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Rania Mabrouk, Oliwia Kurtyka

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**Mabrouk, Rania
Kurtyka, Oliwia**

December 14, 2020

JEL codes: D43, H23, L13, Q42, Q58

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contact : agnes.vertier@inrae.fr



Strategic use of environmental innovation in vertical chains and regulatory attitudes

Rania Mabrouk

Univ. Grenoble Alpes, CNRS, INRAE, Grenoble INP, GAEL, 38000 Grenoble, France
Email: Rania.Kamoun@univ-grenoble-alpes.fr

Oliwia Kurtyka

Univ. Grenoble Alpes, CNRS, INRAE, Grenoble INP, GAEL, 38000 Grenoble, France
Email: oliwia.kurtyka@grenoble-inp.fr

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Abstract

We analyze firm's choice of abatement technology in vertical chains. A downstream polluting monopoly can buy a license from an upstream supplier with mature end-of-pipe equipment (outsider) or develop an in-house clean technology. Insider's innovation may be undertaken only to increase bargaining power of the polluter. We put the light on the strategic role of environmental regulation to influence this choice. We find that the role of regulator as a technology forcing authority is confirmed in regions of under-investment. However, under certain conditions, an over-investment occurs that forces the regulator to become laxer. Paradoxically, the regulator may oppose innovation even if the resulting technology is used by the innovator. All these results rely upon the creation of total profits from the integrated vertical structure.

Keywords: environmental innovation, abatement technology, clean technology, end-of-pipe equipment, vertical chain, regulation, bargaining.

JEL Code: D43, H23, L13, Q42, Q58

1 Introduction

In response to economic and ecological crises that are becoming increasingly pressing, governments are trying to promote environmental innovations as shown, for example, by the European commission report "Europe 2020" that followed the report of Lisbon (2000). In order to reach this objective, the economic analysis of environmental policy suggests using market-based instruments since they provide stronger dynamic incentives for environmentally technological innovation (Baumol and Oates, 1988).

Environmental innovations are typically divided in two distinct types: end-of-pipe solutions and clean technologies. The former occurs at the end of production process to mitigate environmental impacts of economic activities without changing the production process itself. In contrast, clean innovations, which are generally argued as being preferable in the long run (Frondel et al (2007), Porter and van der Linde (1995), Yarime (2008)), minimize pollution at source by using cleaner inputs and production methods. However, in most cases, they require an intensive change in productive systems and a significant commitment in terms of financial and human resources. After more than thirty years since the creation of environmental policies, it is strikingly obvious to note, not without regrets, that the majority of technologies used are end-of-pipe solutions (Hammar and Lofgr en (2010)). While studies examining the impact of environmental regulations on innovation are widespread¹, only few papers have tried to address the issue of investment and technology choice.

Our paper addresses the question of technology choice through the lenses of strategic use of environmental innovation. The purpose of this paper is to contribute to environmental literature by examining the innovation and technology adoption decisions in vertical chains. Our framework challenges the hypothesis that innovation is done only by eco-industries and assumes that environmental innovation can be done by the polluter as well. A monopolist liable to an environmental taxation has a possibility either to buy an end-of-pipe technology from an independent eco supplier² or to develop a clean technology on his own. This type of in-house innovation is supported by empirical research. Lanjouw and Mody (1999) estimate that worldwide 20% of patents for pollution control technologies are taken up by insiders. Jaffe and Palmer (1997), Brunnermeier and Cohen (2003) and others evidence outlays on pollution-control R&D made by polluting firms and environmental services sector. Our main hypothesis is that polluting firm can develop R&D activities for clean technologies in order to increase its strategic advantage over an existing supplier of an end-of-pipe solution.

¹See the excellent surveys of Jaffe et al (2003) and Requate (2005).

²David and Sinclair-Desgagn e (2005) launched the literature on the independent eco-industry supplying abatement goods and services to a polluting industry.

In our setting the end-of-pipe supplier has a mature technology and he does not invest in further research.

Our contribution to the literature on strategic use of innovation is twofold. First, we explain that the adoption of abatement technology is a result of a competition between different types of technologies. On one hand, a clean technology developed by the downstream firm is more efficient in abating the pollution (but more expensive) and, on the other hand, the end-of-pipe technology sold by an upstream firm is cheaper but results in lower abatement. In order to investigate the value of a technology, it is helpful to start from a certain benchmark. For this purpose, we assume that the regulator has levied an emission tax to incentivize firms to undertake abatement by maximizing welfare given technology choices of polluter. Second, we study how environmental policy should be adjusted when innovation is used strategically in vertical chains.

To this end, we develop a simple vertical relationship model with three players: 1) the regulator who fixes an environmental tax to mitigate the environmental damage due to the economic activities of the monopoly; 2) a monopoly generating by-product emissions of a harmful pollutant and facing a price-sensitive consumer demand on the final market; and 3) an upstream eco-industry supplier who develops an end-of-pipe technology that it licenses to the polluting monopoly. As expected, we show that the introduction of the environmental tax necessarily involves the use of an environmental abatement technology. However, under certain conditions, we argue that the polluting monopoly can develop an in-house clean technology only to strengthen its bargaining position with respect to the eco-industry supplier. Our primary focus is on a case where both insider innovates and outsider strikes a bargaining deal with the polluter. However, for completeness we also consider the case when outsider drops out of market or no innovation is undertaken. Furthermore, the discontinuity in insider's profit function is considered, but all calculations are relegated to the appendix. We discuss the role of regulator in such situations.

Our analysis brings to light some important findings. It is well known that in a framework where firms expect the regulator to ratchet up the standards *ex post* innovation, policymaker encounters the problem of underinvestment. In our setting, as the R&D effort of polluting firm has no impact on the solution proposed by the regulator, strategic reasons mentioned above for under-investment are absent. However, the problem of under-investment and of over-investment nevertheless occurs. They stem from the misalignment of interests between the regulator and innovating firm.

Endogenous determination of R&D incentives results in different consequences the industrial choices have on welfare. From the welfare point of view, the duplication of R&D expenses is unwarranted in case of purely substitutable nature of innovations. In our model two types of innovation are not perfect substitutes. The technology developed by the in-

sider is more efficient in terms of emissions abated. This stems from the fact that insider has more precise knowledge concerning their production process, materials used and potential for change. Hence duplication of R&D procures the social planner a benefit from higher pollution abatement. Intuitively, this should decrease regulator's incentive to be more complacent when firms innovate.

Moreover, investment impacts not only marginal abatement costs but also production cost. The direction of the impact is unknown. In reality, the impact of clean technologies on variable cost can be either positive or negative depending on the technology in question. For example, paper industry in Sweden moved to a closed-loop production process and its variable costs consequently decreased. The same applies to solar electricity production. However, for biological agriculture, moving to no pesticide production increases the costs (or decreases the agricultural yields). Since the clean technology changes production level, this additionally has an impact on the size of the total cake produced in the economy and therefore changes regulator's approach to innovation. We show that the size of the total cake produced in the economy may increase or decrease as a result of innovators' competition. We show that even if the impact on production cost is positive (i.e. it becomes more expensive to produce) the insider and the regulator have interests in developing this option, however for different reasons.

We derive some surprising results. The polluting firm may have interest in innovating whereas the regulator prefers the end-of-pipe technology to be adopted therefore leading to over-investment. This comes from the fact that innovation does not necessarily imply that the results of innovative solutions would be applied and consequently, that the clean technology would prevail. The intuitively convincing reason for this result is as follows. The polluter decides to innovate in order to increase his bargaining power. For the regulator, the resulting solution represents only the transfer of benefits between outsider and insider, a transfer that is costly from the society point of view.

The role of regulator as a technology forcing authority is confirmed in regions of under-investment. In region of over-investment, the regulator must be laxer in order to deter the insider from innovating for the bargaining reasons only. Indeed, integrated technology is only interesting where taxation is sufficiently strong and this may lead the polluting company to innovate for bad reasons. The resulting integrated profits may be below the ones with no innovation. However the insider's share of the profits may be bigger when he innovates, motivating him to take bad decisions from the welfare point of view. To counteract insider's wasteful R&D expenses, the regulator must decrease the taxation and render the clean technology less interesting. Finally and paradoxically, the regulator may oppose the research even if the resulting technology is used by the innovator. But he might not be able to deter the innovation and wasteful innovation may nevertheless occur.

We should mention that all these results rely upon the creation of total profits from the integrated vertical structure.

The paper is organized as follow. Section 2 reviews existing literature, section 3 sets up the model. Section 4 and 5 characterize the production and bargaining stage. Section 6 turns toward R&D incentives. Finally, section 7 explores the question of the regulators response. At the end, conclusion follows.

2 Literature review

In empirical field on different types of technology Frondel et al. (2007) and Hammar and Lofgr en (2010) analyze factors that may enhance firm's propensity to implement clean technologies rather than end-of-pipe ones. Frondel et al. (2007) use a survey on OECD firms and find that environmental regulations are more likely to lead to the adoption of end-of-the-pipe solutions and that market forces, such as cost savings or environmental management tools lead to the adoption of cleaner production processes. On the other hand, Hammar et Lofgr en (2010) use a panel of Swedish firms to test for other explanatory variables. They find that learning by doing and knowledge, measured by expenditures on green R&D, increase the probability of investment in clean technologies. In contrast, the size of firms measured by the revenue, and energy prices are important determinants for investing in the end-of-pipe technologies.

In theoretical literature few papers have recently begun to investigate the question of abatement technology choice. Meunier and Nicolai (2012) show that, depending on the type of technology used, the impact of environmental regulation on firms' profits can be either positive or negative. In the same logic, Christin et al. (2013) study the effect of a cap-and-trade system on industry profits under imperfect competition and highlight that the abatement technology type is fundamental to answer this question. They show that industries that use process-integrated technologies are more affected than those using end-of-pipe abatement technologies.

Early approaches to environmental innovation assume that a polluter is also an innovator and that a technological discovery results in a downward shift in the marginal abatement curve (Milliman and Prince (1989), Montero (2002 and 2002a)). This initial hypothesis was soon replaced with vertical structure considerations. Parry (1997) models the R&D sector as a competitive free entry sector where the innovator gets a patent and sells the discovery to polluting firms. At the same time, alternative assumptions on the impact of innovation cost structure appear. Requate (1998) was the first to consider that innovation leads to a lower rate of emissions per output but at the same time imposes a higher marginal cost of production. Requate (2003) models the R&D sector as a

monopolistic one with a certain probability of discovery whereas the polluting firms have heterogeneous abatement costs. The innovation decreases those costs but to a different degree. In other words, the innovation may be more suitable to some firms and less to others. This kind of modeling is consistent with the end-of-pipe type of abatement.

In majority of papers on environmental innovation in vertical relationships it is assumed that only the upstream firm is responsible for innovation. Nimubona and Sinclair-Desgagne (2011) allow for both types of technology to be used: in-house technology and an outsourced one from independent supplier. Moreover, they show that the existence and performance of eco-industry depend on the substitutability or complementarity of technologies. Heyes and Kapur (2011) allow both sectors to develop abatement technologies on their own and their paper is the closest to ours.

The literature on strategic use of innovation is abundant. Quite a few papers study innovation decision taken vis-à-vis competitors. Majority of them study horizontal R&D, i.e. where research is lead by firms that are competitors on the product market. In such pure horizontal R&D set-up, a firm's cost-reducing investment results from two effects: a cost minimizing effect and a strategic effect (Montero (2002)). The latter enables the innovator to steal market share from its rivals without affecting their cost structures.

Vertical R&D are also studied but to a smaller extent. Banerjee and Lin (2003) study R&D decisions in vertically related industries and find that downstream firms have more incentives to innovate if a price adjustment by the input supplier leads to a higher production cost for all rival firms. Biglaiser and Horowitz (1995) study research and adoption decisions where innovation decreases emissions. They find that standards may discourage innovation as firms may prefer to adopt someone else's technology rather than innovate on their own.

Several papers study strategic innovations in order to influence regulatory policy (see: Puller (2006), Requate (2005)). This strand of literature relates very much to the timing of a game and commitment issue. Requate (2003) shows, that when the regulator commits to regulation *ex ante* innovation, the optimal adjustment of its policy to overpricing problem by an R&D firm is to adopt taxes rather than permits. Moreover, an optimal policy for the regulator is to think of a menu of instruments conditional on innovation. The earlier the regulator acts, the higher the welfare given some flexibility over instrument setting. When regulation is set *ex post* innovation two countervailing incentives drive firms' innovation decisions. First, when regulator cannot commit to a policy, firms have lower incentives to innovate as they expect the regulator to ratchet up the policy once the innovation developed (Puller (2006)). This may happen in order to expropriate gains that occur to innovators. Second, when rising rival costs (Salop and Scheffman (1987)) becomes possible as well, firms may decide to increase their R&D to influence positively the policy and penalize

their competitors (Puller (2006)). Note that in presence of rent seeking behavior unbiased regulator is not welcomed. Heyes and Kapur (2011) show, that there is a need for the social planner to delegate the regulation to an unbiased authority in order to correct for the regulatory influence and the consequent underinvestment.

Literature on the topic of environmental policy in vertical chains is scarce. Sinclair-Desgagne and David (2008) were the first to consider environmental regulation in vertical chains. They show that combining an emission tax to a subsidy to polluters cannot lead to first-best, while the opposite conclusion holds if the subsidy is granted instead to eco-industry. David et al. (2011) point out that when abatement is provided by an oligopolistic eco-industry with free-entry, the optimal emission tax may exceed, fall short or be equal to the Pigouvian rate, depending on its effect on total abatement supply relative to entry in the eco-industry. However, innovation is absent in their framework. Biglaiser and Horowitz (1995) find that, technology adoption standards are part of the optimal regulation. They also show that making the adoption standard stricter reduces research. To the best of our knowledge, this paper is the first one to consider innovation with different types of technologies and regulatory attitudes in the same setting.

3 The model

A firm with a monopoly power faces a linear demand function $D(p) = a - bp$ where a and b are positive parameters and p is the price on the final market. Production costs are quadratic $\delta D(p)^2$, with $\delta > 0$. While producing, the firm generates pollution e as a by product of its business activity. A pollutant e is proportional to output $D(p)$ and given by $e = \theta D(p)$. For simplicity we assume that $\theta = 1$.

An environmental tax t is imposed by a regulator on the polluting monopoly in order to motivate him to undertake costly abatement. The regulator's choice of taxation is based on an evaluation of a welfare function including environmental damage. This function e^2 and abatement levels depend, as detailed below, on technology choice in equilibrium. For the regulator, research and development is not sunk yet. When evaluating welfare, the regulator knows that he can influence the state of technology. From this point of view, we follow the literature on technology forcing regulation.

The polluting company has two options to address this regulation: to continue polluting and paying the tax on total emissions or to use a technology to abate some or all emissions. In case the decision to abate is taken, the polluter must decide on the type of technology he will use. The abatement technology stems from two different sources: internal research done by the polluter (insider) that modifies its production process (and therefore its production costs) or external licensing of an end-of-pipe equipment from an

upstream supplier (outsider).

In our model, three points render the insider's investment decision attractive. First, due to innovation, production costs may decrease. This motivates the insider, other things equal, to do research. Examples of such innovations can be found in a paper and pulp industry (bleaching technology- see A-K. Bergquist and K.Soderholm, 2015) as well as in metallurgy in quenching process. In case of the increase of production cost, this hampers the insider's innovation incentives. This clearly applies to organic products where production becomes more expensive. Second, we assume that the internal technology, which is a process-integrated one, results in zero pollution level after adoption while the external end-of-pipe technology has a lower marginal efficiency of depollution and imposes an additional cost of adoption. In other words, the abatement technology efficiencies are different for the insider's and the outsider's technology. Third, the insider is also motivated by the possibility to obtain a larger share of a pie in bargaining due to a higher outside option created by the new investment (see also Heyes and Kapur (2011)). However, the increase in bargaining position of the insider is done at a cost of technology development r . The insider must incur this cost whether he strikes a deal with the outsider or not.

Total costs borne by the polluter when he uses the end-of-pipe technology are of four different types: production costs δ that remain unchanged with respect to no technology case, a two-part tariff licence fee (whose value changes with the bargaining position), the adoption costs ω^2 for the technology where ω represents the level of abatement and the tax he owes to the regulator. The clean technology generates only two costs: production cost λ and the fixed R&D cost. As production costs differ depending on the technology choice, this also modifies the output level and consequently the surplus of consumers- the impact that is neglected in literature on end-of-pipe type of equipment. The consequences of industrial choices thus differ from the welfare point of view.

As mentioned before, in our paper the regulation is of an innovation- incentivizing type. For the sake of clarity, let us explicit the timing of the game as follows:

Stage 1) (Regulation) The regulator sets a pollution tax t for each unit of pollutant emitted e .

Stage 2) (R&D stage) The polluting firm (insider) decides whether or not to invest in R&D to develop a clean technology at a cost r .

Once developed, the technology becomes a common knowledge.

Stage 3) (Bargaining) The insider decides which option to choose: paying the tax without any abatement, using a process-integrated technology if such technology has been invented in stage 2, or bargaining with external supplier (outsider) to use the end-of-pipe technology.

Stage 4) (Production) The polluting monopoly decides on the price on the final market

and the abatement level if any.

As usual, we solve the model backwards.

In our analysis, we rely on several assumptions detailed below.

Assumption 1: We suppose that R&D cost is as follows:

$$0 \leq r \leq \frac{a^2}{4b(1+b\lambda)} \quad \text{if } \lambda > \delta \quad (1)$$

$$\frac{a^2}{4b(1+b\lambda)} - \frac{a^2}{4b(1+b\delta)} \leq r \leq \frac{a^2}{4b(1+b\lambda)} \quad \text{if } \lambda < \delta.$$

These assumptions ensure that the monopoly's profit is positive when using clean technology but the use of this technology is never profitable before the introduction of a tax.

Assumption 2: $t < a/b$:Demand stays positive after taxation

4 Production

Let p_\emptyset^* , p_c^* , p_{eop}^* denote the equilibrium prices absent abatement technology, with clean technology and with end-of-pipe equipment respectively. ω_{eop}^* on the other hand, represents the performance of the end-of-pipe technology. These strategic variables result from the following maximization programmes:

$$p_\emptyset^* = \arg \max_p \pi_\emptyset(p) = pD(p) - \delta D(p)^2 - tD(p), \quad (2)$$

$$p_c^* = \arg \max_p \pi_c(p) = pD(p) - \lambda D(p)^2 - r, \quad (3)$$

$$p_{eop}^*, \omega_{eop}^* = \arg \max_{p, \omega} \pi_{eop}^{down}(p, \omega) = pD(p) - \delta D(p)^2 - v\omega - f - \omega^2 - t(D(p) - \omega) - r, \quad (4)$$

where r is a fixed R&D cost of clean technology, ω^2 adoption costs of end-of-pipe technology, (v, f) represent the two-part tariff for end-of-pipe equipment and $\lambda, \delta > 0$ represent variable production costs. As mentioned above the relationship between λ and δ are industry specific.

Easy calculations³ show that, as expected, in the benchmark case with no abatement technology environmental tax increases the price of the monopoly p_\emptyset^* , decreasing the total demand $D(p_\emptyset^*)$ and the polluter's profit $\pi_\emptyset(p_\emptyset^*)$. Monopoly decisions with clean technology are independent of environmental regulation as the firm generates no emissions. However, the decision about the development of clean technology is driven by the taxation. Indeed, when the clean technology increases variable cost of production ($\lambda > \delta$), the polluter never adopts this technology without environmental regulation. In addition, the higher R&D cost

³All calculations are in the appendix

gets, the less incentivizing the technology development is. Contrary to the clean technology, taxation does influence the abatement decisions under the end-of-pipe technology. Note that production decisions with partial abatement (when $D(p) - w > 0$) are unaltered by the use of the end-of-pipe technology and are equal to the case where abatement technology is absent.

One element of this model merits some attention. When the polluting company has an access to end-of-pipe equipment, a problem of discontinuity in profit function with respect to abatement effort ω arises. For very strong taxation, the company may decide to abate all its emissions. We can talk about a total abatement case. With moderate taxation, the abatement is partial. The threshold taxation is given by $t_{cont} = \frac{a}{1+b(\delta+1)} + \frac{v(1+b\delta)}{1+b(\delta+1)}$. This issue is important and gives rise to an interesting result for welfare maximization, a result that is studied in regulation section.

Remark 1 (*Production*) *Output decisions with no technology and with end-of-pipe technology are the same, whereas the production under clean technology differs depending on production cost change induced by innovation.*

5 Bargaining

To acquire the end-of-pipe technology, the polluting monopoly bargains with an external company over a two-part tariff contract (v, f) , where v is a per-unit charge and f is a lump-sum fee.

We assume that the monopolist's bargaining power in negotiations is $\alpha \in [0, 1]$ and $(1 - \alpha)$ is the bargaining power of the external supplier. The Nash product of bargaining is given by:

$$B(v, f) = (\pi_{eop}^{down} - \pi^{down*})^\alpha (\pi_{eop}^{up} - \pi^{up*})^{(1-\alpha)} \quad (5)$$

where π_{eop}^{down} as defined in (4) and $\pi_{eop}^{up} = v * \omega + f$ are the profits of the polluter and supplier respectively. The outside options for these companies, i.e the alternative source of profits if negotiations fail, are given by π^{down*} and π^{up*} . We assume that the outside option of the supplier is zero. However, π^{down*} , the outside option of the monopoly is positive. It is the profit from the clean technology or the profit without any technology if he chooses not to invest in R&D. The results of the bargaining stage depend on which outside option prevails. Below, we solve the negotiation stage for the two cases.

5.1 No technology as the monopoly's outside option

When the polluter decides to not develop the clean technology, the Nash product of bargaining is given by

$$B_{\emptyset}(v, f) = (\pi_{eop}^{down} - \pi_{\emptyset}^*)^{\alpha} (\pi_{eop}^{up})^{(1-\alpha)} \quad (6)$$

where π_{\emptyset}^* is defined in (2). Maximizing $B_{\emptyset}(v, f)$ with respect to v and f gives $v^* = 0^4$ and $f^* = (1 - \alpha)(\Pi_{eop}^{Ind} - \pi_{\emptyset}^*)$ where Π_{eop}^{Ind} is the profit generated by the integrated industry using the end-of-pipe technology. The integrated industry profit is defined as follows:

$$\Pi_{eop}^{Ind} = \max_{p, \omega} pD(p) - \delta D(p)^2 - \omega^2 - t(D(p) - \omega). \quad (7)$$

The total size of the cake Π^{Ind} increases as the end-of-pipe technology is introduced. The reason is the following. The polluting company no longer pays the environmental tax as a part of its emissions are abated. The cost of adoption being lower than tax savings, this profits the industry. Remark that the double marginalisation problem is absent in our framework. The outsider company is licensing the technology at a zero marginal cost and extracting a part of the total gains in the form of a lump sum payment. The insider's profit in this case is $\pi_{eop/\emptyset}^{down*} = \pi_{\emptyset}^* + \alpha(\Pi_{eop}^{Ind} - \pi_{\emptyset}^*)$ and reflects the well known result of the bargaining game. As the polluting monopoly has a positive outside option, this is the minimum amount it must receive from negotiations, the rest of the cake being shared with the outsider according to bargaining powers

The situation is slightly more complicated when the clean technology becomes an outside option.

5.2 Clean technology as the monopoly's outside option

In this subsection we consider that the polluting monopoly uses the profit with clean technology π_c^* as an outside option. When the polluter decides to develop the clean technology, the Nash product of bargaining is given by:

$$B_c(v, f) = (\pi_{eop}^{down} - \pi_c^*)^{\alpha} (\pi_{eop}^{up})^{(1-\alpha)}, \quad (8)$$

where the polluter's outside option $\pi_c^*(p)$ is equal to $\frac{a^2}{4b(1+b\lambda)} - r$. Solving the maximization stage of $B_c(v, f)$ with respect to v and f yields $v^* = 0$ and $\pi_{eop/c}^{up*} = f^* = (1 - \alpha)[(\Pi_{eop}^{Ind} - r) - \pi_c^*]$ for the outsider and $\pi_{eop/c}^{down*} = \pi_c^* + \alpha[(\Pi_{eop}^{Ind} - r) - \pi_c^*]$ for the insider. Whenever $(\Pi_{eop}^{Ind} - r)$ is higher (lower) than the outside option π_c^* of the insider, the polluting firm adopts the end-of-pipe (clean) technology.

⁴The variable part of the tariff v^* is set so as to maximize the joint profits of the supply chain.

Two points deserve particular scrutiny. First of all, the insider's and outsider's payoff can be reexpressed in the following way: $\pi_{eop/c}^{down*} = \pi_c^* + \alpha(\Pi_{eop}^{Ind} - \pi_c^*) - \alpha r$ and $\pi_{eop/c}^{up*} = (1 - \alpha)(\Pi_{eop}^{Ind} - \pi_c^*) - (1 - \alpha)r$. The first two elements follow the standard rules of equilibrium partition of the cake in the bargaining literature. They represent the need to compensate the parties for their outside options and the sharing rule for the remaining surplus (as for the case where no technology was available) (see: Muthoo 1999). Nevertheless, since the insider undertakes a costly investment to increase its bargaining position, a part of the integrated industry profit is lost due to unnecessary innovation. The insider's payoff decreases in consequence as shown by the third element of the profit $\pi_{eop/c}^{down*}$. Interestingly, the innovator does not cover all its investment costs. A part of these costs are passed on the outsider. In other words, the investment in new technology represents a loss for the integrated industry and therefore decreases the total size of industry profits available to both firms in bargaining process. However, the loss is shared by both downstream and upstream firm according to their bargaining powers.

Secondly, environmental taxation influences the integrated industry profits, Π_{eop}^{Ind} . Recall that the outside option π_c^* is independent of taxation. Therefore, the insider's and outsider's payoffs depend on taxation only through its impact on integrated industry profit. To sum up, the integrated industry profit, insider's and outsider's payoffs, and hence the incentive for bargain, decrease as taxation gets stronger.

6 R&D stage

We turn now to R&D choices of the insider. The polluting company decides to undertake research for two reasons. First, it may innovate purely for bargaining considerations: this increases its negotiating position and hence the clean technology is not used once negotiations are concluded. This happens when two conditions are verified: the end-of-pipe technology is preferred to the clean one, $(\Pi_{eop}^{Ind} - r) > \pi_c^*$ and the clean technology is preferred as the outside option when bargaining, $\pi_c^* > \pi_\emptyset^* + \frac{\alpha}{1-\alpha}r$. Second, the clean technology may be interesting in itself and the firm decides to innovate and to use it. This happens when $\pi_c^* > \max\{(\Pi_{eop}^{Ind} - r); (\Pi_{eop}^{Ind} - (1 - \alpha)(\Pi_{eop}^{Ind} - \pi_\emptyset^*))\}^5$. The above conditions are equivalent to saying that as long as the clean profit lies within the $[\pi_\emptyset^* + \frac{\alpha}{1-\alpha}r, \Pi_{eop}^{Ind} - r]$ range, the company undertakes research in order to boost its bargaining position (see the figure 1). Once the profit obtained through the clean technology increases further, the polluting firm uses this technology and hence eliminates the outsider from the market.

⁵It means that the profit with integrated technology is higher than the profit with end-of-pipe technology whatever the outside option.

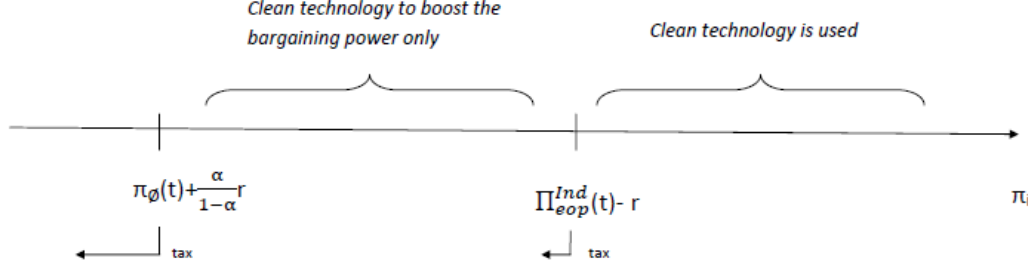


Figure 1. R&D incentives and impact of environmental taxation

Consider again the Figure 1. Environmental regulation changes the threshold levels for the case where the clean technology is used $\pi_c^* > \Pi_{eop}^{Ind}(t) - r$ and where the technology is developed to boost the bargaining power only $\pi_{\emptyset}^*(t) + \frac{\alpha}{1-\alpha}r < \pi_c^* < \Pi_{eop}^{Ind}(t) - r$. Taxation increases the incentive to develop the clean technology for its own use (the threshold $\Pi_{eop}^{Ind}(t) - r$ decreases). This is due to the fact already mentioned above that integrated industry profits shrink with taxation, therefore there are less and less profits to share in bargaining. Furthermore, close look at derivatives of $\Pi_{eop}^{Ind}(t)$ and $\pi_{\emptyset}^*(t)$ with respect to taxation⁶ reveal that the lower threshold $(\pi_{\emptyset}^*(t) + \frac{\alpha}{1-\alpha}r)$ decreases faster than the upper threshold $(\Pi_{eop}^{Ind}(t) - r)$. In other words, environmental policy, other things equal, makes the firm undertake innovation sooner but paradoxically, at the same time increases the polluting firm's likelihood to innovate but for the bargaining reasons only.

7 Regulation

We begin by examining the regulator's problem. Social welfare is the sum of consumers' surplus, profits of both (or just one) companies, tax revenue and environmental damage. As we have already mentioned in the introduction, environmental damage depends on technology choice in equilibrium. Note that the tax revenue for the government and taxes paid by the polluting firm cancel out in the welfare formula. Under clean technology there are no emissions, so that taxation generates no revenues for the government. However, the level of environmental tax plays an important role as explained above. It makes the

⁶ $\frac{\partial \Pi_{eop}^{Ind}(t)}{\partial t} = -[D(p^*) - w^*]$ and $\frac{\partial \pi_{\emptyset}^*(t)}{\partial t} = -D(p^*)$.

Given that for both cases price and output are the same, the first impact will be smaller in absolute value due to abatement activity.

polluter undertake research and also decides for which purpose this technology is developed.

Recall that the main interest of the paper is to study firm's strategic use of innovation and regulator's optimal response to it. To this aim, we shall consider only two welfare functions: one resulting from the use of the clean technology and second resulting from the use of the end-of-pipe technology. We will study first the tax rule chosen by the regulator to maximize welfare under the end-of-pipe technology, then we will compare polluting firm's and regulator's preferences for the technology. Finally, we will discuss the regulator's options how to reconcile interests of both parties.

7.1 Optimal taxation when there is no conflict concerning technology choice

Let W_c^* , $W_{eop}^*(t)$ denote welfare functions under clean and end-of-pipe technology respectively⁷. These functions are given by the following equations:

$$W_c^* = \int_{p_c^*}^{a/b} D_c(p)dp + D_c^*(p_c^*)p_c^* - \lambda D_c^*(p_c^*)^2 - r, \quad (9)$$

$$W_{eop}^*(t) = \int_{p_{eop}^*}^{a/b} D_{eop}(p(t))dp + p_{eop}^* D_{eop}(p^*(t)) - \delta D_{eop}(p^*(t))^2 - w^*(t)^2 - (D_{eop}(p^*(t)) - w^*(t))^2. \quad (10)$$

Note that we consider here only the case where end-of-pipe technology results in partial abatement⁸. In addition, we consider only the welfare $W_{eop}^*(t)$ where profit with no technology is used as an outside option in negotiations. The reason for that is straightforward. From the welfare point of view, using clean technology in the bargaining process serves only to redistribute the industry profit in favor of the insider. Consequently, the welfare decreases by the amount of the level of R&D expenses r . Maximization of the welfare function $W_{eop}^*(t)$ implies the maximization of the same welfare under different outside option.

Under the end-of-pipe solution, a tax must be imposed so as to force the polluter to buy abatement equipment. The regulator maximizes the welfare function $W_{eop}^*(t)$ with respect to a tax that yields the formula for the optimal tax:

$$t^* = 2E + \frac{D(p^*(t))D_p(p^*(t))p_t(t^*)}{[D_p(p(t^*))p_t(t^*) - w_t(t^*)]} - \frac{w_t(t^*)v}{[D_p(p(t^*))p_t(t^*) - w_t(t^*)]}, \quad (11)$$

⁷It can be shown that welfare with no technology available ($W_\emptyset^* = \int_{p_{eop}^*}^{a/b} D_{eop}(p(t))dp + p_{eop}^* D_{eop}(p^*(t)) - \delta D_{eop}(p^*(t))^2 - \varphi(D_{eop}(p^*(t)))^2$) is always dominated by the welfare with end-of-pipe technology. Therefore, in the rest of the paper this case is excluded from the study.

⁸The case of total abatement is available upon request.

where $E = D(p(t)) - w(t)$ are emissions. First part of the above expression is the marginal damage - Pigouvian part of taxation. This has to be adjusted for the monopoly power of the polluting firm (second part of the expression) as in Barnett (1980). The third part comes from the existence of upstream supplier. Since the supplier charges a price higher than marginal cost, a part of the regulator's effort to induce abatement is hindered by a higher price of equipment. This needs to be corrected by an even higher tax (see Sinclair Desgagné 2008). Note that the third expression is proportionate to the price v the upstream firm charges. In our case, thanks to the two part tariff, the contract is efficient and hence $v = 0$.

Lemma 1 *The optimal tax rate is*

$$t^* = 2E + \frac{D(p^*(t))D_p(p^*(t))p_t(t^*)}{[D_p(p(t^*))p_t(t^*) - w_t(t^*)]} - \frac{w_t(t^*)v}{[D_p(p(t^*))p_t(t^*) - w_t(t^*)]}.$$

It accounts for the external damage, market power of polluter and a higher price of abatement equipment set by a supplier.

7.2 Regulator's preferences concerning technology choice

To remind you, in this section, we study how each component of welfare function varies with polluting firm's technology choice, thus giving a first hint at the reasons the government may prefer certain technologies. In the following section, we compare the regulator's preferences with the firm's choices. The suggestions for the regulator's response follow.

Consider again the two welfare functions $W_{eop}^*(t)$ and W_c^* . Table 1 allows better understanding of different components that stimulate welfare under each technology choice. Let us start with consumers' surplus. The surplus is the same under no technology regime and under bargaining solution whatever the outside option used. This is due to the fact that end-of-pipe technology has no impact on production decisions. However, the clean technology modifies the production costs, and therefore the impact on consumers is ambiguous⁹. Environmental tax plays an important role in determining the preferences concerning technology choice from the consumers' point of view. Whenever the clean technology decreases costs, no matter how low the tax is (as long as it stays positive), the clean technology is always preferred. When production costs are higher with clean technology, as the taxation increases but stays at moderate levels, the resulting consumers' surplus shifts the preferences towards the end-of-pipe type of equipment. Only very strong taxation encourages the clean technology from the consumers' point of view.

⁹Production decision under no technology is defined by first order condition: $D(p) + pD'(p) = 2\delta D(p)D'(p) + tD'(p)$ whereas the clean technology optimization yields: $D(p) + pD'(p) = 2\lambda D(p)D'(p)$. The comparison of outputs depend on the relative value of the left hand sides of both equations.

TABLE 1: Welfare components under different technology choices.

	consumers' surplus	industry profits		
no technology	CS_{\emptyset}	π_{\emptyset}^*		
clean technology	CS_c	π_c^*		
eop with no technology as outside option	CS_{\emptyset}	$\Pi_{eop}^{Ind} = \pi_{\emptyset}^* + (tw^* - w^{*2})$		
eop with clean technology as outside option	CS_{\emptyset}	$\Pi_{eop}^{Ind} - r = \pi_{\emptyset}^* + (tw^* - w^{*2}) - r$		
downstream profit	upstream profit	environmental damage	emissions	
π_{\emptyset}^*	—	$(D_{\emptyset})^2$	D_{\emptyset}	
π_c^*	—	0	0	
$\pi_{\emptyset}^* + \alpha(\Pi_{eop}^{Ind} - \pi_{\emptyset}^*)$	$(1 - \alpha)(\Pi_{eop}^{Ind} - \pi_{\emptyset}^*)$	$(D_{\emptyset} - w^*)^2$	$D_{\emptyset} - w^*$	
$\pi_c^* + \alpha(\Pi_{eop}^{Ind} - r - \pi_c^*)$	$(1 - \alpha)(\Pi_{eop}^{Ind} - r - \pi_c^*)$	$(D_{\emptyset} - w^*)^2$	$D_{\emptyset} - w^*$	

The impact of technology choice on profits was studied in details in production and bargaining sections. One issue merits some attention. Taxation has an important impact on the total industry profits as shown in third column of Table 1. The gains in integrated industry profits under the end-of-pipe equipment stem from the savings companies make in taxes less adoption costs, $(tw^* - w^{*2})$. The higher the tax, the higher potential gain for the whole industry with respect to no technology. Moreover, the clean outside option negatively influences the industry profits. It results in a pure loss r . We will return to the profits issue once again in section below when studying alignment of preferences between the polluter and the regulator. Furthermore, welfare under clean technology yields no pollution and therefore necessitates no tax and the environmental damage is the lowest.

Note that for some levels of production cost λ , the end-of-pipe solution prevails in equilibrium even though it leads to higher pollution. This is so due to several reasons. Firstly, when clean technology leads to higher variable cost of production, the end-of-pipe technology will most probably prevail. The probability of clean technology imposing itself decreases with cost difference¹⁰. In other words, welfare difference between clean solution and end-of-pipe one in optimum gets higher with cost difference. Secondly, as cost of R&D gets higher, clean technology loses its advantage and it gets more difficult to make the firm choose this technology on its own. At optimum, the clean technology can only be chosen for low R&D cost (and equal variable costs).

¹⁰The probability being defined as a range of taxes leading to a higher clean welfare than eop welfare.

Indeed, welfare with partial abatement can be higher or lower than the welfare with clean technology as we can see on Figure 1.

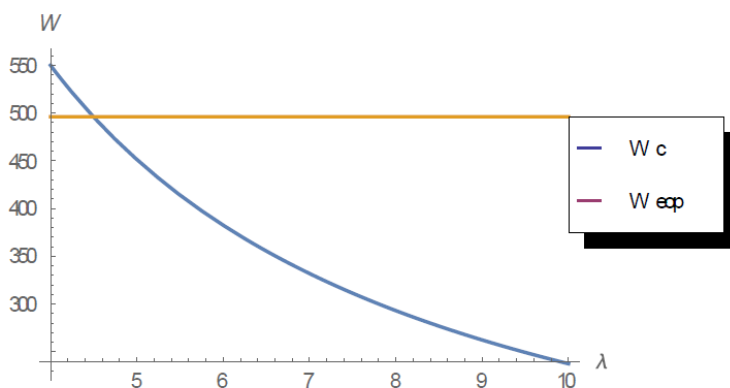


Figure 1. Comparison of clean welfare and end-of-pipe welfare as a function of production cost λ (for $a = 100$, $b = 1$, $\delta = 4$ and $r = 10$).

7.3 Alignment of preferences when regulator promotes the end-of-pipe technology

Let us consider the first case where $W_c^* < W_{eop}^*(t^*)$. While the regulator sets the tax equal to t^* , the polluting firm reacts to this tax in three different ways. Depending on a value of λ , we can find three regions of investment as seen below (numerical simulations on request):

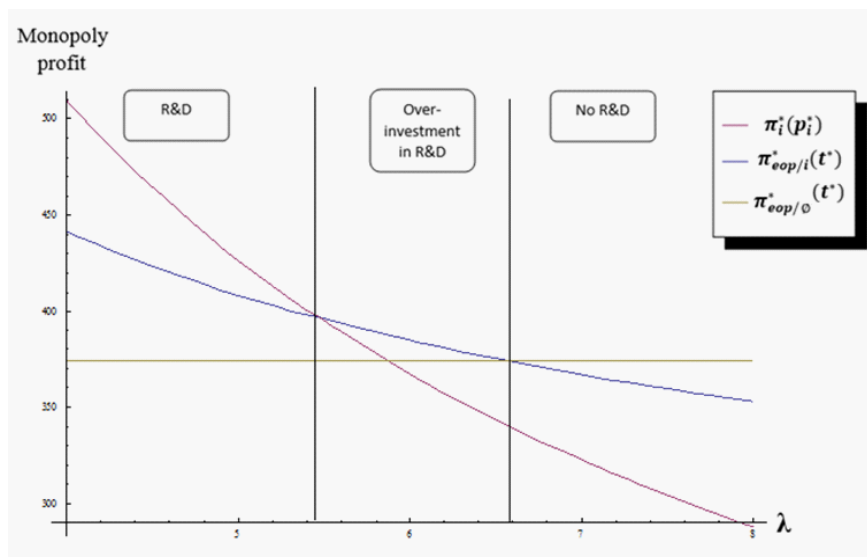


Figure 2. Polluting firm profits under different technology choices as a function of production cost λ when $W_c^* < W_{eop}^*(t^*)$.

First, a zone where R&D is undertaken and technology developed in order to use it. Second, a region of over-investment, where the R&D is undertaken only to boost the bargaining power of the insider, that represents a pure loss from the welfare point of view. Finally a region where no R&D is undertaken and the polluting company uses the end-of-pipe equipment in line with regulator's desire.

As mentioned above, the region of *no investment in R&D* in the second stage, $\pi_c^* < \pi_{eop/c}^*(t^*) < \pi_{eop/\emptyset}^*(t^*)$, poses no problem to the regulator. The best response of the regulation to maximize the welfare and set the optimal tax t^* .

In the region of *R&D investment* where $\max\{\pi_{eop/\emptyset}^*(t^*); \pi_{eop/c}^*(t^*)\} < \pi_c^*$, the monopoly profit is higher with clean technology than with end-of-pipe. Confronted with this situation, the regulator can keep the optimal tax unchanged and undergo a net welfare loss, i.e. a loss from consumers and industry components but a gain from environmental point of view.

Since $W_c^* < W_{eop}^*(t^*)$, the regulator may also modify its policy and set a tax \hat{t} such that:

$$\begin{aligned} & \max_t W_{eop}(t), \\ & s.t. \pi_c^* < \max\{\pi_{eop/\emptyset}(t), \pi_{eop/c}(t)\}. \end{aligned} \quad (12)$$

In either case, compared to the optimal situation, the resulting tax is lower and so is the welfare. When $\pi_{eop/\emptyset}(\hat{t}) > \pi_{eop/c}(\hat{t})$ the regulator manages to deter the monopoly from R&D investment. In the contrary case, the research nevertheless takes place.

Proposition 2 *In a case where the end-of-pipe regime dominates the clean regime in terms of welfare, under certain parameter values, the polluting industry invests in R&D and environmentally innovates. Paradoxically, the regulator may oppose such an effort and set environmental policy so as to make the firm adopt existing end-of-pipe solution. Unfortunately, even by doing so, it might not prevent the polluting firm from useless innovation if $\max\{\pi_{eop/\emptyset}(t), \pi_{eop/c}(t)\} = \pi_{eop/c}(t)$. The welfare results in the third best.*

In the third region where investment is undertaken to *boost bargaining power*, i.e. where $\max\{\pi_{eop/\emptyset}^*(t^*); \pi_c^*\} < \pi_{eop/c}^*(t^*)$, the society incurs the investment cost decreasing the welfare. Indeed, the polluting monopoly invests in R&D in order not to use the clean technology in the production process, but only to enhance its outside option when bargaining with the end-of-pipe technology supplier. From this point of view, there is an over-investment in R&D which lowers the total welfare. Similarly to the preceding case, facing this situation, the regulator must adjust its policy. The regulator may sustain the level of taxation and undergo a loss equal to R&D cost ($W_{eop}^*(t^*) - r$) or to set the tax according to the following program:

$$\begin{aligned} & \max_t W_{eop}(t), \\ & s.t. \pi_{eop/c}(t) < \pi_{eop/\emptyset}(t) \text{ if } \pi_{eop/c}^*(t^*) > \pi_{eop/\emptyset}(t) > \pi_c^* \\ & \quad \text{or} \\ & \quad \pi_{eop/c}(t) < \pi_c^* \text{ if } \pi_{eop/c}^*(t^*) > \pi_c^* > \pi_{eop/\emptyset}(t). \end{aligned} \quad (13)$$

If the profit from bargaining with the clean technology as outside option dominates the profit of end-of-pipe with no technology as well as the clean technology profit, $\pi_{eop/c}^*(t^*) >$

$\pi_{eop/\emptyset}(t) > \pi_c^*$, a tax $\underline{t} < t^*$ can be chosen such that $\pi_{eop/\emptyset}^*(\underline{t}) = \pi_{eop/c}^*(\underline{t}) - \varepsilon$. The regulator prevents thus the monopoly from R&D investment. Recall Figure 1 to see how taxation influences technology choices. In this case, the regulator certainly avoids the deadweight loss r but, on the other side it loses on environmental quality (as tax gets lower and so does abatement). The resulting welfare is equal to $W_{eop/\phi}(\underline{t})$. Whenever $W_c^* < \max\{W_{eop}(t^*) - r; W_{eop/\phi}(\underline{t})\}$ the regulator sticks to end-of-pipe technology.

When $W_c > \max\{W_{eop}(t^*) - r; W_{eop/\phi}(\underline{t})\}$ the regulator sets the tax so high as to force the polluting firm to adopt clean technology. In a case where $\pi_{eop/c}^*(t^*) > \pi_c^* > \pi_{eop/\emptyset}^*(t^*)$, taxation forces the insider to adopt the clean technology.

To sum up, as seen above, the regulator compares the welfare functions: $W_{eop}^*(t^*) - r$, W_c^* and $W_{eop/\emptyset}(\underline{t})$ and chooses the tax that generates the highest one.

Proposition 3 *In a case where the end-of-pipe regime dominates the clean regime in terms of welfare, under certain parameter values, the polluting industry overinvests in R&D just to boost its bargaining power resulting in a decrease in total welfare. This forces the regulator to adapt its taxation policy and either to support the consequences of the firm's choice, or to change the level of taxation to incentivize the firm to change its behavior. Unusually, the option to develop a clean technology may make the regulator become laxer when it comes to taxation. The welfare however always results in the third best.*

7.4 Alignment of preferences when regulator promotes the clean technology

Let us now consider the next case where $W_{eop}^*(t^*) < W_c^*$. Assuming partial abatement, two situations can occur.

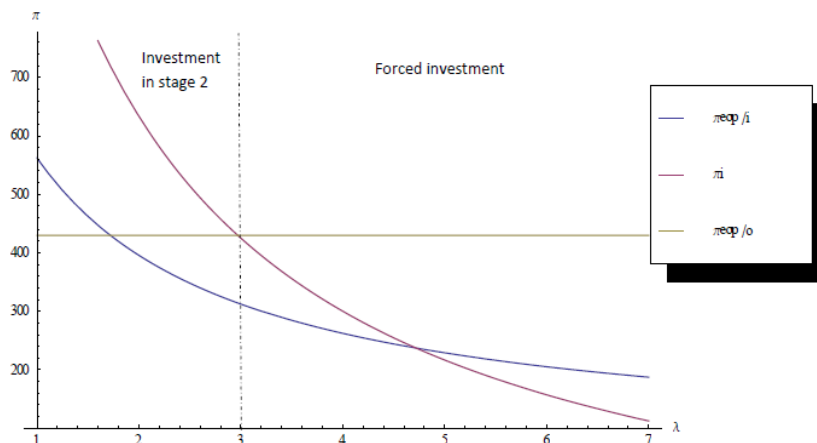


Figure 3. Polluting firm profits under different technology choices as a function of production cost λ when $W_c^* > W_{eop}^*(t^*)$.

First, investment in stage 2, $\max\{\pi_{eop/\emptyset}^*(t^*); \pi_{eop/c}^*(t^*)\} < \pi_c^*$, where the monopoly profit with clean technology is higher than with end-of-pipe technology. In this case, the regulator

can set t^* since $t^* \in [\tilde{t}, +\infty[$. It is the clean technology that is used¹¹.

Second, a region of forced investment in stage 2, $\pi_c^* < \max\{\pi_{eop/c}(t^*), \pi_{eop/\emptyset}^*(t^*)\}$ implying that the monopoly profit with clean technology is lower than the one with end-of-pipe technology. In this case the regulator must increase the tax in order to decrease the profit of end-of-pipe technology:

$$\begin{aligned} & \max_t W_{eop}(t), \\ & s.t. \pi_c^* > \max\{\pi_{eop/c}(t^*), \pi_{eop/\emptyset}^*(t^*)\}, \\ & \quad \text{or} \\ & \pi_c^* > \min\{\pi_{eop/c}(t^*), \pi_{eop/\emptyset}^*(t^*)\}. \end{aligned} \tag{14}$$

It therefore sets any tax $t \in [\tilde{t}, +\infty[$ and thus encourages monopoly to use clean technology. There are no welfare losses since we end up with a clean technology and welfare independent of the tax.

Proposition 4 *In a case where the end-of-pipe regime is dominated by the clean regime in terms of welfare, under certain parameter values, the polluting industry does not want to innovate. The regulator must set a higher tax in order to incentivize the firm to undertake the research and use the free emission technology. The welfare is at its optimum.*

Finally, as mentioned in the beginning of the paper, an interesting case of laissez-faire situation appears where

$$\pi_c^* < \max\{\pi_{eop/c}(t^*), \pi_{eop/\emptyset}^*(t^*)\} |_{total\ abatement} < \pi_{eop/c}(t^*).$$

The monopoly profit with clean technology is lower than the one with end-of-pipe technology with total abatement. In this case, setting any tax higher than t^* decreases the welfare. Indeed, since $\pi_c^* < \pi_{eop/c}|_{total\ abatement}$, when the tax increases, the monopoly abates the pollution using the end-of-pipe technology so the welfare goes down to $W_{eop}|_{total\ abatement}$ instead of increasing to W_c^* (we have $W_{eop}(t^*) > W_{eop}|_{total\ abatement}$). In what follows, the regulator prefers fixing t^* to leave the firm do the partial abatement. So the regulator can never reach W_c^* in this situation.

Proposition 5 *In the case where the end-of-pipe regime is dominated by the clean regime in terms of welfare, under certain parameter values, the regulator cannot do anything to make firm undertake R&D as the further tax increases make firm abate all emissions with end-of-pipe equipment resulting in even lower welfare.*

8 Conclusion

The principal goal of environmental regulation is to correct the market failures due to negative externalities. Nowadays, it is common to measure their efficiency by the incentives

¹¹ Actually, the regulator can set any tax higher than \tilde{t} , the tax that equals $\max\{\pi_{eop/\emptyset}(\tilde{t}); \pi_{eop/i}(\tilde{t})\}$ and π_i^* .

they give to spur both R&D and adoption of better abatement technologies. In this article, we examined the role that environmental taxation can play in reducing environmental pollution and inducing the choice of greener technology by a profit-maximizing monopoly. We show that, the strategic interaction between a monopoly and an upstream industry can alter the adoption of the best available abatement technology. Indeed, after the introduction of an emission tax, the polluter can, under some conditions, invest in R&D to develop a free emission technology not to use it but only to have a better outside option while bargaining with the end-of-pipe technology supplier. In such a way he obtains a more profitable license contract. This effect may give rise to conflicts between a regulator and the innovator. The regulator has no other choice but to set the environmental tax such that the polluter chooses the technology preferred by the policymaker. This results in a lower welfare as the level of taxation need to be modified to influence adoption decisions. Damages from environment get higher than what could be attained if the preferences of regulator and polluter were aligned. We also show that sometimes the regulator cannot influence innovation and adoption decisions and therefore needs to incur unavoidable welfare loss.

Several questions are not treated in this paper and merit some further study. First, we assume that the two technologies are substitutable. However, our results do not repose on this assumption. Recent research (Hammar et Lofgr n (2010)) shows however, that companies that use end-of-pipe equipment engage as well in clean (in-house) innovation. Unfortunately, the research does not show neither the timing of adoption of these technologies nor by whom they were developed. This alternative assumption can be incorporated in our framework as well. The complementarity of technologies could be explained by increased capability of polluter to undertake research or to perceive other opportunities as a result of getting accustomed to environmental technology. In-house research could lead to a decreased need for the end-of-pipe equipment and would allow renegotiation of existing contracts with upstream suppliers. A potential example could come from metallurgy industry where substantial amounts of water are used in production process. Quenching¹² in the past was associated with the use of oils in hardening process. Production of ball bearing for automobile and aerospace industry requires fast cooling of steel. In certain industries till 1980ties it was done using oil as coolant. However, the steel afterwards had to be quenched in water, giving need to waste water purifying station to filter out inter alia the oil. In following years a substantial research has been performed by the polluting industry and oil has been replaced directly by water as coolant. Empirical validation of this hypothesis would necessitate a close study of contracts between polluters and the associated independent end-of-pipe producers.

Second, our results suggest some tensions between a regulator that maximizes welfare and a regulator that minimizes environmental damage. If there are two principals, each responsible for industrial and environmental policy, their efforts should be coordinated. The industrial policy may call for increasing innovation efforts that may be unwarranted from the other principal point of view. These two points are left for further research.

¹²In materials science, quenching is the rapid cooling of a workpiece to obtain certain material properties. Many variables influence the quality and mechanical properties of hardened steel and they are all important to control: the quenching temperature; the soaking time; the cooling rate (cooling rate); the chemical composition of the material.

8.1 Appendix A- Optimal tax

Under end-of-pipe, the welfare is given by

$$W_{eop}^*(t) = \int_{p_{eop}^*}^{a/b} D_{eop}(p(t))dp + p_{eop}^* D_{eop}(p^*(t)) - \delta D_{eop}(p(t))^2 - \gamma \frac{w(t)^2}{2} - \varphi(D(p(t)) - w(t))^2.$$

Maximizing $W_{eop}^*(t)$ with respect to tax yields:

$$\frac{\partial W_{eop}^*(t)}{\partial t} = -DD_p p_t + p_t D + p D_p p_t - 2\delta DD_p p_t - \gamma w w_t - 2\varphi E(D_p p_t - w_t).$$

Inserting FOC from polluter's profit maximization: $2\delta DD_p = D + p D_p - t D_p$ and $-v - \gamma w + t = 0$ yields:

$$\begin{aligned} -DD_p p_t + p_t D + p D_p p_t - D p_t - p D_p p_t + t D_p p_t - w_t(t - v) - 2\varphi E(D_p p_t - w_t) &= 0, \\ -DD_p[-DD_p + D + p D_p - D - p D_p] + t D_p p_t - w_t t + w_t v - 2\varphi E(D_p p_t - w_t) &= 0, \end{aligned}$$

yielding optimal tax:

$$t = 2\varphi E + \frac{-DD_p p_t}{D_p p_t - w_t} - \frac{w_t v}{D_p p_t - w_t}.$$

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