Cooperation in green R&D and Environmental Policies: Tax or Standard*

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March 14, 2024

Abstract

In this article, we compare a tax and a standard as environmental tools depending on firms' R&D strategy and the government's ability to credibly commit to its policy. We consider a duopoly model where production is polluting and in an effort to mitigate emissions, firms invest in green R&D (in the presence of technological spillovers) either cooperatively or non-cooperatively. We explore two policy games in which the regulator establishes an emission tax or an emission standard either before or after firms engage in R&D. We endogenize both the firms' R&D strategy and the regulator's choice of policy instrument. We find that an emission standard is adopted only when firms choose not to cooperate. Conversely, a tax is desirable when firms collaborate in green R&D. Moreover, we expand our framework by offering the opportunity for the regulator to authorize or ban cooperation in green R&D before the firms make their strategic decisions.

Keywords: R&D Cooperation, Spillovers, Taxes, Standards, Cournot competition, Policy games, Competition policy.
Code JEL: L13, 032, P48, Q55.

1 Introduction

Over the past 20 years or so, political initiatives have been undertaken in many OECD countries to encourage R&D spending through binding environmental policies. Faced with these new environmental constraints, firms have organized themselves around joint R&D projects aimed at reducing their environmental impact, facilitated by professional associations, such as the Research Association of Refinery Integration for Group-Operation (RING) in Japan, the Electric Power Research Institute (EPRI) in the United

*We thanks two anonymous referees for their helpful comments and all the participants to the EAERE 2022, ASSET 2022 conferences and the EC-FIN EU Economics seminar.

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States, or the Canada's Oil Sands Innovation Alliance (COSIA). However, while these cooperative green R&D endeavors might hold promise for environmental improvements, they may also raise concerns regarding consumer protection. Specifically, it prompts us to consider whether a well-designed competition policy that encourages horizontal agreements could contribute to achieving environmental objectives.

In this article, we investigate from a theoretical point of view, how the cooperative or non-cooperative nature of environmental R&D may affect the effectiveness of environmental policies, depending on the chosen instrument and the government's ability to commit to its policy *ex-ante*. We also emphasize implications not only for environmental policy but also for the regulatory decision of whether public authorities should allow horizontal R&D agreements in the context of pollution abatement.

As described by Requate (2005), pollution can be limited by command and control or market-based instruments. Command and control instruments, which are 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 (2005), p.178). This article focuses on two widely used policy instruments: i) an emission standard, and ii) an emission tax. In the presence of these binding environmental policies, firms decide how much to invest in green R&D on end-of-pipe technologies, either to minimize the costs associated with the tax or to ensure compliance with the specified cap in the case of an emission standard. Our research focuses on "end-of-pipe" technologies, designed to eliminate contaminants already present in streams of air, water, waste, etc.. These technologies are typically implemented at the final stage of a process, just before the stream is disposed of or delivered. Real-life examples of such end-of-pipe technologies abound including scrubbers on smokestacks, water treatment plants, and catalytic converters on automobile tailpipes that reduce emissions of pollutants after they have formed.

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 or Article 101-3 of the TFEU) 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 specific 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

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

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), 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 article, we examine the impact of cooperation in green R&D on the effectiveness of environmental policies, depending on whether the instrument is a emission tax or an emission standard.

Another relevant dimension that should be taken into account when comparing standards and taxes, given whether firms collaborate or not in R&D, is the government's ability to enforce its policy. This issue of enforcement has been widely studied in the literature. First, uncertainty about the importance of environmental issues for future governments may limit regulators' commitment to enforcing present policies (Ulph and Ulph, 2013). Second, firms may strategically use innovation to lower regulatory constraints and increase profits (Gersbach and Glazer, 1999). Third, firms may not necessarily have the same innovation agenda as regulators and may pressure them to delay regulation. These reasons all affect the regulator's ability to commit to its policy, as evidenced by several examples: Strict automobile emission standards introduced under the 1970 Clean Air Act Amendments, also known as the "Muskie Law", were delayed due to vigorous opposition from the American automobile industry, arguing that their implementation would be economically detrimental and technically unfeasible. Similarly, the European Union's Industrial Emissions Directive (IED), aimed at regulating industrial emissions to reduce air pollution, has been repeatedly delayed due to pressures from various industries, including those in the chemical, metallurgical, and energy sectors. European companies have argued that implementing the proposed standards would result in high costs and harm their competitiveness in the globalized market.[2] To address the inherent challenges in the temporal implementation of environmental policies, we therefore examine two specific policy game timings: i) the policy game (referred to as the *precommitment* policy game) where regulator adopts its environmental policy before firms choose their R&D investments; ii) the policy game (referred to as the *time-consistent* policy game) where the firms choose their R&D efforts before the regulator chooses which policy instrument to use.

The question we address in this article is ambitious as it relates both the choice of the most appropriate environmental policy instrument by the government and the organization of R&D by firms, according to the timing of policy games. We do not compare the effectiveness of R&D cooperation versus non-cooperation, nor do we compare the performance of the two policy games. Previous studies (mentioned in Table 1) have examined green R&D agreements, but only when the environmental policy instrument is a tax, by comparing cooperative and non-cooperative R&D strategies. It emerges that

[2] Additional cases in the automobile and nuclear industries are discussed in the works of Petrakis and Xepapadeas (2001), Puller (2006), Moner-Colonques and Rubio (2016), and Ouchida and Goto (2022).

the performance of R&D cooperation depends on the timing of the policy game and model parameters, notably R&D efficiency. Other studies go further by comparing the outcomes of different policy games, but still only considering the environmental tax.[3] The only contribution related to environmental standards is that of Moner-Colonques and Rubio (2015, 2016).The authors compare the tax and the standard in both policy games, but without consideration for green R&D cooperation.

In our article, we explore different scenarios along three dimensions: i) the nature of the instrument (a standard or a tax); ii) the firms' R&D strategy (cooperation or non-cooperation); and iii) the timing of the policy game (precommitment vs. time-consistent). Based on the equilibrium outcomes obtained for each scenario, we compare the performance of the two environmental policies. Table 1 offers an overview of the literature on the three dimensions mentioned above. Our contribution complements these studies since the combination of R&D cooperation and an environmental standard has never been studied. Therefore, evaluating the performance of a standard and a tax in the context of cooperative and non-cooperative R&D allows us to shed new light on the choice of the environmental policy instrument. More broadly, these findings pave the way for an examination of endogenous decisions on the conduct of R&D and on the selection of environmental policy tools. Lastly, we expand our framework by considering the effects of the regulator authorizing or banning cooperation in green R&D before the firms make their strategic decisions.

We present a theoretical model of a multi-stage game. In both policy games, in stage 0, firms decide whether to cooperate or not in R&D (sign a green R&D agreement or not). In a first step, we assume that cooperation is allowed. In a second step, we consider a pre-stage game where the regulator chooses to ban or authorize cooperation before firms decide on their R&D organization. In stage 1 of the precommitment game, the regulator leads and optimally sets the level of the emission standard or the emission tax rate. Then, in stage 2, the firms (followers) invest cooperatively or non-cooperatively in green R&D before competing in quantities (in stage 3). Notice that if the regulator chooses to set an optimal emission standard, production levels depend on the equilibrium levels of (cooperative or non-cooperative) R&D: direct competition in quantities vanishes. In stage 1 of the time-consistent game, firms lead and optimally set their green R&D efforts. Then in stage 2, the regulator, as the follower, chooses the policy instrument and its stringency. Finally, in the last stage, the firms compete in quantities. Hence, depending on three relevant model parameters, namely the levels of spillover, environmental damage and R&D efficiency, we investigate the relative environmental and economic performances of the two policy instruments depending on the firms' R&D strategy. Finally, we solve both games backward and determine the Subgame Perfect Nash Equilibrium (SPNE). In contrast with previous studies, the decisions of firms and authorities are not exogenously given and may emerge as the equilibrium of the multi-stage game.

We can then provide a comprehensive analysis of the endogenous choice of the regu-

[3]Recent literature examines the effects of cooperative and non-cooperative green R&D strategies in a context where firms can invest in CSR activities but primarily focused on the tax (Hirose et al., 2020; Xing and Lee, 2023). The temporal dimension of the policy game is also addressed in this literature.

R&D strategy			
		Non-cooperation	Cooperation
Green policy tool	Tax	• Lambertini et al. (2017) *[PC*]* • Petrakis and Xepapadeas (1999, 2001) *[PC vs TC]* • Poyago-Theotoky and Teerasuwannajak (2002) *[PC vs TC]* • Montero (2011)*[TC]* • Moner-Colonques and Rubio (2015, 2016) *[PC vs TC]*	• Chiou and Hu (2001) • McDonald and Poyago-Theotoky (2017) *[PC]* • Ouchida and Goto (2016a,b) *[PC]* and *[TC]* • Ouchida and Goto (2022) *[PC vs TC]* • Poyago-Theotoky (2007) *[TC]*
	Standard	• Moner-Colonques and Rubio (2015, 2016)*[PC vs TC]*	

*: PC, precommitment; TC, time-consistent.

Table 1: Literature review.

latory authority in term of environmental policy (standard or tax) as well as competition policy (permission or prohibition of R&D cooperation among competing firms). We obtain two clear-cut results. The first result concerns the choice of the instrument by the regulator: The environmental tax emerges as the only equilibrium choice when firms initiate a green R&D coordination strategy; Conversely, the environmental standard is adopted only for a non-cooperative organization of R&D. This result holds regardless of the regulator's ability to commit over time to its environmental policy. The second result concerns the regulator's intervention in permitting or prohibiting R&D cooperation. While no regulation is necessary when the government can commit to its environmental policy, this is no longer true in the time-consistent policy game: It is up to the regulator to prohibit R&D cooperation for sufficiently efficient R&D.

The remainder of the paper is organized as follows. Section 2 describes the model. Sections 3 and 4 respectively present the equilibrium results of the precommitment and time-consistent policy games. Section 5 compares the economic performance of taxes and standards as environmental policies. In Section 6, we solve the SPNE of both games and extend the benchmark model. Section 7 then 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 linear function $p(Q) = a - Q$, where $Q = q_i + q_j$ is the total amount of production (with $i \neq j$) and $a(> 0)$ is a measure of market size.

The production process in both firms is environmentally degrading: each unit of output generates exactly one unit of polluting emissions. However, the firms can reduce their emissions by investing in green R&D, z_i. Moreover, we assume that there are green R&D spillovers such that both firms benefit from their rival's pollution mitigation efforts in an exogenous proportion $\beta \in (0, 1]$, at no cost.[4] Accordingly, firm i's net emissions after R&D investment can be expressed as:

$$e_i = e(q_i, z_i) = q_i - z_i - \beta z_j \tag{1}$$

Firm i's cost function is additively separable and given by $C(q_i, z_i) = cq_i + \frac{\gamma}{2} z_i^2$, where c is the constant marginal cost of production ($c > 0$, $A \equiv a - c > 0$) and the R&D cost function is quadratic, leading to diminishing returns on R&D investments. In this context, $\gamma > 0$ is usually interpreted as a measure of R&D efficiency, with firms having to spend $\frac{\gamma}{2} z_i^2$ to reduce their emissions by z_i.

Given the firms' net emissions, the total level of emissions is $E = \sum_i^j e(q_i, z_i)$, and the level of environmental damage is $D(E)$. As usual in the literature, the damage function is assumed to be quadratic, with $d > 1$ being the slope of the marginal environmental damage curve, *i.e.* the severity of the damage, $D(E) = \frac{d}{2} E^2$. [5]

To protect the environment, the government either implements an emission standard or a per unit tax on emissions. In what follows, we also investigate the effectiveness of these two environmental policy tools depending on the firms' green R&D strategy: non-cooperation ($h = nc$) or cooperation ($h = c$). We assume that competing firms are allowed to cooperate in R&D provided this is authorized by the regulator before the start of the game. This assumption is relaxed in Section 6.2.

- *When the regulator implements an Emission Standard Policy (ESP)*, in the absence of green R&D, firm i's production level (*i.e.* its level of polluting emissions) is limited by the emission standard $\bar{e}_i$: $q_i = e_i \leq \bar{e}_i$, $\forall i, j$. Firms can produce more, $q_i > \bar{e}_i$, $\forall i, j$, provided they invest in R&D, but their net emissions must satisfy the following constraint: $\bar{e}_i = \bar{q}_i - \bar{z}_i - \beta \bar{z}_j$, $\forall i, j$.[6] Therefore, once the cap on emissions is set by the regulator and the firms set their R&D efforts, per-firm outputs are governed by the following constraint: $\bar{q}_i = \bar{e}_i + \bar{z}_i + \beta \bar{z}_j$, $\forall i, j$. Because the firms are identical and the goods produced are homogeneous, we assume the

[4] In our approach, based on AJ's (1988), spillovers occur in abatement technologies and firms can freeride off their competitors' abatement efforts (*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. They suggest AJ's model (1988) *"..is more suitable for modelling green technologies."*.

[5] In their analyses of an emission tax, Lambertini et al. (2017) and Ouchida and Goto (2016a, 2022) set a less restrictive threshold value for d of between 0.5 and 1. However, for our analysis of an emission standard in the time-consistent policy game, $d > 1$ is required to ensure strictly positive R&D efforts. See Section 4 below.

[6] All variables under an ESP are denoted by superscript $\bar{x}$.

same emission standard applies to both firms $\bar{e} = \bar{e}_i = \bar{e}_j$.[7] When the firms do not cooperate in R&D ($h = nc$), the profit maximization program $\mathcal{P}_1$ is, $\forall i, j$:

$$\mathcal{P}_1 \begin{cases} \max_{\bar{z}_i} & \bar{\pi}_i = & (A - \bar{Q})\bar{q}_i - \frac{\gamma}{2}\bar{z}_i^2 \\ \text{s.t.} & \bar{q}_i = & \bar{e} + \bar{z}_i + \beta \bar{z}_j \end{cases}$$

Alternatively, when the firms cooperate in R&D ($h = c$), they choose the level of green R&D that maximizes their joint profit under the two individual constraints defined by the emission standard.[8] The program for the firms i, j is now:

$$\mathcal{P}_2 \begin{cases} \max_{\bar{z}_i} & \sum \bar{\pi}_i = & (A - \bar{Q})(\bar{q}_i + \bar{q}_j) - \frac{\gamma}{2}\bar{z}_i^2 - \frac{\gamma}{2}\bar{z}_j^2 \\ \text{s.t.} & \bar{q}_i = & \bar{e} + \bar{z}_i + \beta \bar{z}_j \\ & \bar{q}_j = & \bar{e} + \bar{z}_j + \beta \bar{z}_i \end{cases}$$

- *When the regulator adopts an Emission Tax Policy (ETP)*, the cap on emissions is replaced by a per unit tax on production (τq_i, with the emission tax $\tau > 0$) if they do not invest in green R&D. If they invest in green R&D on the other hand, the tax is applied on net emissions only. Therefore, they separately choose their levels of green R&D and production to maximize profits under the constraint given by equation (1). In the non-cooperative scenario ($h = nc$), the profit maximization program is, $\forall i, j$:

$$\mathcal{P}_3 \begin{cases} \max_{z_i} & \pi_i = & (A - Q)q_i - \frac{\gamma}{2}z_i^2 - \tau e_i \\ \text{s.t.} & e_i = & q_i - z_i - \beta z_j \end{cases}$$

  Alternatively, when the firms coordinate their green R&D investments ($h = c$), they maximize the sum of their profits with regard to z_i, $\forall\, i, j$, based on their own constraints and their rival's. Nevertheless, they still compete in production. The firms' program is thus:

$$\mathcal{P}_4 \begin{cases} \max_{z_i} & \sum \pi_i = & (A - Q)(q_i + q_j) - \frac{\gamma}{2}z_i^2 - \frac{\gamma}{2}z_j^2 - \tau(e_i + e_j) \\ \text{s.t.} & e_i = & q_i - z_i - \beta z_j \\ & e_j = & q_j - z_j - \beta z_i \end{cases}$$

The government chooses which policy instrument to use based on social welfare outcomes. In both scenarios, $h = nc, c$, the government maximizes its objective function and derives the optimal design of the standard or the tax. Under an ESP, social welfare (SW) is defined as the sum of consumer surplus and firm profits minus environmental damage:

$$\bar{SW}^h = \underbrace{\frac{(\bar{Q}^h)^2}{2}}_{\text{Consumer surplus=CS}} + \underbrace{(\bar{\pi}_i^h + \bar{\pi}_j^h)}_{\text{Producer surplus=PS}} - \underbrace{D(\bar{E}^h)}_{\text{Environmental damage}} \tag{2}$$

[7] In this symmetric case, the results would nevertheless be the same if the firms had different emission caps.

[8] 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. This remark holds for both environmental policy instruments.

Under an ETP, tax revenue needs to be included, such that:

$$SW^h = \frac{(Q^h)^2}{2} + (\pi_i^h + \pi_j^h) + \underbrace{\tau^h E^h}_{\text{Tax revenue}} - D(E^h) \tag{3}$$

Finally, we consider a multistage game with observable actions. To do this, we investigate two timing arrangements with either the government or the two competing firms choosing first (see Figure 1). Under both arrangements, the firms' choice to cooperate or not in green R&D at stage $t = 0$ is endogenous and can emerge as an equilibrium of the whole game. This hypothesis is consistent with real-life situations in which firms need to plan R&D partnerships in advance (signing R&D agreements is a potentially lengthy process) with no certainty regarding which environmental policy the government will chose.

The time structures of the game are described as follows:

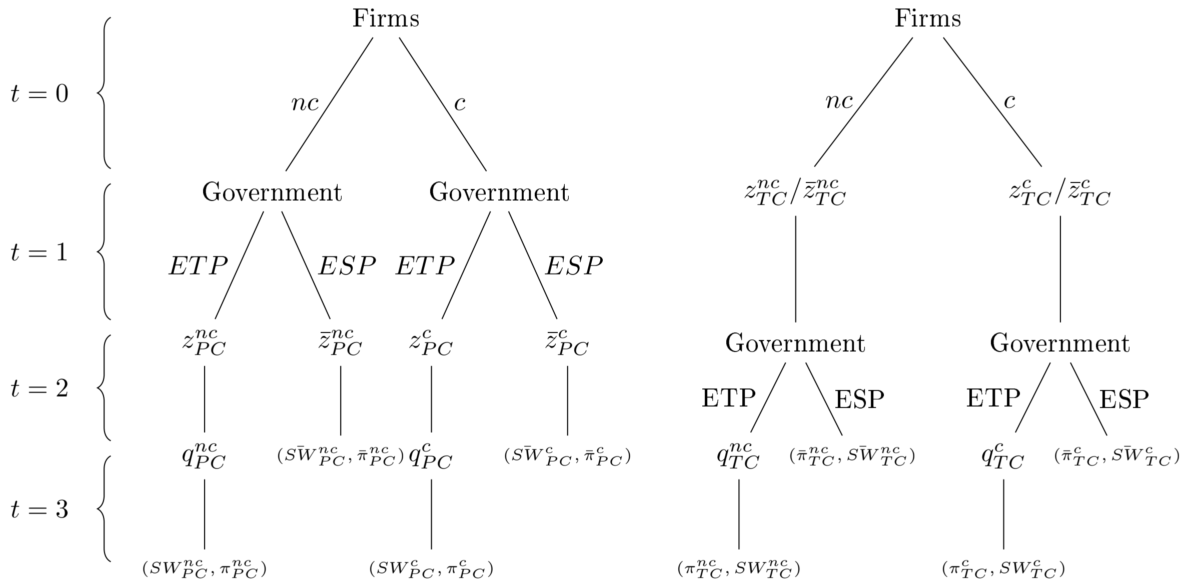
1. In the precommitment game (indexed $\nu = PC$), the regulator commits to an emission standard or an emission tax depending on whether firms cooperate in green R&D or not (at stage $t = 0$). At stage $t = 1$, the government either sets the emission standard or the tax rate that maximizes social welfare. At stage $t = 2$, the firms set their green R&D efforts to maximize their profits (or their joint profit when they choose to cooperate in R&D at $t = 0$). At stage $t = 3$, the firms always set their production levels non-cooperatively.

2. In the time-consistent game (indexed $\nu = TC$), the government cannot credibly commit to an environmental policy. At stage $t = 1$, the two firms choose their levels of green R&D having decided to cooperate or not at $t = 0$, and the government chooses the environmental policy instrument (standard or tax) at stage $t = 2$. Once the environmental policy instrument is chosen, the government sets the standard or the tax rate that maximizes social welfare. At stage $t = 3$, the firms set their production levels non-cooperatively.

We solve the two policy games by backward induction for the two types of environmental policy (emission standard or emission tax) and R&D strategies (non-cooperation or cooperation). Notice however that the production stage vanishes under an ESP in both timing arrangements (See also Moner-Colonques and Rubio (2015, 2016).). Only three stages remain since outputs are pre-determined once the regulator has set the emission standard and both firms have chosen their green R&D efforts (See the presentation of the emission standard instrument above.).

3 Precommitment game

In this section, we present the equilibrium outcomes for the two environmental policies in the non-cooperative and cooperative R&D subgames after the regulator commits to its policy tool (See Figure 1a.).



(a) Precommitment game

(b) Time-consistent game

Figure 1: Timing of policy games.

3.1 Equilibrium Results

3.1.1 ESP

Since under an ESP, the competitive production stage of the game vanishes, we can begin our analysis directly at stage 2.

When the two firms do not cooperate in green R&D, firm i chooses the level of R&D investment that maximizes its profits given its environmental constraint $\bar{e}$, but ignoring its rival's environmental constraint.[9] The maximization program, $\forall\, i, j$: $\mathcal{P}_1$ allows us to derive the first-order condition (FOC)

$$\frac{\partial \bar{\pi}_i}{\partial \bar{z}_i} = \frac{\partial \bar{q}_i}{\partial \bar{z}_i}(A - 2(\bar{e} + \bar{z}_i + \beta \bar{z}_j) - (\bar{e} + \bar{z}_j + \beta \bar{z}_i)) - \gamma \bar{z}_i = 0$$

By symmetry, $\bar{z}_i^{nc} = \bar{z}_j^{nc} = \bar{z}^{nc}(\bar{e})$ and the solution of the above FOC yields the equilibrium level of R&D investment:

$$\bar{z}^{nc}(\bar{e}) = \frac{A - 3\bar{e}}{3(1+\beta) + \gamma} \tag{4}$$

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 if the government lowers the emission cap. The equilibrium output level as a function of emissions can then be directly deduced from the firms' environmental constraint:

$$\bar{q}^{nc}(\bar{e}) = \frac{(1+\beta)A + \gamma \bar{e}}{3(1+\beta) + \gamma} \tag{5}$$

[9]This amounts to assuming that firm i anticipates that it cannot influence its rival's level of production and thus $\bar{z}_j$. Therefore it takes $\bar{q}_j$ as given.

Quite intuitively, at equilibrium, the stricter the standard, the lower the production, but this effect is mitigated when spillovers are high. Using equation (4) and assuming it is positive, we can also claim that spillovers boost production, despite their disincentive effect on green R&D.

Considering now the case where the firms cooperate in R&D, at stage 2, they choose the level of green R&D that maximizes their joint profit under the two individual constraints defined by program $\mathcal{P}_2$. Then, the FOC w.r.t z_i, can be written, $\forall\, i, j$ and $i \neq j$:

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

As mentioned above, R&D cooperation implies that when maximizing their joint profit with respect to z, the firms tie their hands on production levels. Since polluting emissions are constrained, it is as if the firms simultaneously choose their levels of production and of R&D investment in a cartel-like manner.[10] This behavior also prevails in the time-consistent policy game ($\nu = TC$).

In the symmetric equilibrium, $\bar{z}^c = \bar{z}_i^c = \bar{z}_j^c$, the solution of the above FOC yields the firms' equilibrium R&D level as a function of the emission standard:

$$\bar{z}^c(\bar{e}) = (1+\beta)\frac{(A - 4\bar{e})}{4(1+\beta)^2 + \gamma} \tag{6}$$

Similarly to the non-cooperative scenario, the firms invest more in R&D when the government lowers the emission cap. However, in the cooperative scenario, the emission standard has a stronger effect ($|\frac{\partial z^c}{\partial \bar{e}}| > |\frac{\partial z^{nc}}{\partial \bar{e}}|$). Furthermore, whereas spillovers always have a negative effect on the equilibrium R&D effort in the non-cooperative scenario, in the cooperative scenario, this effect becomes positive for sufficiently high values of γ. The equilibrium output level can be deduced from the firms' constraint in program $\mathcal{P}_2$:

$$\bar{q}^c(\bar{e}) = \frac{(1+\beta)^2 A + \gamma \bar{e}}{4(1+\beta)^2 + \gamma} \tag{7}$$

It is straightforward to check that for a given $\bar{e}$, this equilibrium output is lower in the cooperative scenario than in the non-cooperative one (See equation (5).), thereby confirming the cartel behavior.

At stage 1, since the regulator credibly commits to its environmental policy, it maximizes social welfare based on the firms' R&D strategies (See Figure 1a.). Then, equation (2) and the equilibrium levels $\bar{z}^h(\bar{e})$ and $\bar{q}^h(\bar{e})$ (with $h = nc, c$) yield social welfare as a function of the emission standard only:

$$S\bar{W}^h(\bar{e}) = 2\left(A\left(\bar{q}^h(\bar{e})\right) - \left(\bar{q}^h(\bar{e})\right)^2 - \frac{\gamma}{2}\left(\bar{z}^h(\bar{e})\right)^2 - d\bar{e}^2 \right) \tag{8}$$

The optimal standard chosen by the regulator is such that the marginal benefit measured by the reduction in environmental damage is exactly offset by the loss of economic

[10] Notice that when $\beta = 0$, we obtain the FOC of a production cartel for i: $\frac{\partial \bar{\pi}_i}{\partial \bar{q}_i} + \frac{\partial \bar{\pi}_j}{\partial \bar{q}_i} = \gamma \bar{z}_i$.

performance measured by the reduction in consumer surplus (from lower output) and the increase in investment costs, both caused by a stricter standard. The equilibrium emission standard is obtained from the FOC with respect to $\bar{e}$ in each scenario:[11]

$$\begin{cases} \bar{e}_{PC}^{*,nc} = \gamma \frac{4+\beta+\gamma}{X} A \\ \bar{e}_{PC}^{*,c} = \gamma \frac{6(1+\beta)^2+\gamma}{W} A, \end{cases} \tag{9}$$

with $X = 2d(3(1+\beta)+\gamma)^2+\gamma(9+2\gamma) > 0$ and $W = 2d(4(1+\beta)^2+\gamma)^2+2\gamma(8(1+\beta)^2+\gamma) > 0$. The equilibrium outcomes in both scenarios $h = nc, c$ are obtained from equations (9) (See Table 3.).

3.1.2 ETP

In this section, we briefly present the equilibrium outcomes when the regulator implements a tax on polluting emissions. This setting has previously been explored by Petrakis and Xepapadeas (2001), Poyago-Theotoky and Teerasuwannajak (2002), Moner-Colonques and Rubio (2015) and Lambertini et al. (2017) for non-cooperating firms and notably by Ouchida and Goto (2016a, 2022) and McDonald and Poyago-Theotoky (2017) for R&D cooperating firms has also been investigated. We therefore summarize the main results and refer the reader to this literature to explore the effects of slightly different assumptions regarding spillovers, products and/or innovation competition settings.

At stage 3, firm i chooses the output level q_i that maximizes its profit $\pi_i = (A - Q)q_i - \frac{\gamma}{2}z_i^2 - \tau e_i$, using equation (1) as a constraint. Regardless of whether the firms cooperate in green R&D or not, the symmetric equilibrium production level is:

$$q(\tau) = \frac{A-\tau}{3} \tag{10}$$

At stage 2, for $h = nc$, the two firms maximize their own profit w.r.t. z (See the program $\mathcal{P}_3$.). On the contrary, when $h = c$, they choose to coordinate their efforts in green R&D and maximize the sum of their profits (See the program $\mathcal{P}_4$.). By symmetry, we find the standard literature results:

$$\begin{cases} z^{nc}(\tau) = \frac{\tau}{\gamma} \\ z^{c}(\tau) = (1+\beta)\frac{\tau}{\gamma} \end{cases} \tag{11}$$

Green R&D investments always increase with the tax rate, leading to a reduction in polluting emissions. Notice that under R&D cooperation, the incentive to invest in green R&D increases with the degree of spillover, which is not the case in the non-cooperative scenario. Indeed, R&D cooperation ensures that free-riding is internalized, as in Ouchida and Goto (2016a, 2022). When the regulator adopts an ETP, the optimal tax is selected to maximize social welfare taking into account how firms will respond to it. Using equation (1) and substituting equations (10) and (11) into (3) yields the

[11] The second-order conditions of the welfare maximization program are always satisfied and this holds for the remainder of the paper.

regulator's net surplus as a function of the tax:

$$SW^h(\tau) = 2\left(A\left(\frac{A-\tau}{3}\right) - \left(\frac{A-\tau}{3}\right)^2 - \frac{\gamma}{2}(z^h(\tau))^2 - d\left(\frac{A-\tau}{3} - (1+\beta)z^h(\tau)\right)^2\right) \tag{12}$$

The equilibrium emission tax is obtained from the FOC with respect to τ in both scenarios, $h = nc, c$:

$$\begin{cases} \tau_{PC}^{*,nc} = \gamma\frac{2d(3(1+\beta)+\gamma)-\gamma}{X}A \\ \tau_{PC}^{*,c} = \gamma\frac{2d(3(1+\beta)^2+\gamma)-\gamma}{Y}A, \end{cases} \tag{13}$$

where $Y = 2d(3(1+\beta)^2+\gamma)^2 + \gamma(9(1+\beta)^2+2\gamma) > 0$. Additional equilibrium outcomes can be calculated using equation (13) (See Table 3.).

3.2 Environmental performance in the precommitment policy game: ESP vs ETP

To compare the two environmental policy tools, we first focus on environmental performance only, on the basis that the primary goal of any environmental policy is to reduce environmental damage. We therefore compare equilibrium emission levels. Even though environmental damage is a component of the social welfare function, we argue that considering the environmental measure separately is relevant as this is the regulator's main objective. Another motivation for this analysis is that the environmental measure has so far been rather neglected in the economic literature.

Using results from the previous subsections, we can derive two pairwise comparisons between individual equilibrium emissions[12] depending on the firms' R&D strategy. The following proposition summarizes our first set of results:

Proposition 1 (Environmental performance)**.** *For all admissible parameter values, when the government credibly commits ($\nu = PC$),*

- $e_{PC}^{*,nc} - \bar{e}_{PC}^{*,nc} = 0$;
- $e_{PC}^{*,c} - \bar{e}_{PC}^{*,c} > 0$.

Proof. See Appendix A. □

We first justify the equivalency between an ESP and an ETP in the precommitment policy game as stated in Proposition 1. In the R&D/production stage, the firms compete in the same way under the two instruments. Under an ETP, the tax burden vanishes: the increase in tax from one additional unit of polluting production is exactly offset by the decrease in taxation due to one additional unit of R&D effort. 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 whether the

[12] To be precise, we compare after-tax equilibrium emission levels with equilibrium emission standards.

policy instrument is an emission tax or an emission standard. Formally, for the same level of emissions under an ESP and an ETP $\bar{e} = e(\tau) = q(\tau) - (1+\beta)z(\tau) = \frac{A}{3} - \frac{3(1+\beta)+\gamma}{3\gamma}\tau$, the green R&D efforts are identical ($z^{nc}(\tau) = \bar{z}^{nc}(e(\tau)) = \tau/\gamma$) and consequently, so are production levels ($q^{nc}(\tau) = \bar{q}^{nc}(e(\tau))$). Therefore, whether the government chooses an optimal tax or an optimal standard, its objective function is:

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

This directly implies that for a given optimal ETP, there is one and only one optimal ESP that yields an identical level of welfare. This result has already been partially reported in the literature (See Moner-Colonques and Rubio (2015, 2016).). However, in our setup, it is obtained in a duopoly game rather than for a monopoly, and in the presence of R&D spillovers.

Interestingly, this correspondence between tax and standard vanishes when the firms cooperate in R&D: equilibrium emissions become lower under an ESP. The mechanisms involved under an ESP differ considerably from those under an ETP, particularly when the firms cooperate in green R&D. An ETP provides firms with an additional degree of freedom that does not exist under an ESP. Under an optimal ETP, the firms choose their R&D expenditure and their levels of production separately (which allows them to endogenize the level of emissions). Under an optimal ESP on the other hand, the firms simultaneously choose their levels of production and R&D investment, since polluting emissions are limited by the cap on emissions. The firms' incentive is then to circumvent the environmental constraint by forming a cartel, choosing to produce less rather than invest in R&D, irrespective of the efficiency of green technology and spillovers (See Section 3.1.1.). Faced with the economic costs of the firms' cartel behavior, and to mitigate the reduction in consumer surplus, the government is then inclined to enforce a tighter emission standard to benefit from reduced environmental damage. On the contrary, since R&D cooperation stimulates greater R&D efforts under an ETP, the government reacts by lowering the tax rate (Ouchida and Goto, 2016a). This further stimulates production and thus individual emissions.

4 Time-consistent game

In this section, we present the equilibrium outcomes for the two environmental policies as they arise in the non-cooperative and cooperative R&D subgames when the regulator is unable to commit to its policy tool (See Figure 1b.).

4.1 Equilibrium results

4.1.1 ESP

Just as in the previous policy game, when the regulator implements an emission standard, stage 3 of the game vanishes. Recall also that in the time-consistent policy game the firms choose their optimal levels of green R&D before the regulator chooses which policy to implement. We therefore jump to stage 2 of the game where the regulator selects the emission standard that maximizes social welfare. The social welfare function is the same in both scenarios $h = nc, c$. Using the firms' environmental constraints and equation (2), social welfare can be expressed as follows:

$$\begin{aligned} S\bar{W}(\bar{e}, \bar{z}_i, \bar{z}_j) &= \frac{(\bar{q}_i + \bar{q}_j)^2}{2} + (A - \bar{Q})(\bar{q}_i + \bar{q}_j) - \frac{\gamma}{2}\bar{z}_i^2 - \frac{\gamma}{2}\bar{z}_j^2 - \frac{d}{2}(2\bar{e})^2 \\ &= A(2\bar{e} + (1+\beta)(\bar{z}_i + \bar{z}_j)) - \frac{1}{2}(2\bar{e} + (1+\beta)(\bar{z}_i + \bar{z}_j))^2 - \frac{\gamma}{2}\bar{z}_i^2 - \frac{\gamma}{2}\bar{z}_j^2 - \frac{d}{2}(2\bar{e})^2 \end{aligned} \quad (14)$$

Maximizing this function w.r.t. $\bar{e}$, we obtain the equilibrium emission standard as a function of the two firms' R&D efforts:

$$\bar{e}(\bar{z}_i, \bar{z}_j) = \frac{A - (1+\beta)(\bar{z}_i + \bar{z}_j)}{2(1+d)} \quad (15)$$

Since the firms play first, the optimal emission standard becomes less stringent as the firms' R&D efforts decrease, whenever they choose to cooperate in R&D or not. In addition, this effect becomes larger as β increases and d decreases.

At stage 1, we can solve for the firms' equilibrium R&D levels, depending on their cooperation strategy and given that they anticipate the effect this choice will have on the regulator's decision.

Again, in the non-cooperative scenario ($h = nc$), the firms take no account of their rival's environmental constraint. Hence, inserting equation (15) into program $\mathcal{P}_1$, the FOC on $\bar{z}_i$ is:

$$\frac{\partial \bar{\pi}_i}{\partial \bar{z}_i} = \left(\frac{\partial \bar{q}_i}{\partial \bar{e}} \frac{\partial \bar{e}(\bar{z}_i, \bar{z}_j)}{\partial \bar{z}_i} + 1 \right) (A - 2(\bar{e}(\bar{z}_i, \bar{z}_j) + \bar{z}_i + \beta \bar{z}_j) - (\bar{e}(\bar{z}_i, \bar{z}_j) + \bar{z}_j + \beta \bar{z}_i)) - \gamma \bar{z}_i = 0$$

In the cooperative scenario ($h = c$), inserting equation (15) into program $\mathcal{P}_2$ yields the FOC on $\bar{z}_i$:

$$\frac{\partial \sum \bar{\pi}_i}{\partial \bar{z}_i} = \left(\frac{\partial \bar{e}(\bar{z}_i, \bar{z}_j)}{\partial \bar{z}_i} \left(\frac{\partial \bar{q}_i}{\partial \bar{e}} + \frac{\partial \bar{q}_j}{\partial \bar{e}} \right) + (1+\beta) \right) (A - 2(2\bar{e}(\bar{z}_i, \bar{z}_j) + (1+\beta)(\bar{z}_i + \beta \bar{z}_j)) - \gamma \bar{z}_i = 0$$

At the symmetric equilibrium, $\bar{z}_i = \bar{z}_j = \bar{z}$, the solutions of the above FOCs yield the equilibrium green R&D efforts in both scenarios:

$$\begin{cases} \bar{z}_{TC}^{*,nc} = \frac{(-1+4d^2+\beta-2d\beta)}{\Theta} A > 0, \\ \bar{z}_{TC}^{*,c} = (1+\beta)\frac{d(d-1)}{\Psi} A > 0 \end{cases} \quad (16)$$

where $\Theta = 4\gamma(1+d)^2 + 6d(1+2d-\beta)(1+\beta) > 0$ and $\Psi = \gamma(1+d)^2 + 4d^2(1+\beta)^2 > 0$. Finally, inserting equations (16) into (15), yields the equilibrium emission standards:

$$\begin{cases} \bar{e}_{TC}^{*,nc} = \frac{A-2(1+\beta)\bar{z}_{TC}^{*,nc}}{2(1+d)} = \frac{2\gamma(1+d)+(1+2d-\beta)(1+\beta)}{\Theta} A, \\ \bar{e}_{TC}^{*,c} = \frac{A-2(1+\beta)\bar{z}_{TC}^{*,c}}{2(1+d)} = \frac{\gamma(1+d)+2d(1+\beta)^2}{2\Psi} A \end{cases} \quad (17)$$

Additional equilibrium outcomes can be calculated using equation (17) (See Table 4.).

4.1.2 ETP

Stage 3 of this policy game is identical to the one under precommitment: the equilibrium outputs are therefore given by equation (10). In stage 2, under an ETP and in both scenarios $h = nc, c$, the regulator considers the following social welfare function, obtained by inserting equations (1) and (10) into equation (3):

$$\begin{aligned} SW(\tau, z_i, z_j) &= \frac{(2q(\tau))^2}{2} + (A - 2q(\tau))(2q(\tau)) - \gamma\frac{z_i^2}{2} - \gamma\frac{z_j^2}{2} - \frac{d}{2}\left(2q(\tau) - (1+\beta)\sum_i z_i\right)^2 \\ &= 2A\left(\frac{A-\tau}{3}\right) - 2\left(\frac{A-\tau}{3}\right)^2 - \gamma\frac{z_i^2}{2} - \gamma\frac{z_j^2}{2} - \frac{d}{2}\left(2\left(\frac{A-\tau}{3}\right) - (1+\beta)\sum_i z_i\right)^2 \end{aligned}$$

The government's reaction function when selecting the welfare maximizing emission tax rate is:

$$\tau(z_i, z_j) = \frac{(2d-1)A - 3d(1+\beta)(z_i + z_j)}{2(1+d)} \tag{18}$$

The emission level as a function of the firms' R&D efforts can be deduced from equation (1):

$$\begin{aligned} e(z_i, z_j) &= q(\tau(z_i, z_j)) + z_i + \beta z_j \\ &= \frac{A - (d(1-\beta)+2)z_i + (d(1-\beta) - 2\beta)z_j}{2(1+d)} \end{aligned} \tag{19}$$

In contrast with the outcomes under an ESP, the firms' emissions do not necessarily mirror their R&D efforts. For high enough values of d ($> \frac{2\beta}{(1-\beta)}$) for instance, an increase in one firm's R&D effort increases emissions for both firms . Again, the welfare performance of an ETP when the regulator is forced to introduce a time-consistent emission tax has already been studied (Ouchida and Goto, 2016b, 2022; Moner-Colonques and Rubio, 2015, 2016; Petrakis and Xepapadeas, 2001; Poyago-Theotoky and Teerasuwannajak, 2002; Poyago-Theotoky, 2007). Hence, we only briefly describe the main results when the two firms set their R&D levels in stage $t = 1$, taking into account how the regulator will react to this. In the non-cooperative scenario, in line with program $\mathcal{P}_3$, firm i maximizes its profits expressed as follows:

$$\pi_i(z_i, z_j) = (A - 2q(\tau(z_i, z_j)))q(\tau(z_i, z_j)) - \frac{\gamma}{2}(z_i)^2 - \tau(z_i, z_j)(q(\tau(z_i, z_j)) - z_i - \beta z_j)$$

In the cooperative scenario, firm i instead maximizes $\sum_i \pi_i(z_i, z_j)$ (See program $\mathcal{P}_4$.). In both cases $h = nc, c$, $\tau(z_i, z_j)$ is given by equation (18).

At the symmetric equilibrium $z_i = z_j = z_{TC}$, the solutions of the FOCs yield the equilibrium green R&D efforts for $h = \{nc, c\}$:

$$\begin{cases} z_{TC}^{*,nc} = \frac{(2d-1)(1+d)+d(1+\beta)}{\Omega}A \\ z_{TC}^{*,c} = (1+\beta)\frac{(2d-1)(1+d)+2d}{\Delta}A \end{cases} \tag{20}$$

where $\Omega = 2\gamma(1+d)^2 + d(1+\beta)(3(3+\beta) + d(7+\beta)) > 0$ and $\Delta = 2\gamma(1+d)^2 + 4d(3+2d)(1+\beta)^2 > 0$.

The equilibrium emissions of each firm are obtained by inserting equations (20) into (19):

$$e_{TC}^{*,h} = \frac{A - 2(1+\beta)z_{TC}^{*,h}}{2(1+d)} \tag{21}$$

Interestingly, in the time-consistent policy game, the government reacts in the same way to the firms' prior R&D choices no matter what the chosen environmental policy tool or R&D strategy is: the lower the green R&D investment, the higher the emissions, by a factor $\frac{1+\beta}{1+d}$ (See also equation (17) for the ESP.).

Notice also that all the equilibrium outcomes of this policy game can be deduced from equations (20) (See Table 4.).

4.2 Environmental performance in the time-consistent policy game: ESP vs ETP

The results from subsections 4.1.1 and 4.1.2 can be used to compare equilibrium emissions under an ESP and an ETP in the time-consistent policy game, depending on the firms' R&D strategy. The following proposition summarizes our second set of results:

Proposition 2 (Environmental performance)**.** *For all admissible parameter values, when the government cannot commit ex-ante ($\nu = TC$),*

- $e_{TC}^{*,nc} - \bar{e}_{TC}^{*,nc} \geq 0$ *if* $\gamma \in (0, \bar{\gamma}(\beta, d)]$ *and* $e_{TC}^{*,nc} - \bar{e}_{TC}^{*,nc} < 0$ *if* $\gamma > \bar{\gamma}(\beta, d)$*;*
- $e_{TC}^{*,c} - \bar{e}_{TC}^{*,c} < 0$*,*

with $\bar{\gamma}(\beta, d) = \frac{d(1+\beta)(2d-3)(2d+1-\beta)}{2(1+d)(4d-1)}$, $\bar{\gamma}'_{\beta}(\beta, d) > 0$ *and* $\bar{\gamma}'_{d}(\beta, d) > 0$ *when* $\bar{\gamma}(\beta, d) > 0$.

Proof. See Appendix B. □

In the time-consistent policy game, when the firms do not cooperate in green R&D, the relative environmental performance of the two instruments crucially depends on the parameters of the model: equilibrium emissions under an ESP can be lower than under an ETP when R&D efficiency is high (γ is low), but when γ is relatively high, emissions are always lower under an ETP. While a tax and a standard always have the same environmental performance in the precommitment game, this is only the case in the time-consistent game for $\gamma = \bar{\gamma}(\beta, d)$. Notice that the higher the degree of spillovers and/or the more severe the environmental damage is/are, the higher the threshold $\bar{\gamma}$ is.

Also in contrast with the results of the precommitment policy game (See Proposition 1.), when the firms cooperate in green R&D, equilibrium emissions are higher under an ESP than under an ETP. Under an ESP, the firms' incentive is to diminish their R&D efforts in both policy games, albeit because of different underlying mechanisms. In the precommitment policy game, the firms, who play after the government, adapt to the environmental policy by reducing their R&D efforts, resulting in lower outputs – a manifestation of cartel behavior. In the time-consistent policy game, cartel behavior also arises, but here the firms proactively aim to influence the government's policy in their favor by advocating for a less stringent emission standard. This phenomenon is analogous to the 'ratchet' effect observed in US automobile emissions regulations in the 1970s: manufacturers' slowness in developing emission reduction technologies forced the Environmental Protection Agency to delay the implementation of regulations.

Under an ETP, the firms also use their leading role in the time-consistent game to shape government policy. However, in this framework, both firms will spend more on green R&D to mitigate their tax burden (See equation (18).). This increase in R&D efforts leads to a reduction in emissions, which become lower than under an ESP. In the following indeed, we show that under an ETP, R&D efforts are always higher, especially when the firms cooperate (See Proposition 3.).

Together, propositions 1 and 2 show that neither of the two policy instruments is environmentally preferable under all circumstances, but rather than the timing of the policy game and the firms' R&D strategy play a crucial role in determining the relative performance of the policy instruments. The following section compares the two instruments in terms of innovation, output and social welfare.

5 Economic performance: ESP vs ETP

The differences in equilibrium emission levels allow us to directly compare the economic performance of the ESP and ETP in the two policy games and R&D scenarios. In particular, we can show that differences in economic performance in terms of innovation, production, and welfare are linearly related to the relative environmental performance of the two instruments. The following lemma formally establishes this result.

Lemma 1. *For all admissible parameter values, the equilibrium differences in R&D, production and social welfare can be expressed as functions of the equilibrium difference in emissions:*

- $z_\nu^{*,h} - \bar{z}_\nu^{*,h} = \frac{\mathcal{Z}_\nu^h}{(1+\beta)}(e_\nu^{*,h} - \bar{e}_\nu^{*,h})$
- $q_\nu^{*,h} - \bar{q}_\nu^{*,h} = \mathcal{Q}_\nu^h(e_\nu^{*,h} - \bar{e}_\nu^{*,h})$
- $SW_\nu^{*,h} - \bar{SW}_\nu^{*,h} = \mathcal{SW}_\nu^h(e_\nu^{*,h} - \bar{e}_\nu^{*,h})$

with $\nu = \{PC, TC\}$, $h = \{nc, c\}$ *and where* $\mathcal{Z}_\nu^h, \mathcal{Q}_\nu^h, \mathcal{SW}_\nu^h$ *are constants that depend on parameters* d, γ, *and* β.

Proof. See Appendix C. □

Lemma 1 shows that $\mathcal{Q}_\nu^h - \mathcal{Z}_\nu^h = 1$ for all $h = \{nc, c\}$ and $\nu = \{PC, TC\}$ because of the binding environmental target presented in equation (1). These results can then be used to assess differences in welfare, leading to the four following pairwise comparisons:

Proposition 3 (Economic performance)**.** *For all admissible parameter values and using the results of Propositions 1, 2 and Lemma 1,*

i) When the government credibly commits ($\nu = PC$),

– *for any values of* $\mathcal{Z}_{PC}^{nc}, \mathcal{Q}_{PC}^{nc}$ *and* $\mathcal{SW}_{PC}^{nc}$*,* $z_{PC}^{*,nc} - \bar{z}_{PC}^{*,nc} = 0$*,* $q_{PC}^{*,nc} - \bar{q}_{PC}^{*,nc} = 0$ *and* $SW_{PC}^{*,nc} - \bar{SW}_{PC}^{*,nc} = 0$*;*

– $\mathcal{Z}_{PC}^{c}, \mathcal{Q}_{PC}^{c}$ *and* $\mathcal{SW}_{PC}^{c}$ *are positive. Hence,* $z_{PC}^{*,c} - \bar{z}_{PC}^{*,c} > 0$*,* $q_{PC}^{*,c} - \bar{q}_{PC}^{*,c} > 0$ *and* $SW_{PC}^{*,c} - \bar{SW}_{PC}^{*,c} > 0$*.*

ii) When the government cannot commit ex-ante ($\nu = TC$*),* $\mathcal{Z}_{TC}^{h}, \mathcal{Q}_{TC}^{h}$ *and* $\mathcal{SW}_{TC}^{h}$ *are negative and identical for* $h = nc, c$*. Hence,*

– $z_{TC}^{*,nc} - \bar{z}_{TC}^{*,nc} \leq 0$*,* $q_{TC}^{*,nc} - \bar{q}_{TC}^{*,nc} \leq 0$ *and* $SW_{TC}^{*,nc} - \bar{SW}_{TC}^{*,nc} \leq 0$ *if* $\gamma \in (0, \bar{\gamma}(\beta, d)]$ *and the opposite holds if* $\gamma > \bar{\gamma}(\beta, d)$*;*

– $z_{TC}^{*,c} - \bar{z}_{TC}^{*,c} > 0$*,* $q_{TC}^{*,c} - \bar{q}_{TC}^{*,c} > 0$ *and* $SW_{TC}^{*,c} - \bar{SW}_{TC}^{*,c} > 0$*.*

Proof. See Appendix C. □

Obviously, the identical equilibrium emission levels when the firms do not cooperate and the regulator is able to commit ex-ante imply that the economic equilibrium outcomes are the same. The government is therefore indifferent between the two policy instruments. However, when the regulator implements a time-consistent policy, the differences in economic outcomes are of opposite sign to the difference in emissions (See Lemma 1.). Since the difference in emissions is negative for $\gamma > \bar{\gamma}(\beta, d)$, the ETP performs better both from an environmental and an economic point of view. Obviously, when $\gamma \in (0, \bar{\gamma}(\beta, d))$, it is the ESP that performs better in both regards. To conclude, for all positive values of γ, one of the instruments always outperforms the other in terms of economic and environmental outcomes in the non-cooperative scenario.

Ultimately, irrespective of the game's timing, when the firms cooperate in green R&D, an ETP proves to be economically superior, as firms under an ESP tend to behave as a cartel. However, the potential divergence of economic and environmental outcomes should also be considered. In particular, an ETP encourages increased R&D efforts and higher production levels, contributing to overall welfare improvement. However, in the precommitment policy game, this also leads to higher emissions compared with the ESP. In contrast, in the time-consistent policy game under an ESP, the firms compel the government to loosen the emission standard. This influence is achieved through a greater decrease in green R&D investments than in outputs, which adversely affects environmental performance. Therefore, in the cooperative scenario in the time-consistent policy game, an ETP outperforms an ESP both from an economic and an environmental point of view.

6 Endogenous choices and regulatory implications

In this section, we first solve the SPNE of the whole game for the two policy games. We then consider an extension featuring a pre-game stage where the regulator chooses whether to allow or ban green R&D cooperation.

6.1 Environmental regulation: Tax or Standard

At $t = 0$, the firms compare the equilibrium profits associated with the non-cooperative and cooperative scenarios. R&D cooperation is profitable if firms earn more profit than they would if they did not cooperate. This leads to the following proposition:

Proposition 4 (SPNE)**.** *Equilibrium strategies arise from the SPNE outcomes for all admissible parameter values:*

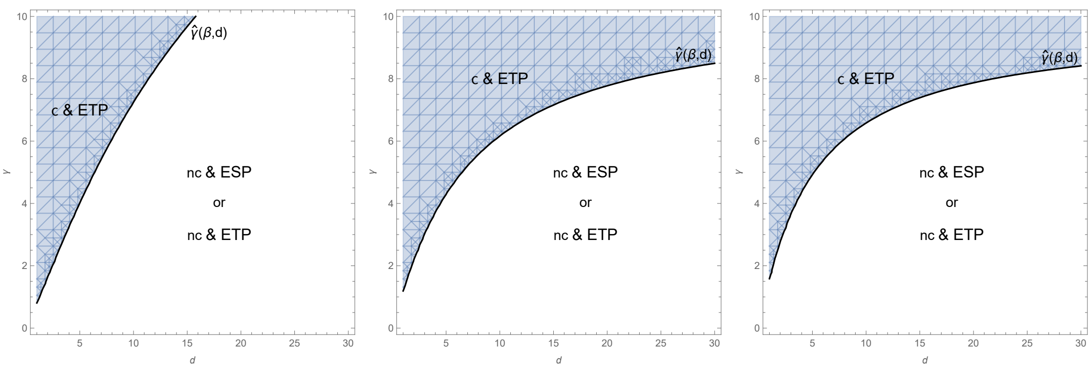
i) When the government credibly commits ($\nu = PC$),

- *for $\gamma \geq \hat{\gamma}(\beta, d)$, the firms cooperate in green R&D and the regulator implements an ETP;*
- *for $\hat{\gamma}(\beta, d) \geq \gamma$, the firms do not cooperate in green R&D and the regulator is indifferent between an ESP and an ETP;*

ii) When the government cannot commit ex-ante ($\nu = TC$),

- *for $\gamma \geq \bar{\gamma}(\beta, d)$, the firms cooperate in green R&D and the regulator implements an ETP;*
- *for $\bar{\gamma}(\beta, d) \geq \gamma \geq \underline{\gamma}(\beta, d)$, the firms do not cooperate in green R&D and the regulator implements an ESP;*
- *for $\bar{\gamma}(\beta, d) \geq \underline{\gamma}(\beta, d) \geq \gamma$, the firms cooperate in green R&D and the regulator implements an ETP.*

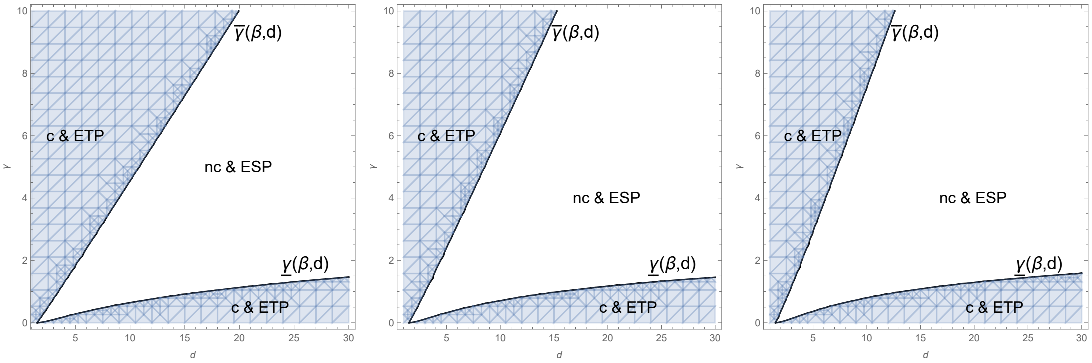
Proof. See Appendix D. □



(a) $\beta = 0.1$ (b) $\beta = 0.5$ (c) $\beta = 0.9$

Figure 2: SPNE in the precommitment policy game.

Building on Proposition 4, we can put forward an initial insightful finding regarding environmental regulation: the selection of the environmental policy instrument hinges on firms' strategic decisions concerning the organization of green R&D. When firms opt for cooperation, the ETP (Emission Tax Policy) is socially preferable irrespective of the regulator's ability to commit to its environmental policy. Conversely, when firms do not



(a) $\beta = 0.1$ (b) $\beta = 0.5$ (c) $\beta = 0.9$

Figure 3: SPNE in the time-consistent policy game.

choose to cooperate, an ESP (Emission Standard Policy) emerges as a preferred option across both policy games. Additionally, it is noteworthy that the strategy of adopting an ESP when firms cooperate (resulting in cartel-like behavior in production) can not emerge as an equilibrium choice in the two games under examination. This observation is consistent with antitrust regulations implemented in many jurisdictions.

Figure 2 illustrates how spillovers promote the "cooperation-ETP" combination in the precommitment policy game (as shown by the expanding gray areas with increasing β). However, in the time-consistent policy game, this trend is reversed. According to Proposition 2, we know that $\bar{\gamma}(\beta, d)$ increases with the degree of spillovers, thereby reducing the area where R&D cooperation is adopted at the equilibrium (upper gray area of Figure 3). Referring to Table 2 (in the Appendix D), which provides threshold limits, we observe that the limit of $\underline{\gamma}(\beta, d)$ (as d tends to infinity) decreases with β. Therefore, the conditions for the sustainability of the "non-cooperation-ESP" combination are broader when spillovers are significant.

Finally, although the thresholds on γ are different, some parameter configurations lead to similar outcomes in both policy games: i) for high values of γ and moderate values of d, "cooperation-ETP" emerges as the SPNE; ii) for intermediate values of γ and relatively large values of d, "non-cooperation-ESP" may prevail at equilibrium. The crucial difference between the two policy games lies in the respective ranges of d and γ. Specifically, when R&D is efficient, "cooperation-ETP" is endogenously adopted only in the time-consistent policy game, while it will never be adopted in the precommitment game.

6.2 Competition regulation: Preemptive Authorization or Ban on Green R&D Cooperation

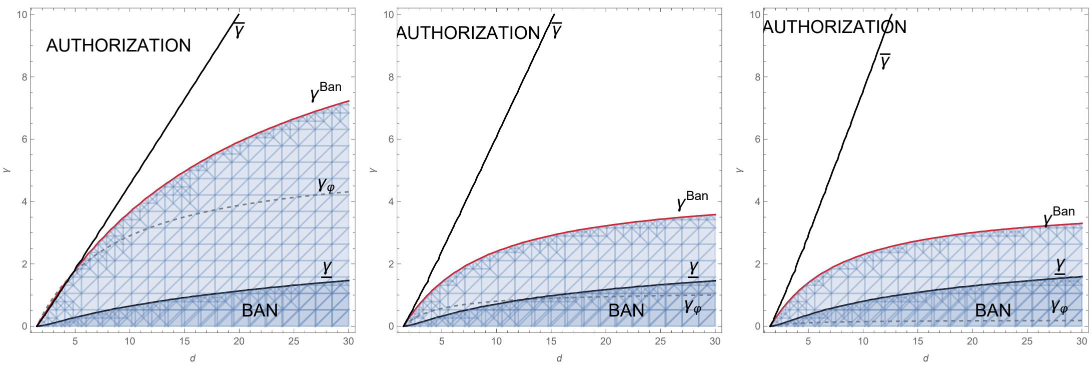
Let us now assume that the regulator determines whether to permit or prohibit green R&D cooperation before the firms make their strategic decisions. This introduces an additional pre-game stage, ensuring that the firms' endogenous choices align with the regulator's interests. Moreover, this expanded time structure is justified by the relatively inflexible nature of regulations allowing or prohibiting cooperation, as these decisions occur at the very outset of the game. Using results from previous sections, we can claim the following:

Proposition 5 (Expanded SPNE)**.**

i) In the precommitment policy game, the regulator never prohibits cooperation in green R&D;

ii) In the time-consistent policy game, the regulator should prohibit green R&D cooperation when R&D is highly efficient.

Proof. See Appendix E. □



(a) $\beta = 0.1$ (b) $\beta = 0.5$ (c) $\beta = 0.9$

Figure 4: Authorization versus ban in the time-consistent policy game.

Overall, the regulator permits green R&D cooperation, except in cases where R&D proves highly efficient in the context of a time-consistent policy game (See Figure 4.).Proposition 4 identifies two areas that may be impacted by the prohibition of R&D cooperation: When $\gamma \geq \bar{\gamma}(\beta, d)$, firms choose to cooperate aligning with the regulator's objectives, and cooperation is permitted without affecting firms' behavior –except for very low spillovers and $d > 3/2$ as delineated by the threshold γ_{φ}.[13] However when $\gamma < \underline{\gamma}(\beta, d)$, despite firms wish to cooperate, it becomes socially non-desirable and thus, the regulator prohibits green R&D cooperation (See Proposition 5 *ii).*). Indeed, since $\gamma < \gamma^{Ban}$, "non-cooperation-ESP" outperforms "cooperation-ETP" ($SW^{*,c}_{TC} < S\bar{W}^{*,nc}_{TC}$). This outcome stems from two key factors: i) as noted in the literature, particularly by Poyago-Theotoky (2007), cooperation under an ETP is less favorable than independent R&D when R&D is highly efficient ($SWC^{*,nc}_{TC} > SWC^{*,c}_{TC}$ for $\gamma < \gamma_{\varphi}$); ii) according to Proposition 3, when firms abstain from cooperation and γ is relatively low, an ESP performs better from an economic perspective. In conclusion, one of the SPNE disappears when the regulator prohibits R&D cooperation in the time-consistent policy game.

[13]See Poyago-Theotoky (2007) and Ouchida and Goto (2016b) for the expression of this threshold value γ_{φ}, defined as the difference between $SWC^{*,nc}_{TC}$ and $SWC^{*,c}_{TC}$.

Specifically, the "cooperation-ETP" combination for low values of γ, depicted in Figure 3, is replaced by the "non-cooperation-ESP" combination.

Moreover, in the time-consistent policy game, the range of parameters for which "non-cooperation-ESP" emerges as the equilibrium of the whole game expands notably when both the degree of spillovers and the extent of damages increase. Indeed, the two equilibrium combinations, "cooperation-ETP" and "non-cooperation-ESP" become delimited by the threshold $\bar{\gamma}(\beta, d)$ only, which increases with β and d, for $d > 3/2$. This deviates from usual findings in the literature, which often highlight the positive impact of spillovers on green R&D cooperation, a trend that remains consistent in the precommitment policy game. Consequently, we can also infer that the precommitment policy game tends to favor the adoption of an ETP over the time-consistent policy game, particularly in scenarios characterized by high spillovers and inefficient R&D. However, as R&D efficiency improves, opting for the environmental standard becomes preferable irrespective of the government's ability to commit to its environmental policy.

6.3 Policy implications

This model presents an opportunity to reconcile two seemingly conflicting objectives of economic policies: environmental policies, focused on preserving ecosystems and often imposing additional costs on firms through taxation or environmental standards, and competition policies, aimed at safeguarding consumer interests by fostering higher production and lower prices, potentially leading to increased pollution. The theoretical framework introduced here not only sheds light on the debate surrounding the selection of appropriate environmental policy instruments but also addresses the issue of competition regulation in the context of pollution reduction.

First, our study delivers valuable insights into the selection of environmental policy instruments contingent upon firms' R&D strategies. We demonstrate that irrespective of the policy game, the government's choice of an environmental tax is inherently associated with coordinated R&D efforts among rival firms. Conversely, the implementation of an environmental standard emerges within the context of environmental R&D competition, although the possibility of adopting a tax remains sustainable in the precommitment game.

Second, our research contributes to the ongoing debate regarding the interactions of competition policy and the attainment of environmental goals. Our findings emphasize the importance of carefully delineated antitrust laws to avoid impeding horizontal cooperation in R&D, which could otherwise deter firms from participating in valuable collaborative efforts toward green R&D. Nevertheless, we also demonstrate that as R&D becomes increasingly effective in mitigating severe environmental damages ($d > 3/2$), the social benefits of competitive R&D outweigh those derived from green R&D cooperation. Consequently, regulatory measures should be implemented to prohibit horizontal R&D agreements that, despite benefiting firms, could potentially hinder overall social welfare. This result holds true only when the government cannot credibly commit to its environmental policy.

7 Conclusion

Our theoretical model provides novel insights into the selection of environmental policies by encompassing firms' green R&D strategy and the regulator's ability to commit to policies *ex-ante*. To do this, we first compare two policy tools, an emission standard and an emission tax in terms of environmental and economic criteria. We then highlight the equilibrium choices that emerge at the SPNE of the two policy games.

We show that when firms coordinate their green R&D efforts, an emission tax is the most socially desirable policy instrument, regardless of the time-structure of the policy game. Conversely, an emission standard is only adopted when firms choose not to cooperate. This provides relevant insights for environmental policy recommendations. Furthermore, we emphasize the importance of a well-designed competition policy that fosters green R&D collaboration, with one notable exception: when R&D is highly efficient and damages are sufficiently severe in a time-consistent policy game, it becomes necessary to prohibit horizontal R&D relationship, as competitive R&D yields greater social benefits. It is crucial that objectives of competition law align with environmental objectives. In this regard, the recent competition rules introduced by the European Commission in June 2023 represent a significant step in that direction, offering consistent guidance on agreements between competitors pursuing sustainability objectives, known as "sustainability agreements".[14]

Finally, this article paves the way for future studies. Our findings rely upon assumptions regarding technological spillovers and market structures that could be more nuanced, in particular about spillover and R&D efficiency symmetry (Strandholm et al., 2018), the Cournot competition type, the restricted number of firms or even the homogeneity of the product. Further insights may also be gained by investigating other types of environmental policies, such as tradable permits (Garcia et al., 2018) or the "performance standard" discussed by (Amir et al., 2018; Montero, 2002), as well as other innovation policy instruments such as R&D subsidies related with voluntary environmental corporate social responsibility strategies by firms (Lee and Park, 2021). Building on the work of Biglaiser and Horowitz (1994), our framework could be also extended to investigate environmental policies that combine a tax and an emission standard.

[14]The document is available on the page http://data.europa.eu/eli/reg/2023/1066/oj.

Appendices

A Proof of Proposition 1

From equations (1) and (10) and (11) the emissions generated by the two firms can be expressed as:

$$e(\tau_{PC}^{*,nc}) = \frac{A - \tau_{PC}^{*,nc}}{3} - (1+\beta)\frac{\tau_{PC}^{*,nc}}{\gamma} \tag{A.1}$$

Using the equilibrium ETP (See equation (13).) we obtain:

$$e_{PC}^{*,nc} = e(\tau_{PC}^{*,nc}) = \gamma\frac{4+\beta+\gamma}{X}A \tag{A.2}$$

and we easily observe that $e_{PC}^{*,nc} = \bar{e}_{PC}^{*,nc}$.

We follow a similar reasoning when the firms cooperate. Equations (1), (10), (11) and (13) yield:

$$e_{PC}^{*,c} = e(\tau_{PC}^{*,c}) = \gamma\frac{4(1+\beta)^2+\gamma}{Y}A \tag{A.3}$$

The emission differential for $h = c$ can then be expressed using equation (9):

$$e_{PC}^{*,c} - \bar{e}_{PC}^{*,c} = \gamma(2d(1+\beta)^2+\gamma)(10(1+\beta)^2+3\gamma)\frac{(1+\beta)^2}{YW}A \tag{A.4}$$

which is always positive.

B Proof of Proposition 2

We follow the same reasoning as in the proof of Proposition 1, but for the sake of simplicity we refer the reader to equilibrium results presented in Table 4. We then compare equilibrium emissions when the firms do not cooperate:

$$e_{TC}^{*,nc} - \bar{e}_{TC}^{*,nc} = -(\gamma - \bar{\gamma})\frac{(1+\beta)^2}{\Omega\Theta}A, \tag{B.5}$$

with $\bar{\gamma}(\beta,d) = \frac{d(1+\beta)(2d-3)(2d+1-\beta)}{2(1+d)(4d-1)}$, $\bar{\gamma}'_\beta(\beta,d) > 0$ and $\bar{\gamma}'_d(\beta,d) > 0$ when $\bar{\gamma}(\beta,d) > 0$. Hence, for $\gamma \in (0,\bar{\gamma}(\beta,d)]$, $(e_{TC}^{*,nc} - \bar{e}_{TC}^{*,nc}) > 0$, otherwise it is negative. Finally, we compare equilibrium emissions when the firms cooperate in green R&D and express the difference as follows:

$$e_{TC}^{*,c} - \bar{e}_{TC}^{*,c} = -\left(8d^2(1+\beta)^2 + (1+d)(5d-1)\gamma\right)\frac{(1+\beta)^2}{\Psi\Delta}A, \tag{B.6}$$

which is always negative.

C Proof of Lemma 1

1) *Precommitment Policy Game*
1.1) *Non-cooperative scenario*: Using the results from Proposition 1, in the precommitment policy game, because the equilibrium emissions are identical with a tax and with a standard, when the firms do not cooperate in R&D, all equilibrium outcome in terms of R&D, production and social welfare are also identical. The proof can be sketched out as follows. First, we show that the social welfare functions (8) and (12) are identical and then we claim that optimization yields only one possible relationship between the two environmental policy instruments. From equations (1), (10) and (11), we can write that $\bar{e} = e(\tau) = q(\tau) - (1+\beta)z(\tau) = \frac{A}{3} - \frac{3(1+\beta)+\gamma}{3\gamma}\tau$. We then deduce that $S\bar{W}^{nc}_{PC}(\bar{e}) = S\bar{W}^{nc}_{PC}(\bar{e}(\tau))$.
a) Using equation (12),

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

and using equation (8),

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

thus $SW^{nc}(\tau) = S\bar{W}^{nc}_{PC}(e(\tau)) \quad \forall\tau$.
b) If $SW^{nc}_{PC}(\tau) = S\bar{W}^{nc}_{PC}(e(\tau)) = S\bar{W}^{nc}_{PC}(\bar{e})$, the maximum values of $S\bar{W}^{nc}_{PC}$ and SW^{nc}_{PC} are the same and obtained for the same $\tau = \tau^{*,nc}_{PC}$. Therefore, we can easily deduce that $z^{*,nc}_{PC} - \bar{z}^{*,nc}_{PC} = 0$, $q^{*,nc}_{PC} - \bar{q}^{*,nc}_{PC} = 0$ and $SW^{*,nc}_{PC} - S\bar{W}^{*,nc}_{PC} = 0$ for any values of $\mathcal{Z}^{nc}_{PC}$, $\mathcal{Q}^{nc}_{PC}$ and $\mathcal{SW}^{nc}_{PC}$.
1.2) *Cooperative scenario*: Using results from Table 3, the difference in optimal R&D efforts when the firms cooperate can be expressed as:

$$z^{*,c}_{PC} - \bar{z}^{*,c}_{PC} = \frac{\mathcal{Z}^c_{PC}}{(1+\beta)}(e^{*,c}_{PC} - \bar{e}^{*,c}_{PC}),$$

with $\mathcal{Z}^c_{PC} = \frac{\left(12d(1+\beta)^4 + (1+7d)(1+\beta)^2\gamma + (1+d)\gamma^2\right)}{(10(1+\beta)^2+3\gamma)} > 0$. Hence, $z^{*,c}_{PC} - \bar{z}^{*,c}_{PC}$ is always positive according to equation (A.4). In addition, from equation (1), it is straightforward to show that:

$$q^{*,c}_{PC} - \bar{q}^{*,c}_{PC} = \mathcal{Q}^c_{PC}(e^{*,c}_{PC} - \bar{e}^{*,c}_{PC}),$$

with $\mathcal{Q}^c_{PC} = \frac{\left[10(1+\beta)^2 + 12d(1+\beta)^4 + 3\gamma + (1+7d)(1+\beta)^2\gamma + (1+d)\gamma^2\right]}{10(1+\beta)^2+3\gamma} > 0$, which according to equation (A.4), is always positive, implying $\Rightarrow q^{*,c}_{PC} > \bar{q}^{*,c}_{PC}$.

Inserting equations (11) and (13) into (12) we obtain:

$$SW^{*,c}_{PC} = \frac{2d(1+\beta)^2\left(4(1+\beta)^2+\gamma\right) + 4\gamma(1+\beta)^2 + \gamma^2}{Y}A^2 \tag{C.7}$$

In addition, using equations (6), (7), (8) and (9), we have:

$$S\bar{W}^{*,c}_{PC} = \frac{2d(1+\beta)^2(6(1+\beta)^2+\gamma) + 6(1+\beta)^2 + \gamma^2}{W}A^2 \tag{C.8}$$

The difference in social welfare is thus:

$$SW_{PC}^{*,c} - \bar{SW}_{PC}^{*,c} = \mathcal{SW}_{PC}^{c}(e_{PC}^{*,c} - \bar{e}_{PC}^{*,c}),$$

with $\mathcal{SW}_{PC}^{c} = \left(\frac{2d(1+\beta)^2+\gamma}{\gamma}A\right) > 0$. According to equation (A.4), $SW_{PC}^{*,c} - \bar{SW}_{PC}^{*,c}$ is always positive.
2) *Time-consistent Policy Game*
Using equations (15) and (19), we obtain:

$$e(z_{TC}^{*,h}) - \bar{e}(\bar{z}_{TC}^{*,h}) = -\frac{(1+\beta)}{(1+d)}(z_{TC}^{*,h} - \bar{z}_{TC}^{*,h})$$

$$z_{TC}^{*,h} - \bar{z}_{TC}^{*,h} = \frac{\mathcal{Z}_{TC}}{(1+\beta)}\left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right), \forall h = \{nc, c\} \tag{C.9}$$

with $\mathcal{Z}_{TC} = \mathcal{Z}_{TC}^{h} = -(1+d) < 0, \forall\, h = \{nc, c\}$. From equation (B.5), we easily deduce that for $\gamma \in (0, \bar{\gamma}]$, $(z_{TC}^{*,nc} - \bar{z}_{TC}^{*,nc}) < 0$, otherwise it is positive. Using equation (B.6), we easily deduce that $z_{TC}^{*,c} - \bar{z}_{TC}^{*,c}$ is always positive. Then, from equation (1), we obtain:

$$q_{TC}^{*,h} - \bar{q}_{TC}^{*,h} = (e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}) + (1+\beta)(z_{TC}^{*,h} - \bar{z}_{TC}^{*,h}) = \mathcal{Q}_{TC}\left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right), \forall h = \{nc, c\} \tag{C.10}$$

with $\mathcal{Q}_{TC} = \mathcal{Q}_{TC}^{h} = -d < 0, \forall\, h = \{nc, c\}$. Using equation (B.5), we deduce that for $\gamma \in (0, \bar{\gamma}]$, $(q_{TC}^{*,nc} - \bar{q}_{TC}^{*,nc}) < 0$, otherwise it is positive. It follows from equation (B.6) that $q_{TC}^{*,c} - \bar{q}_{TC}^{*,c}$ is always positive.

Finally, from the social welfare function and equations (17), (21), (C.9) and (C.10) we obtain:

$$\begin{aligned}
SW_{TC}^{*,h} - \bar{SW}_{TC}^{*,h} &= 2A\left(q_{TC}^{*,h} - \bar{q}_{TC}^{*,h}\right) - 2\left((q_{TC}^{*,h})^2 - (\bar{q}_{TC}^{*,h})^2\right) - \gamma\left((z_{TC}^{*,h})^2 - (\bar{z}_{TC}^{*,h})^2\right) - 2d\left((e_{TC}^{*,h})^2 - (\bar{e}_{TC}^{*,h})^2\right)\\
&= \left(q_{TC}^{*,h} - \bar{q}_{TC}^{*,h}\right)\left(2A - 2\left(q_{TC}^{*,h} + \bar{q}_{TC}^{*,h}\right)\right) - \gamma\left(z_{TC}^{*,h} - \bar{z}_{TC}^{*,h}\right)\left(z_{TC}^{*,h} + \bar{z}_{TC}^{*,h}\right) - 2d\left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right)\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right)\\
&= \left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right)\left((-d)\left(2A - 2\left(q_{TC}^{*,h} + \bar{q}_{TC}^{*,h}\right)\right) + \gamma\frac{(1+d)}{(1+\beta)}\left(z_{TC}^{*,h} + \bar{z}_{TC}^{*,h}\right) - 2d\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right)\right)\\
&= \left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right)\left((-d)\left(2A - 2\left(A - d\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right)\right)\right) + \gamma\frac{(1+d)}{(1+\beta)}\left(z_{TC}^{*,h} + \bar{z}_{TC}^{*,h}\right) - 2d\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right)\right)\\
&= \left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right)\left(-2d^2\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right) + \gamma\frac{(1+d)}{(1+\beta)}\left(z_{TC}^{*,h} + \bar{z}_{TC}^{*,h}\right) - 2d\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right)\right)\\
&= \left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right)\left(-2d(d+1)\left(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}\right) + \gamma\frac{(1+d)}{(1+\beta)}\left(z_{TC}^{*,h} + \bar{z}_{TC}^{*,h}\right)\right)\\
&= \mathcal{SW}_{TC}^{h}\left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right)
\end{aligned} \tag{C.11}$$

with $\mathcal{SW}_{TC}^{h} = \frac{1+d}{1+\beta}\left[-2d(1+\beta)(e_{TC}^{*,h} + \bar{e}_{TC}^{*,h}) + \gamma(z_{TC}^{*,h} + \bar{z}_{TC}^{*,h})\right] < 0, \forall\, h = \{nc, c\}$. The term inside the brackets is always negative for all $\beta \in (0, 1]$, and any values of $\gamma > 0$ and $d > 1$ since $\gamma\bar{z}_{TC}^{*,h} < 2d(1+\beta)\bar{e}_{TC}^{*,h}$ and $\gamma z_{TC}^{*,h} < 2d(1+\beta)e_{TC}^{*,h}$. Hence, when $\left(e_{TC}^{*,h} - \bar{e}_{TC}^{*,h}\right) < 0$, $SW_{TC}^{*,h} - \bar{SW}_{TC}^{*,h} > 0$ and conversely.

D Proof of Proposition 4

Endogenous choices of firms and government are determined by backward induction in each policy game.

i) We first obtain the SPNE by solving the precommitment policy game (See Figure 1a.). From Proposition 3, we know that when the firms cooperate, social welfare is always higher under an ETP, so the regulator chooses to implement a tax. When the firms do not cooperate, the regulator is indifferent between an ETP and an ESP. At $t = 0$, the firms must therefore compare their individual non-cooperative profits under an ESP and an ETP with their individual cooperative profits under an ETP. To sustain cooperation at the SPNE, $\pi_{PC}^{*,c} \geq min\{\pi_{PC}^{*,nc}, \bar{\pi}_{PC}^{*,nc}\}$. To ensure it is always satisfied, we assess the strictest inequality that is $\pi_{PC}^{*,c} \geq \pi_{PC}^{*,nc}$, because $\bar{\pi}_{PC}^{*,nc} - \pi_{PC}^{*,nc} = \tau_{PC}^{*,nc}\bar{e}_{PC}^{*,nc}$ is positive. Since the analytical expression for the profit difference $\pi_{PC}^{*,c} - \pi_{PC}^{*,nc}$ is not tractable, we plot $\hat{\gamma}(\beta, d)$ in Figure 2 such that $\pi_{PC}^{*,c}(\hat{\gamma}(\beta, d)) = \pi_{PC}^{*,nc}(\hat{\gamma}(\beta, d))$. Notice that we consider only the positive root of the fifth-degree polynomial. Hence, for $\gamma < \hat{\gamma}(\beta, d)$, the firms choose not to cooperate and the regulator enforces either an emission standard or a tax. On the contrary, when $\gamma > \hat{\gamma}(\beta, d)$, the firms choose to cooperate and the regulator implements a tax. Finally, we simulate values of the asymptotic limit of the solution, $\hat{\gamma}(\beta, d)$, for different degrees of spillovers as d approaches infinity (See Table 2.).

ii) Second, we obtain the SPNE by solving the time-consistent policy game by backward induction (See Figure 1b.). Again, from Proposition 3, we know that an ETP outperforms an ESP when the firms cooperate in green R&D since $SW_{TC}^{*,c} > \bar{SW}_{TC}^{*,c}$. When the firms do not cooperate in R&D, an ETP only dominates over an ESP if $\gamma > \bar{\gamma}(\beta, d)$. Then, the firms must compare $\pi_{TC}^{*,c} - \pi_{TC}^{*,nc}$ for $\gamma > \bar{\gamma}(\beta, d) = \frac{d(1+\beta)(2d-3)(2d+1-\beta)}{2(1+d)(4d-1)}$. Otherwise, they assess the following difference: $\pi_{TC}^{*,c} - \bar{\pi}_{TC}^{*,nc}$. Following Poyago-Theotoky (2007), the firms always prefer R&D cooperation when the regulator implements a tax ($\pi_{TC}^{*,c} > \pi_{TC}^{*,nc}$), that is for $\gamma > \bar{\gamma}(\beta, d)$. Because the analytical expression for the difference in profits $\bar{\pi}_{TC}^{*,nc} - \pi_{TC}^{*,c}$ is not tractable, we plot $\underline{\gamma}(\beta, d)$ in Figure 3 such that $\bar{\pi}_{TC}^{*,nc}(\underline{\gamma}(\beta, d)) = \pi_{TC}^{*,c}(\underline{\gamma}(\beta, d))$.[15] When $\bar{\gamma}(\beta, d) > \gamma > \underline{\gamma}(\beta, d)$, the firms choose not to cooperate in R&D and the regulator enforces an emission standard. When $\gamma < \underline{\gamma}(\beta, d)$, the firms choose to cooperate in green R&D and the regulator implements a tax. Similar to the first part of the proof, we can study the limits of $\bar{\gamma}(\beta, d)$ and $\underline{\gamma}(\beta, d)$ for values of β and as d tends to infinity (See Table 2.). For all β, $\lim_{d\to\infty} \bar{\gamma}(\beta, d) = +\infty$. We cannot explicitly derive asymptotic line for $\underline{\gamma}(\beta, d)$, but we may obtain simulated values as d tends to infinity depending on β. Both thresholds are defined for all $\beta \in (0, 1]$ and $d > 3/2$ and $\underline{\gamma}'_{\beta}(\beta, d) < 0$ and $\underline{\gamma}'_{d}(\beta, d) > 0$.

E Proof of Proposition 5

We solve the SPNE by backward induction.

i) In the precommitment game, for $\gamma > \hat{\gamma}(\beta, d)$, if cooperation is allowed, the firms

[15] There exist three solutions in γ to the equation $\pi_{TC}^{*,c} - \bar{\pi}_{TC}^{*,nc} = 0$: two complex and one real. We choose to retain only the real one, that is defined over all admissible parameter values.

$d \to \infty$	$\beta = 0.1$	$\beta = 0.5$	$\beta = 0.9$
$\lim_{d\to\infty} \hat{\gamma}(\beta, d) =$	25.25	10.36	9.7
$\lim_{d\to\infty} \bar{\gamma}(\beta, d) =$	$+\infty$	$+\infty$	$+\infty$
$\lim_{d\to\infty} \underline{\gamma}(\beta, d) =$	12.1	4.5	4.011
$\lim_{d\to\infty} \gamma^{Ban}(\beta, d) = 2 + \beta + \frac{1}{\beta}$	12.1	4.5	4.011
$\lim_{d\to\infty} \gamma_{\varphi}(\beta, d) = \frac{(1+\beta)^2(1-\beta)}{2\beta}$	4.7	3.37	0.045

Table 2: Limits of thresholds.

cooperate and the government implements a tax. If R&D cooperation is prohibited, the regulator is indifferent between an ESP and an ETP. At the pre-game stage, the comparison is between $SW^{*,c}_{PC}$ and $SW^{*,nc}_{PC} = S\bar{W}^{*,nc}_{PC}$. Yet, from (Ouchida and Goto, 2016a, 2022), we know that cooperation promotes higher social welfare, so the regulator allows cooperation. In addition, when $\gamma < \hat{\gamma}(\beta, d)$, the firms choose not to cooperate anyway. In the precommitment policy game therefore, the regulator should always allow green R&D cooperation.

ii) In the time-consistent policy game, when $\gamma > \bar{\gamma}(\beta, d)$, the firms cooperate and the regulator implements a tax. If R&D cooperation is banned and the firms do not cooperate, the regulator also implements an ETP. In the pre-game stage, the regulator then compares $SW^{*,c}_{TC}$ and $SW^{*,nc}_{TC}$. According to Ouchida and Goto (2016b), Poyago-Theotoky (2007) shows that $SW^{*,c}_{TC} > SW^{*,nc}_{TC}$ for $\gamma > \gamma_{\varphi} = \frac{d(1+\beta)^2(1-\beta)(2d-3)}{2(2d\beta(d+1)-\beta+d)}$ defined such $\gamma_{\varphi} \equiv \{\gamma > 0 \mid \varphi \equiv SW^{*,c}_{TC} - SW^{*,nc}_{TC} = 0, d > 3/2\}$ and $\lim_{d\to\infty} \gamma_{\varphi} = \frac{(1+\beta)^2(1-\beta)}{2\beta}$ (See Table 2.). We can show that $\gamma_{\varphi} \lesseqqgtr \bar{\gamma}(\beta, d)$ for $\beta \gtreqqless \frac{1}{1+2d}$ and $d > 3/2$ (See the dashed line on Figure 4.). Hence, the regulator allows R&D cooperation for $\gamma \geq max\{\bar{\gamma}(\beta, d), \gamma_{\varphi}\} > 0$. Then, for $\gamma_{\varphi} > \gamma > \bar{\gamma}(\beta, d)$, "non-cooperation-ETP" emerges as an SPNE because R&D cooperation is prohibited. When $\bar{\gamma}(\beta, d) > \gamma > \underline{\gamma}(\beta, d)$, the firms do not cooperate and the regulator is indifferent between allowing and banning cooperation. Finally, from Proposition (4), when $\bar{\gamma}(\beta, d) > \underline{\gamma}(\beta, d) > \gamma$, the firms choose to cooperate and the regulator implements a tax. If R&D cooperation is prohibited, the firms do not cooperate but the regulator adopts an ESP. Thus, in the pre-game stage, the regulator compares $SW^{*,c}_{TC}$ and $S\bar{W}^{*,nc}_{TC}$. We show that cooperation is prohibited if $SW^{*,c}_{TC} < S\bar{W}^{*,nc}_{TC}$ that is for $\gamma < \gamma^{Ban}(\beta, d) = \frac{d(1+\beta)^2(1-\beta+2d)(2d-3)}{(1+d)(-1+6d+(-3+4d(2+d))\beta)}$ defined as $\gamma^{Ban} \equiv \{\gamma > 0 \mid SW^{*,c}_{TC} - S\bar{W}^{*,nc}_{TC} = 0, d > 3/2\}$ and $\lim_{d\to\infty} \gamma^{Ban}(\beta, d) = 2 + \beta + \frac{1}{\beta}$. In this region, we have already shown that the firms have incentives to cooperate for all $\gamma \leq \underline{\gamma}(\beta, d)$. In addition, $\gamma^{Ban}(\beta, 3/2) = \underline{\gamma}(\beta, 3/2) = 0$. Again, we simulate the values of $\gamma^{Ban}(\beta, d)$ and we show that $\gamma^{Ban}(\beta, d) > \underline{\gamma}(\beta, d)\ \forall \beta, d > 3/2$ and that both thresholds tend to the same asymptotic line (See Table 2.), so that $SW^{*,c}_{TC} < S\bar{W}^{*,nc}_{TC}$ (See the red line on Figure 4.). Hence, for all $\gamma < \underline{\gamma}(\beta, d)$, the regulator should prohibit green R&D cooperation.

F Equilibrium results

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

Table 3: Precommitment policy game: Equilibrium outcomes under either an ETP or an ESP.
$A=(a-c)$, $X=2d(3(1+\beta)+\gamma)^2+\gamma(9+2\gamma)$, $Y=2d(3(1+\beta)^2+\gamma)^2+\gamma(9(1+\beta)^2+2\gamma)$, $W=2d(4(1+\beta)^2+\gamma)^2+2\gamma(8(1+\beta)^2+\gamma)$.

	Emission Tax Policy		Emission Standard Policy	
	Non-cooperative R&D	**Cooperative R&D**	**Non-cooperative R&D**	**Cooperative R&D**
τ / $\bar{e}$	$\frac{d(2d-3)(1+\beta)^2+2\gamma(2d^2+d-1)}{2\Omega}A$	$\frac{d(2d-3)(1+\beta)^2+\gamma(2(d)^2+d-1)}{\Delta}A$	$\frac{2\gamma(1+d)+(1+2d-\beta)(1+\beta)}{\Theta}A$	$\frac{(1+d)\gamma+2d(1+\beta)^2}{2\Psi}A$
q	$\frac{2(1+d)\gamma+d(1+\beta)(7+4d+3\beta)}{2\Omega}A$	$\frac{d(2d+5)(1+\beta)^2+\gamma(1+d))}{\Delta}A$	$2\frac{(1+d)\gamma+d(1+2d-\beta)(1+\beta)}{\Theta}A$	$\frac{(1+d)\gamma+2d^2(1+\beta)^2}{2\Psi}A$
z	$\frac{(2d-1)(1+d)+d(1+\beta)}{\Omega}A$	$(1+\beta)\frac{(1+d)(2d-1)+2d}{\Delta}A$	$\frac{(2d-1)(2d+1-\beta)}{\Theta}A$	$(1+\beta)\frac{d(d-1)}{\Psi}A$
E	$\frac{2(1+d)\gamma+(1+\beta)(2+3d+d\beta)}{\Omega}A$	$2\frac{(1+d)\gamma+(1+\beta)^2(2d+1)}{\Delta}A$	$2\frac{2\gamma(1+d)+(1+2d-\beta)(1+\beta)}{\Theta}A$	$\frac{(1+d)\gamma+2d(1+\beta)^2}{\Psi}A$

Table 4: Time-consistent policy game: Equilibrium outcomes under either an ETP or an ESP.
$A=(a-c)$, $\Omega=2\gamma(1+d)^2+d(1+\beta)(3(3+\beta)+d(7+\beta))$, $\Delta=2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2$, $\Theta=4\gamma(1+d)^2+6d(1+2d-\beta)(1+\beta)$, $\Psi=\gamma(1+d)^2+4d^2(1+\beta)^2$.

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