for cooperating firms to invest in green R&D does not always outweigh the increase in emissions associated with the higher production allowed by the lower optimal tax. Cooperation in green R&D thus becomes inefficient from an environmental point of view. This effect is enhanced when R&D is relatively costly and when the pollution is more damaging. Nevertheless, despite this possible perverse effect of cooperation on the environment, the following lemma shows that cooperation is always welfare improving:

Lemma 3. *Under the optimal ETP, $\forall d \geq 1, \gamma > 0, \beta \in (0, 1]$,*

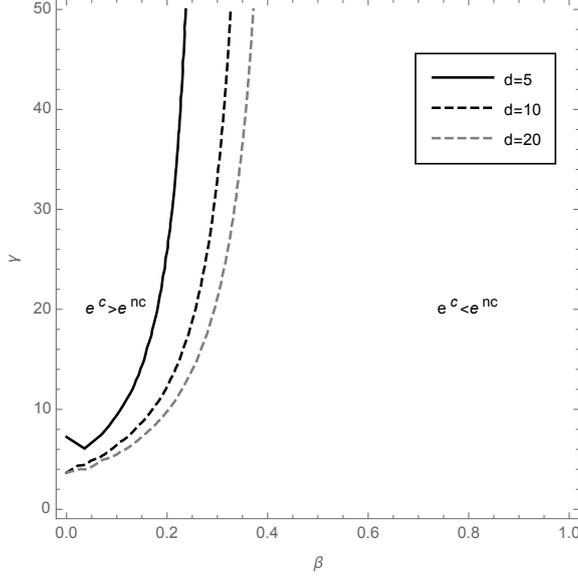


Figure 1: Emissions comparison under an optimal ETP.

1. $CS^{*,c} = 2(q^{*,c})^2 > 2(q^{*,nc})^2 = CS^{*,nc}$,
2. $SW^{*,c} > SW^{*,nc}$.

Proof. See Appendix C. □

The better welfare performance of R&D cooperation stems mainly from the larger consumer surplus when firms cooperate. According to equation (3), output is inversely related to the optimal tax. Since the tax is lower under R&D cooperation, production is higher than under non-cooperation, which benefits consumers. This increase in production leads to increased emissions and therefore additional costs for producers, which for some parameter values reduce their profits. However, producers have a particularly strong incentive to invest in green technologies to reduce the environmental tax burden because in the cooperative scenario, R&D spillovers are internalized (see lemmas (1) and (2) above). While the costs of production and innovation may be higher under R&D cooperation, the tax burden and the environmental damage are reduced. When spillovers are high enough, R&D cooperation always outperforms non-cooperation in terms of environmental protection.

The better performance of green R&D cooperation in the presence of spillovers is confirmed here under an emission tax since it leads to higher social welfare, despite the higher costs induced by the greater R&D efforts. In terms of the environment however, the results are more nuanced since in some cases, cooperation is associated with higher emissions but only when spillovers are small and for an inefficient R&D (high γ). 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:

$$\begin{cases} \max_{\tilde{\zeta}_i} & \tilde{\pi}_i^{nc} = (a - Q)\tilde{q}_i - c\tilde{q}_i - \frac{\gamma\tilde{\zeta}_i^2}{2} \\ \text{s.t.} & \tilde{q}_i = \bar{e} + \tilde{\zeta}_i + \beta\tilde{\zeta}_j \end{cases} \quad (20)$$

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

$$\tilde{\zeta}_i^{nc}(\bar{e}; \tilde{\zeta}_j^{nc}) = \frac{A - 3\bar{e} - (1 + 2\beta)\tilde{\zeta}_j^{nc}}{(2 + \beta + \gamma)} \quad (21)$$

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 (21) shows that the best-response functions are decreasing in $\tilde{\zeta}_j$, 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.⁹ Then, by

⁹The profit function used in the maximization program (see equation (20)), 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:

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

symmetry, the optimal R&D output can be expressed using equation (21) as a function of the emission standard only:

$$\tilde{\zeta}_i^{nc} = \tilde{\zeta}_j^{nc} = \tilde{\zeta}^{nc}(\bar{e}) = \frac{A - 3\bar{e}}{3(1 + \beta) + \gamma} \quad (22)$$

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 (22) 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 (22)), we can now deduce their equilibrium outputs:

$$\tilde{q}^{nc}(\bar{e}) = \frac{(1 + \beta)A + \gamma\bar{e}}{3(1 + \beta) + \gamma} \quad (23)$$

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 allow both firms to produce more. Equation (22), assuming it is positive,¹⁰ 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.

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 (22) and (23):

$$S\tilde{W}^{nc}(\bar{e}) = 2 \left(A \left(\frac{(1 + \beta)A + \gamma\bar{e}}{3(1 + \beta) + \gamma} \right) - \left(\frac{(1 + \beta)A + \gamma\bar{e}}{3(1 + \beta) + \gamma} \right)^2 - \frac{\gamma}{2} \left(\frac{A - 3\bar{e}}{3(1 + \beta) + \gamma} \right)^2 - d\bar{e}^2 \right) \quad (24)$$

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

$$\bar{e}^{*,nc} = \gamma \frac{(3 + (1 + \beta) + \gamma)A}{X} \quad (25)$$

Inserting equation (25) into equation (22) yields the equilibrium level of green R&D investment¹¹:

$$\tilde{\zeta}^{*,nc} = \frac{2d(3(1 + \beta) + \gamma) - \gamma}{X} A \quad (26)$$

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

¹⁰If not, R&D investments would fall to zero and, by definition, there would be no spillovers.

¹¹Notice that $d \geq 1$ also ensures that at the equilibrium, R&D expenditure is always positive, see equation (22).

in both cases and thus $\tilde{\zeta}^{*,nc} = \zeta^{*,nc}$. According to equation (1) indeed, the optimization program (20) 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 output and social welfare at the SPNE follow from the the optimal ESP and R&D efforts:

$$\tilde{q}^{*,nc} = \frac{2d(1+\beta)(3(1+\beta)+\gamma) + \gamma(3+\gamma)}{X} A \quad (27)$$

$$S\tilde{W}^{*,nc} = \frac{2d(4(1+\beta)^2 + \gamma(2\beta+1)) + 4\gamma + \gamma^2}{X} A^2 \quad (28)$$

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.

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:

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

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:

$$\tilde{\zeta}^c(\bar{e}) = \frac{(1+\beta)(A-4\bar{e})}{4(1+\beta)^2 + \gamma} \quad (30)$$

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 (30) from (22) yields:

$$\tilde{\zeta}^c(\bar{e}) - \tilde{\zeta}^{nc}(\bar{e}) = -\frac{((1+\beta)^2 - \beta\gamma)A + (1+4\beta)\gamma\bar{e}}{(4(1+\beta)^2 + \gamma)(3(1+\beta) + \gamma)} \quad (31)$$

Contrary to the usual results in the literature on R&D cooperation, we find that green R&D efforts in the non-cooperative scenario can be higher than those in the cooperative

scenario even when spillovers are high, provided the abatement technology is very efficient (γ is low). 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 (30)), the level of production per firm for a given emissions cap is:

$$\tilde{q}^c(\bar{e}) = \frac{(1 + \beta)^2 A + \gamma \bar{e}}{4(1 + \beta)^2 + \gamma} \quad (32)$$

In the same vein, the production differential between cooperation and non-cooperation under an ESP can be calculated by subtracting equation (23) from equation (32) for a given emission standard:

$$\tilde{q}^c(\bar{e}) - \tilde{q}^{nc}(\bar{e}) = (1 + \beta) \left(\tilde{\zeta}^c(\bar{e}) - \tilde{\zeta}^{nc}(\bar{e}) \right) = -(1 + \beta) \frac{((1 + \beta)^2 - \beta\gamma)A + (1 + 4\beta)\gamma\bar{e}}{(4(1 + \beta)^2 + \gamma)(3(1 + \beta) + \gamma)} \quad (33)$$

The first notable feature of this equation is the positive and linear relationship between the production and R&D differentials. When γ is low therefore, the fact that green R&D expenditure is lower when firms cooperate implies that levels of production are also lower (and conversely for larger values of γ). In addition though, the lower the degree of spillover is, the less cooperating firms account for the twofold effect of their R&D efforts on their rival's output. Recall that each firm's level of production affects its rival's profits through its own environmental constraint and its own profits through its rival's environmental constraint. This means that when γ is low the firms move closer to an R&D cartel the more spillovers decrease. (The cartel solution is reached when spillovers are zero.)¹² A direct and expected consequence is that the cooperative output can be lower than the non-cooperative one and the difference widens as spillovers decrease.

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 (30) and (32):

$$S\tilde{W}^c(\bar{e}) = 2 \left(A \left(\frac{(1 + \beta)^2 A + \gamma \bar{e}}{4(1 + \beta)^2 + \gamma} \right) - \left(\frac{(1 + \beta)^2 A + \gamma \bar{e}}{4(1 + \beta)^2 + \gamma} \right)^2 - \gamma \frac{((1 + \beta)(A - 4\bar{e}))^2}{2(4(1 + \beta)^2 + \gamma)} - d(\bar{e})^2 \right) \quad (34)$$

Formally, the regulator selects the optimal emission standard by maximizing equation (34) with respect to \bar{e} :

$$\bar{e}^{*,c} = \gamma \frac{(6(1 + \beta)^2 + \gamma)}{W} A, \quad (35)$$

¹²Under an ESP, the joint profit to be maximized, given by equation (29), 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 $\tilde{\zeta}_i$, 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 : $\frac{\partial \tilde{\pi}_i}{\partial \tilde{q}_i} + \frac{\partial \tilde{\pi}_j}{\partial \tilde{q}_i} = \gamma \tilde{\zeta}_i$

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

Inserting equation (35) into equations (30), (32) and (34) yields the levels of green R&D, production and social welfare at the SPNE:

$$\tilde{\zeta}^{*,c} = (1 + \beta) \frac{2d(4(1 + \beta)^2 + \gamma) - 2\gamma}{W} A \quad (36)$$

$$\tilde{q}^{*,c} = \frac{2d(1 + \beta)^2(4(1 + \beta)^2 + \gamma) + \gamma(4(1 + \beta)^2 + \gamma)}{W} A \quad (37)$$

$$S\tilde{W}^{*,c} = \frac{2d(1 + \beta)^2(6(1 + \beta)^2 + \gamma) + 6(1 + \beta)^2\gamma + \gamma^2}{W} A^2 \quad (38)$$

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. We first investigate the conditions under which R&D cooperation allows for more ambitious environmental goals, despite R&D investments not being the driving force, as stated in the following Lemma:

Lemma 4. *Under an optimal ESP,*

1. for $\beta \geq 0.5$,

$$\tilde{e}^{*,c} < \tilde{e}^{*,nc}, \forall d \geq 1, \gamma > 0$$

2. for $\beta < 0.5$,

•

$$\tilde{e}^{*,c} < \tilde{e}^{*,nc} \text{ if } \begin{cases} d \leq \tilde{d}_e, \\ d > \tilde{d}_e \end{cases} \text{ and } \gamma < \tilde{\gamma}_e^-$$

• $\tilde{e}^{*,c} > \tilde{e}^{*,nc}$, otherwise, that is for $d > \tilde{d}_e$ and $\gamma > \tilde{\gamma}_e^-$, with,

$\tilde{\gamma}_e^\pm$ and \tilde{d}_e provided in Appendix D.

Proof. See Appendix D. □

Lemma 4 highlights the channels through which the environmental policy affects firms' choices. The ranking in Lemma 4 is similar to the one in Lemma 2. When β is large enough, green R&D expenditure is higher in the cooperative scenario – as likewise it is under an ETP – and so is production. The regulator is therefore inclined to enforce a tighter emission standard to reduce production-induced pollution. The mechanisms differ from those under an ETP in the sense that environmental regulations are more stringent when firms cooperate under the optimal ESP but are looser in the case of an ETP because firms invest more in green R&D (see Lemma 1). When β and/or γ are low, cooperating firms are more likely to behave as a cartel, reducing their levels of production and their green R&D investments. Consumer surplus decreases but this can be offset by the decrease in pollution: the cap on emissions set by the regulator is lower than in the non-cooperative scenario. The results are illustrated in Figure 2.

The following lemma provides broad insights into the ranking of economic outputs in the cooperative and non-cooperative scenario under an optimal ESP.

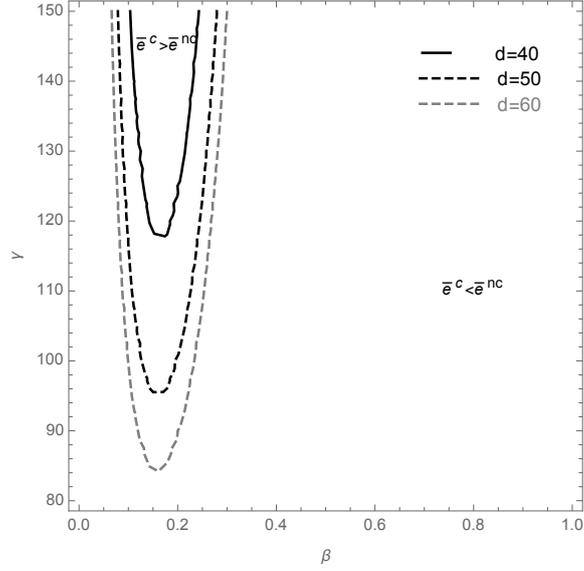


Figure 2: Comparison of emissions under an optimal ESP.

Lemma 5. *Under the optimal ESP and for certain levels of spillover and R&D efficiency:*

- $\tilde{\zeta}^{*,c} > \tilde{\zeta}^{*,nc}$, $\tilde{q}^{*,c} > \tilde{q}^{*,nc}$ and $S\tilde{W}^{*,c} > S\tilde{W}^{*,nc}$ (Region A);
- $\tilde{\zeta}^{*,c} < \tilde{\zeta}^{*,nc}$, $\tilde{q}^{*,c} < \tilde{q}^{*,nc}$ and $S\tilde{W}^{*,c} < S\tilde{W}^{*,nc}$ (Region B);

Proof. See Figure 3. □

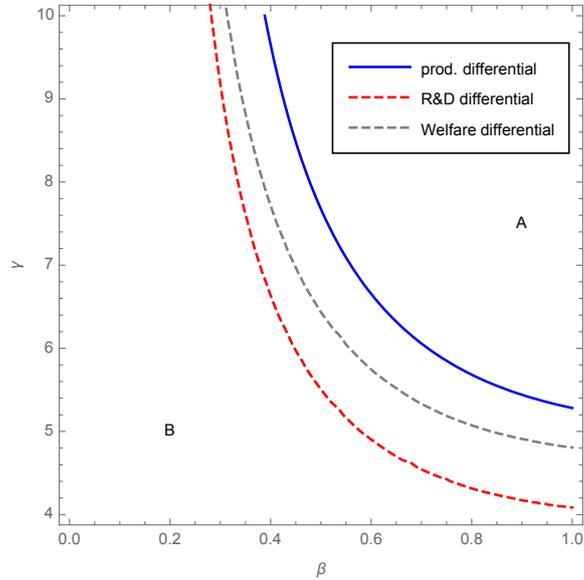


Figure 3: Comparisons under an optimal ESP.

For certain ranges of β and γ therefore, cooperation in green R&D outperforms non-cooperation.

In line with the literature on R&D cooperation, firms benefit from investing in cooperative R&D as spillovers increase. But under an ESP and high spillovers, the ranking of the two scenarios depends crucially on the efficiency of green R&D (see equation (31)): when R&D is inefficient (γ is high), the incentive for firms to invest in cooperative R&D increases, pushing up levels of production and making environmental regulations stricter (see Lemma 4). Welfare is then higher in the cooperative scenario (Region A). Region A expands as the pollution becomes more damaging. However, when green R&D is efficient (low γ), firms have a greater interest in investing non-cooperatively and cooperative R&D efforts becomes weaker, even when spillovers are high.

At low spillover levels, to circumvent the environmental constraint in the cooperative scenario, firms choose to produce less rather than invest in R&D regardless of the efficiency of the green technology. The decrease in production is offset by an increase in prices, which has a negative effect on consumer surplus. As a consequence, social welfare is lower in the cooperative scenario (Region B).

5 ETP versus ESP

In this section, we compare the two environmental policy instruments when firms cooperate in R&D and when they do not. In particular, building on the above analysis, we rank emission and welfare levels to separately consider environmental and welfare objectives. Accordingly, let us first establish the similarity of the two policy instruments when firms do not cooperate.

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 E. □

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 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:

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

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. Then, we can state that:

Proposition 2. *In the cooperative R&D scenario, the two instruments, the emission tax and the emission standard, are not equivalent:*

$\forall \beta \in (0, 1], d \geq 1, \gamma > 0,$

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

Proof. See Appendix F. □

Proposition 2 shows that when firms cooperate in green R&D, an optimal ETP outperforms an optimal ESP except in terms of the environment. Under an optimal ETP, green innovation is always boosted, which is not the case under an optimal ESP. Indeed, for a given level of polluting emissions, it is clear that cooperative R&D investments under an ETP are higher than under an ESP (the difference between equations (15) and (30) is always positive). Moreover, the production differential between ETP and ESP is linear and increases with the difference in R&D efforts, which implies that the consumer surplus is larger under an ETP. At the equilibrium of the game, this positive relationship is reinforced by the positive and linear effect of the difference in polluting emissions, since $e^{*,c} - \tilde{e}^{*,c} > 0$ (see equation (1)). Finally, R&D cooperation under an ETP is always more efficient in terms of consumer surplus than R&D non-cooperation and than R&D cooperation under an ESP.

The two environmental policy instruments therefore 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. As a result, when firms coordinate their green R&D efforts, this amounts to their choosing levels of production that maximize the sum of profits. Since each firm accounts for the positive impact of its R&D expenditure on the other's

production, and if $\beta > 0.5$ (provided γ is high), this stimulates green innovation (and therefore boosts production). However, this internalization of spillovers by cooperation in R&D still leaves consumer surplus lower than under an ETP with R&D cooperation. When $\beta < 0.5$ moreover, both production and R&D investment are lower under an optimal ESP, further reducing consumer surplus. Although polluting emissions are lower under an optimal ESP, social welfare is higher under an optimal ETP.

Our results highlight the differences between the two instruments when firms cooperate in green R&D. Although an optimal ETP under R&D cooperation is economically more efficient, an optimal ESP is better for the environment. Under an optimal ESP, firms that cooperate in R&D emit less than they would under an optimal ETP, mainly because they produce less. Nevertheless, since the optimal welfare differential is a linear and positive function of the equilibrium emission differential, social welfare is higher under an ETP than under an ESP at the equilibrium of the game. The regulator should choose an ESP if its main preoccupation is the environment and an ETP if it is mainly concerned with the economy.

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 when spillovers are high. Under an ESP, R&D competition performs better than R&D cooperation at high spillover levels when abatement technologies are sufficiently efficient. Second, our results provide interesting insights for environmental policy recommendations. Governments prioritizing economic criteria (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. But from an environmental point of view, R&D cooperation under an ESP is always preferable. Governments focusing on the environment should adopt an ESP and promote cooperative R&D.

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 pre-commit to environmental regulations, the outcome is the same regardless of the policy instrument adopted; however, if governments do not commit, the two environmental policy instruments perform differently. The outcomes of our model depend on the choice of instrument when firms cooperate in R&D even if the government credibly commits to its environmental policy. It would be worthwhile to compare the effects of the two instruments when the 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, i.e. that an emission tax is still preferable for the economy and an emission standard is still better for the environment. Finally, our setup and results pave the way for future studies, for instance by introducing another instrument such as an R&D subsidy, which could be Pareto improving, especially in the case of an ESP.

Appendices

A Proof of Lemma 1

Subtracting equation (18) from (11), the difference between the optimal environmental taxes can be expressed as:

$$\tau^{*,nc} - \tau^{*,c} = \frac{3\beta\gamma(A_2d^2 + A_1d + A_0)}{X.Y}A, \quad (\text{A.1})$$

with the following coefficients:

$$A_2 = 4(1 + \beta)(3(1 + \beta) + \gamma)(3(1 + \beta)^2 + \gamma) > 0,$$

$$A_1 = 2\gamma(3(1 + \beta)^2(1 - \beta) + \gamma(2 - \beta)) > 0,$$

$$A_0 = -3\gamma^2(2 + \beta) < 0.$$

Since the denominator of equation (A.1) is always positive:

$$\text{sign}\{\tau^{*,nc} - \tau^{*,c}\} = \text{sign}\{A_2d^2 + A_1d + A_0\}, \quad (\text{A.2})$$

The second degree polynomial in d is positive (negative) outside (inside) the interval defined by the following roots:

$$d^\pm = \frac{-A_1 \pm \sqrt{A_1^2 - 4A_2A_0}}{2A_2}, \quad (\text{A.3})$$

with $d^- < 0 < d^+$. In addition, we have $d^+ < 1$ iff

$$-A_0 < A_2 + A_1 \Leftrightarrow 4(1 + \beta)(3(1 + \beta) + \gamma)(3(1 + \beta)^2) + \gamma(3(1 + \beta)^2(1 - \beta) + \gamma(2 - \beta)) > 0$$

which implies that $(\tau_{nc}^* - \tau_c^*)$ is always positive for $d \geq 1$. Moreover, it is easy to check that $d_1 < d^+$. We then have $d^- < 0 < d_2 < d_1 < d^+ < 1$. The two optimal levels of green R&D efforts can be compared in a similar manner. Inserting equation (11) into (6) and equation (18) into (13) yields the sign of the difference between the two equilibrium levels of R&D.¹³ Notice that it depends on the sign of the numerator, which is also a second degree polynomial in d :

$$\text{sign}\{\zeta^{*,c} - \zeta^{*,nc}\} = \text{sign}\{(B_2d^2 + B_1d + B_0)\}, \quad (\text{A.4})$$

with the following coefficients:

$$B_2 = 4(3(1 + \beta) + \gamma)(3(1 + \beta)^2 + \gamma) > 0,$$

$$B_1 = 2[3(1 + \beta)^2(3(1 + \beta)^2 + \gamma) + \gamma(3\beta(1 + \beta) + \gamma)] > 0,$$

$$B_0 = -\gamma(2\gamma - 9(1 + \beta)).$$

Let us define $\hat{\gamma} = \frac{9(1+\beta)}{2}$ such that for $\gamma \leq \hat{\gamma}$, B_0 is positive, and negative otherwise. Then, for $\gamma \leq \hat{\gamma}$, the $\text{sign}\{(B_2d^2 + B_1d + B_0)\}$ is always positive. When, $\gamma > \hat{\gamma}$, B_0 is negative and the polynomial given by equation (A.4) is positive (negative) outside (inside) the interval defined by the following roots:

$$d_\zeta^\pm = \frac{-B_1 \pm \sqrt{B_1^2 - 4B_2B_0}}{2B_2}, \quad (\text{A.5})$$

with $d_\zeta^+ < d_1$. Since B_2 is positive, this means that R&D efforts when firms cooperate are larger provided $d > 1$. Therefore, $\zeta^{*,c} > \zeta^{*,nc}$ for all values of γ .

¹³See Table 1 in Appendix G for the equilibrium levels of R&D.

B Proof of Lemma 2

Emission levels at the equilibrium can be compared by substituting equation (11) into (7) and equation (18) into (14):¹⁴

$$e^{*,nc} - e^{*,c} = \frac{A\beta\gamma(C_2\gamma^2 + C_1\gamma + C_0)}{XY} \quad (\text{B.6})$$

with the following coefficients:

$$C_2 = (\beta + (4\beta - 2)d + 4),$$

$$C_1 = 9(\beta + 1)^2(2\beta d + 1) > 0,$$

$$C_0 = 18(\beta + 1)^4 d > 0.$$

Since the denominator of equation (B.6) is always positive:

$$\text{sign}\{e^{*,nc} - e^{*,c}\} = \text{sign}\{C_2\gamma^2 + C_1\gamma + C_0\}, \quad (\text{B.7})$$

It is clear that C_2 is positive for $\beta \geq 1/2$. Then, $e^{*,nc} - e^{*,c} > 0$. When $\beta < 1/2$, then, this depends on the sign of C_2 . We show that C_2 is positive if the following condition is satisfied; otherwise it is negative.

$$4 + \beta + d(4\beta - 2) > 0 \Leftrightarrow d \leq \frac{4 + \beta}{-(4\beta - 2)} \equiv d_e \quad (\text{B.8})$$

Notice that $d_e \in [2, +\infty)$ —and thus $d_e > 1$ —for all $\beta \in [0, 1/2)$. Therefore, for $d \leq d_e$ and $\beta < 1/2$, $C_2 > 0$ and $e^{*,nc} - e^{*,c} > 0$. For $d > d_e$, $C_2 < 0$ and the second degree polynomial in d is positive inside the interval defined by the following roots:

$$\gamma_e^\pm = \frac{-C_1 \pm \sqrt{C_1^2 - 4C_2C_0}}{2C_2}, \quad (\text{B.9})$$

Since $C_2 < 0$, if $\gamma < \gamma_e^-$, then $\beta < 1/2$ and $d > d_e$, $e^{*,nc} - e^{*,c} > 0$. On the contrary, if $\gamma > \gamma_e^-$, $\beta < 1/2$ and $d > d_e$, $e^{*,nc} - e^{*,c} < 0$.

C Proof of Lemma 3

Using equations (19) and (12), the difference between the SPNE levels of social welfare can be written as follows:

$$SW^{*,c} - SW^{*,nc} = \frac{\beta\gamma(F_2d^2 + F_1d + F_0)}{X.Y} A^2 \quad (\text{C.10})$$

with the following coefficients:

$$F_2 = 4(6 + 24\beta + 36\beta^2 + 24\beta^3 + 6\beta^4 + 2\gamma + 8\beta\gamma + 10\beta^2\gamma + 4\beta^3\gamma + \beta\gamma^2) > 0,$$

$$F_1 = 2\gamma(4 + 2\gamma + 7\beta + \beta^2(2 - \beta)) > 0$$

$$F_0 = -\gamma^2(2 + \beta) < 0$$

Since the denominator of equation (C.10) is positive:

$$\text{sign}\{SW^{*,nc} - SW^{*,c}\} = \text{sign}\{F_2\gamma^2 + F_1\gamma + F_0\}, \quad (\text{C.11})$$

¹⁴See Table 1 in Appendix G for the equilibrium emission levels.

For $F_2 > 0$, the second degree polynomial in d is positive outside the interval defined by the following roots:

$$d_{SW}^{\pm} = \frac{-F_1 \pm \sqrt{F_1^2 - 4F_2F_0}}{2F_2} \quad (\text{C.12})$$

Since only $d_{SW}^+ > 0$ and $d_{SW}^+ < 1$, for $d \geq 1$, $SW_c^* - SW_{nc}^*$ is always positive.

D Proof of Lemma 4

Using equations (25) and (35), the difference between optimal emission standards is given by the following expression:

$$\tilde{e}^{*,nc} - \tilde{e}^{*,c} = \frac{A\gamma}{XW} [G_2\gamma^2 + G_1\gamma + G_0] \quad (\text{D.13})$$

with the following coefficients:

$$\begin{aligned} G_2 &= (2\beta(2\beta(d+1) - d + 5) + 3), \\ G_1 &= 2(1+\beta)^2(8\beta + (4\beta(4\beta+1) + 3)d + 5) > 0 \\ G_0 &= 4(8\beta+5)(1+\beta)^4d > 0 \end{aligned}$$

Since the denominator of equation (D.13) is positive:

$$\text{sign}\{\tilde{e}^{*,nc} - \tilde{e}^{*,c}\} = \text{sign}\{G_2\gamma^2 + G_1\gamma + G_0\}, \quad (\text{D.14})$$

We show that G_2 is positive if the following condition is satisfied; otherwise, it is negative:

$$2d\beta(2\beta-1) + 4\beta^2 + 10\beta + 3 \geq 0 \Leftrightarrow d \leq \frac{4\beta^2 + 10\beta + 3}{-2\beta(2\beta-1)} \equiv \tilde{d}_e \quad (\text{D.15})$$

A quick look at equation (D.15) shows that it is satisfied for $\beta \geq 1/2$ and $\tilde{e}^{*,nc} - \tilde{e}^{*,c} > 0$. For $\beta < 1/2$, $G_2 \geq 0$ if $d \leq \tilde{d}_e$ and thus $\tilde{e}^{*,nc} - \tilde{e}^{*,c} > 0$. If $\beta < 1/2$, $G_2 < 0$ if $d > \tilde{d}_e$, then the sign of the second degree polynomial in γ has to be investigated. Since $G_2 < 0$, the polynomial is positive in the interval defined by the following roots:

$$\tilde{\gamma}_e^{\pm} = \frac{-G_1 \pm \sqrt{G_1^2 - 4G_2G_0}}{2G_2}, \quad (\text{D.16})$$

Since $G_2 < 0$, if $\gamma < \tilde{\gamma}_e^-$, then $\beta < 1/2$, $d > \tilde{d}_e$, and $\tilde{e}^{*,nc} - \tilde{e}^{*,c} > 0$. On the contrary, if $\gamma > \tilde{\gamma}_e^-$, $\beta < 1/2$, $d > \tilde{d}_e$ and $\tilde{e}^{*,nc} - \tilde{e}^{*,c} < 0$.

E Proof of Proposition 1

The proof can be sketched out as follows. First, we show that the social welfare functions(10) and (24) 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),

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

and using Equation (24),

$$\begin{cases} \frac{\partial \tilde{S}W^{nc}(\bar{e}(\tau))}{\partial \tau} = \frac{\partial \tilde{S}W^{nc}(\bar{e}(\tau))}{\partial e} \cdot \frac{\partial e}{\partial \tau} = \frac{2}{9\gamma^2} (\gamma A(2d(3(1+\beta) + \gamma) - \gamma) - \tau(2d(3(1+\beta) + \gamma)^2 + \gamma(9 + 2\gamma))) \\ \text{cst}(\tilde{S}W^{nc}(e(0))) = \frac{2(2-d)}{9} A^2 \end{cases}$$

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

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

F Proof of Proposition 2

From Table 1, the difference in emission levels between the two policy instruments when firms cooperate in R&D is given by the following expression:

$$e^{*,c} - \tilde{e}^{*,c} = \frac{A\gamma}{YW} (1+\beta)^2 (2d(1+\beta)^2 + \gamma) (10(1+\beta)^2 + 3\gamma) > 0$$

The difference between $\zeta^{*,c}$ and $\tilde{\zeta}^{*,c}$ is given by

$$\zeta^{*,c} - \tilde{\zeta}^{*,c} = \frac{A\gamma(1+\beta)}{YW} (2d(1+\beta)^2 + \gamma) (12d(1+\beta)^4 + (1+7d)(1+\beta)^2\gamma + (1+d)\gamma^2) > 0$$

In addition, from equation (1), the difference between $q^{*,c}$ and $\tilde{q}^{*,c}$ is

$$q^{*,c} - \tilde{q}^{*,c} = (e^{*,c} - \tilde{e}^{*,c}) + (1+\beta)(\zeta^{*,c} - \tilde{\zeta}^{*,c}) > 0$$

We deduce that:

$$CS^{*,c} - \tilde{C}S^{*,c} = \frac{1}{2} ((2q^{*,c})^2 - (2\tilde{q}^{*,c})^2) > 0$$

and

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

G Table 1: Perfect Nash Equilibrium outputs

	Emission Tax Policy		Emission Standard Policy	
	Non-cooperative R&D	Cooperative R&D	Non-cooperative R&D	Cooperative R&D
τ / \bar{e}	$\frac{\gamma \frac{2d(3(1+\beta)+\gamma)-\gamma}{X} A}{2d(1+\beta)(3(1+\beta)+\gamma)+\gamma(3+\gamma)} A$	$\frac{\gamma \frac{2d(3(1+\beta)^2+\gamma)-\gamma}{Y} A}{2d(1+\beta)^2(3(1+\beta)^2+\gamma)+\gamma(3(1+\beta)^2+\gamma)} A$	$\frac{\gamma \frac{4+\beta+\gamma}{X} A}{2d(1+\beta)(3(1+\beta)+\gamma)+\gamma(3+\gamma)} A$	$\frac{\gamma \frac{(6(1+\beta)^2+\gamma)}{W} A}{2d(1+\beta)^2(4(1+\beta)^2+\gamma)+\gamma(4(1+\beta)^2+\gamma)} A$
q	$\frac{2d(1+\beta)(3(1+\beta)+\gamma)+\gamma(3+\gamma)}{X} A$	$\frac{2d(1+\beta)^2(3(1+\beta)^2+\gamma)+\gamma(3(1+\beta)^2+\gamma)}{Y} A$	$\frac{2d(1+\beta)(3(1+\beta)+\gamma)+\gamma(3+\gamma)}{X} A$	$\frac{2d(1+\beta)^2(4(1+\beta)^2+\gamma)+\gamma(4(1+\beta)^2+\gamma)}{W} A$
ζ	$\frac{2d(3(1+\beta)+\gamma)-\gamma}{X} A$	$(1+\beta) \frac{2d(3(1+\beta)^2+\gamma)-\gamma}{Y} A$	$\frac{2d(3(1+\beta)+\gamma)-\gamma}{X} A$	$(1+\beta) \frac{2d(4(1+\beta)^2+\gamma)-2\gamma}{W} A$
E	$2\gamma \frac{4+\beta+\gamma}{X} A$	$2\gamma \frac{4(1+\beta)^2+\gamma}{Y} A$	$2\gamma \frac{4+\beta+\gamma}{X} A$	$2\gamma \frac{(6(1+\beta)^2+\gamma)}{W} A$
SW	$\frac{2d(4(1+\beta)^2+\gamma(2\beta+1))+4\gamma+\gamma^2}{X} A^2$	$\frac{2d(1+\beta)^2(4(1+\beta)^2+\gamma)+4\gamma(1+\beta)^2+\gamma^2}{Y} A^2$	$\frac{2d(4(1+\beta)^2+\gamma(2\beta+1))+4\gamma+\gamma^2}{X} A^2$	$\frac{2d(1+\beta)^2(6(1+\beta)^2+\gamma)+6\gamma(1+\beta)^2+\gamma^2}{W} A^2$

Table 1: Perfect Nash Equilibrium outputs under either ETP or ESP and $h = nc, c$.
 $A = (a-c)$, $X = 2d(3(1+\beta)+\gamma)^2+\gamma(9+2\gamma)$, $Y = 2d(3(1+\beta)^2+\gamma)^2+\gamma(9(1+\beta)^2+2\gamma)$, $W = 2d(4(1+\beta)^2+\gamma)^2+2\gamma(8(1+\beta)^2+\gamma)$

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