Monopoly and Abatement Technology Choice: The Impact of Environmental Taxes and Bargaining

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Abstract

The purpose of this paper is to contribute to the theoretical literature dealing with firms' choice of abatement technology types. We set up a model in which a polluting monopoly can license an end-of-pipe technology from a specialist supplier or develop an in-house clean-integrated technology. We try to put the light on the strategic role of the environmental regulation to influence this choice. We show that the introduction of the environmental tax necessarily involve the use of an environmental abatement technology. However, under certain conditions, the integrated technology is never invented even if it is more beneficial to the global welfare or it can be invented but never used. In this latter case, the R&D effort of the polluting monopoly is redundant and there is an over-investment from a social point of view.

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1 Introduction

In response to the economic and ecological crises that are becoming increasingly pressing, governments are trying to promote environmental innovations

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as shown, for example, by the European commission report "Europe 2020" that followed the report of Lisbon (2000). Indeed, environmental innovations are typically divided in two distinct types: end of pipe solutions and clean innovations[1]. The former occur at the end of the production process to mitigate the environmental impacts of economic activities without changing the production process itself. This kind of innovations requires less commitment and is considered an unsustainable solution since firms engage sunk costs that do not increase productivity. Moreover, sometimes these innovations do not even reduce the pollution on a global scale but transfer it from one stage of the products life cycle to another, from one period of time to another or from one geographical area to another. This is the case for example of the nuclear waste treatments. In contrast, clean innovations, which are generally argued as being preferable in the long run (Frondel et al (2007), Rennings (2007), Porter and van der Linde (1995), Yarime (2008)), minimize pollution at source by using cleaner inputs and production methods. Hence, they increase the efficiency without increasing environmental damages. However, in most cases, they require an intense change in the productive system and a significant commitment in terms of financial and human resources. After more than thirty years of 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 Lofgrën (2010)), meanwhile, some specialists affirm that clean solutions can be available (Yarime (2008)) and that environmental regulations based on economic incentives can trigger innovation and eventually increase profitability of firms (Porter and van der Linde (1995)). One of the arguments of this phenomenon is that polluting firms are not aware of economic opportunities (new markets, lower production costs) and that the environmental regulation may reduce organizational failures (Gabel (1996)). Nevertheless, the traditional view of environmental regulation held by economists until the Porter's article was that requiring firms to reduce an externality like pollution necessarily restricts their options and thus by definition reduces their profits. After all, if profitable opportunities existed to reduce pollution, profit-maximizing firms would already be taking advantage of them. In other terms, the current debate focuses on the question of the profitability *per se* of clean solutions.

Our paper addresses another complementary debate: the conditions of the adoption of clean technologies. While studies examining the impact of environmental regulations on innovation are widespread, [2] only a few papers have

[1]In this article, end of pipe solutions, end of pipe technology in one hand, and clean innovations, clean solutions, integrated technologies, clean integrated technologies in the other hand are used interchangeably.

[2]See the excellent surveys of Jaffe et al (2003) and Requate (2005).

tried to address the issue of the firms' technologies choice. In empirical field, Frondel et al (2007) and Hammar et Lofgrën (2010) addressed this point by analyzing factors that may enhance a firm's propensity to implement clean technologies rather than end-of-pipe ones. Frondel et al (2007) used a survey on OECD firms and found that environmental regulations were more likely to lead to the adoption of end-of-the-pipe solutions and in contrast market forces, such as cost savings or environmental management tools, lead to the adoption of cleaner production processes. On the other hand,Hammar et Lofgrën (2010) used a panel of Swedish firms to test for five explanatory variables. They found that learning by doing and knowledge, measured by expenditures on green R&D, increases the probability of investment in clean technologies. In contrast the size of the firms, measured by the revenue, and energy prices are important determinants for investing in the end-of-pipe technologies. Their work also suggests that the two investments are complementary. In other words, firms that decide to invest in environmental protection are likely to invest in both types of technologies.

In theoretical literature however, there is a big void. Few papers have recently begun to investigate the question. Meunier and Nicolaï (2012)focusing on the impact of environmental regulation on firms profits, showed that depending on the type of technology used, this impact can be either positive or negative. In the same logic, Christin et al (2013) studied the effect of a cap-and-trade system on industry profits under imperfect competition and also highlighted that the abatement technology type is fundamental to answer this question. Calel (2011) presented a theoretical survey to answer the question dealing with the relationship between market-based instrument and firm's technology choice. For his part, Sibailly (2013) explained that the trade-off between two given types of technologies depends on their relative cost-efficiency, on the ownership structure of the abatement technology suppliers (public, independent, a research joint venture) and on the licensing environments (exclusive or non-exclusive licensing contracts).Moreover, one of the major innovation incentives is the expectation of innovation rents, even if these rents are temporary. For instance, Carraro (2000) shows that, in addition to R&D investment profits, strategic advantages over rivals are also motivating forces for innovations.

The purpose of this paper is to contribute to this new literature by examining the technology adoption choice of a monopolist liable to an environmental taxation and that has the possibility either to buy an end of pipe technology from an independent eco supplier[3] or to develop an integrated one. Our main

[3] David and Sinclair-Desgagné (2005) launched the literature on the independent eco-industry supplying abatement goods and services to a polluting industry.

hypothesis is that polluting firms can develop R&D activities for clean technologies in order to increase their strategic advantages over their suppliers of end of pipe solutions, and without necessarily use the results of their innovative clean solutions. To this end, we develop a simple monopoly 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.

We show that the introduction of the environmental tax necessarily involve 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. We discuss the role of regulator in such situations.

The paper is organized as follow. Section 2 sets-up the model. Section 3 characterizes its equilibrium. Section 4 explores the question of the optimal taxation. Finally, Section 5 concludes.

2 The model

Consider a monopolist facing 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 monopoly generates a pollutant e that is proportional to output $D(p)$ and given by $e = \theta D(p)$. For simplicity we assume that $\theta = 1$. In order to incite the polluter to undertake costly abatement, the government sets an environmental tax t. The polluting firm has two options to face this regulation: continuing polluting and paying the tax on the total emissions or using a technology to abate some or all the emissions. Abatement technology stems from two different sources: internal research done by polluter that modifies its production process (and therefore production costs) or external licensing of an end of pipe equipment. We assume that the internal technology, which is a process-integrated one, results in zero pollution level after adoption while external end of pipe technology decreases pollution by ω and imposes an additional cost of adoption of $\gamma\omega^2$.

The timing of the game is as follows:

Stage 1) the regulator sets a pollution tax t.

Stage 2) the polluting firm decides whether or not to invest in R&D to develop a process integrated clean technology.

Stage 3) The polluting firm decides which option to choose: paying the tax without any abatement, using an process-integrated clean technology if any such technology has been invented in stage 2, or bargaining with external eco-industry to use an end of pipe technology.
Stage 4) Monopoly decides on the price and the abatement level if any on final market
Note that the regulator is assumed to set taxation prior to technology choice of the polluter. So, we are considering an innovation-incentivizing type of environmental regulation.

3 Equilibrium

In order to find the subgame-perfect Nash equilibrium of the whole game, we have to solve the sub-games of the three scenarios by backward induction and compare their outcomes. We will leave the resolution of the first stage (optimal tax) to the 4th section.

3.1 Scenario 1: Pollueter's behavior absent abatement technology

Absent abatement technology, polluter maximizes its profit function with respect to prices:

$$\pi(p) = pD(p) - \delta D(p)^2 - tD(p),$$

yielding

$$p^*_\emptyset = \frac{a(1+2b\delta)+bt}{2b(1+b\delta)},$$

$$D^*_\emptyset = \frac{a-bt}{2(1+b\delta),}$$

$$\pi^*_\emptyset = \frac{(a-bt)^2}{4b(1+b\delta)}.$$

As expected environmental tax increases the price of the monopoly, decreasing the total demand and the polluter's profit comparing to the laissez-faire situation. For any tax value higher than $\frac{a}{b}$, monopoly profit is equal to zero.

3.2 Scenario 2: Pollueter's behavior with integrated technology

When the polluter decides to invest in integrated technology, it bears R&D costs r and changes its variable costs from $\delta D(p)^2$ to $\lambda D(p)^2$ with $\lambda > 0$[4] The monopolist's profit become:

$$\pi_i(p) = pD(p) - \lambda D(p)^2 - r$$

yielding:

$$p_i^* = \frac{a(1+2b\lambda)}{2b(1+b\lambda)},$$
$$D_i^*(p_i^*) = \frac{a}{2(1+b\lambda)},$$
$$\pi_i^*(p_i^*) = \frac{a^2}{4b(1+b\lambda)} - r.$$

Note that monopoly decisions are independent of environmental regulations as the firm generates no emissions. However, the incentive to develop the integrated technology increases with stringer taxation. In this sense, we can talk about "technology forcing" regulation. Moreover, when the integrated technology increases variable cost of production, the polluter will never adopt this technology without environmental regulation. The higher R&D cost gets, the less incentivizing the technology development is[5].

3.3 Scenario 3: Pollueter's behavior with end-of-pipe technology

This section assumes the existence of an eco-industry specialized in provision of end of pipe equipment, meaning that emissions are addressed at the end

[4]The impact of clean technologies on variable cost can be either positive ($\lambda < \delta$) or negative ($\lambda > \delta$) 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).

[5]We suppose that R&D cost is as follows $\begin{cases} 0 \leq r \leq \frac{a^2}{4b(1+b\lambda)} & if \lambda > \delta \\ \\ \frac{a^2}{4b(1+b\lambda)} - \frac{a^2}{4b(1+b\delta)} \leq r \leq \frac{a^2}{4b(1+b\lambda)} & if \lambda < \delta \end{cases}$.

These assumptions ensure that the monopoly profit is positive when using integrated technology but the use of this technology is never profitable without the introduction of a taxation.

of production process and therefore do no impact firm's production costs. To acquire the end of pipe equipment, the polluting monopoly bargains with the eco-supplier a two part tariff contract (v, f), where v is a per-unit charge and f is a lump-sum fee. In addition, the monopoly incurs an adoption cost for installing the technology that is equal to $\gamma\omega^2$ where $\gamma > 0$ and ω is the performance of the end of pipe technology.
If we consider $\alpha \in [0, 1]$ being the power of the monopolist in the bargaining process and $(1 - \alpha)$ the power of the eco-supplier, the Nash product of bargaining is given by this general equation

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

where π_{eop}^{down} and π_{down}^{up} are the inside options i.e the profits generated by the sell and the use of the technology and they are as follows

$$\pi_{eop}^{up}(\omega) = v * \omega + f$$

and $\pi_{eop}^{down}(p, \omega)$ is equal to:

$$\begin{cases} pD(p) - \delta D(p)^2 - v\omega - f - \gamma\omega^2 - t(D(p) - \omega) - r^{6}, & if \quad t < \frac{a\gamma}{1+b(\delta+\gamma)} \\ \\ pD(p) - \delta D(p)^2 - v\omega - f - \gamma\omega^2 - r, & otherwise \end{cases}$$

Indeed, if the level of the tax is not very high compared to the use of the end of pipe technology($t < \frac{a\gamma}{1+b(\delta+\gamma)}$), the monopoly will abate a part of emissions and pay tax fees on the remaining part. But when the amount of the tax is very high ($t > \frac{a\gamma}{1+b(\delta+\gamma)}$), monopoly will abate all emissions.
Respecting this discontinuity and solving the forth stage of the game yields

Outputs	Partial abatement $t < \frac{a\gamma}{1+b(\delta+\gamma)}$	Total abatement $t \geq \frac{a\gamma}{1+b(\delta+\gamma)}$
p_{eop}^*	$\frac{a(1+2b\delta)+bt}{2b(1+b\delta)}$	$\frac{a(1+2b(\delta+\gamma))+bv}{2b(1+b(\delta+\gamma))}$
D_{eop}^*	$\frac{a-bt}{2(1+b\delta)}$	$\frac{a-bv}{2(1+b(\delta+\gamma))}$
ω_{eop}^*	$\frac{t-v}{2\gamma}$	$D_{eop}^* = \frac{a-bv}{2(1+b(\delta+\gamma))}$

Note that production decisons with partial abatement are unaltered by the use of the end of pipe technology and are equal to the scenario 1.

This is because the end of pipe technology doesn't change the production process and so the monopoly set the marginal return on output equal to the marginal cost in one hand and the marginal cost of abatement equal the marginal benefit of abatement in the other hand as if it wants to maximize two independant activities. However, if the tax is very high, the monopoly couldn't reach the interior solution of the abatement activity because it can not abate more than what it pollutes and in this case it will abate all the pollution generated.

To solve the stage of the bargaining maximization, we have to consider now the outside options π^{down*} and π^{up*} of the two firms. The outside option of the supplier is its profit when it dosn't sell the technology to the monopoly. We assume it to be zero. However, π^{down*}, the profit of the monopoly if it dosn't use the end of pipe technology, isn't zero but is its profit using the integrated technology or its profit without any technology if it chooses to not invest in R&D. We solve the model's third stage for the two cases.

Profit without any technology as the monopoly's outside option

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

$$B(v, f) = (\pi^*_{eop/\emptyset} - \pi^*_\emptyset)^\alpha (\pi^{up*}_{eop/\emptyset})^{(1-\alpha)}.$$

where the polluter's its outside option $\pi^*_\emptyset$ is as follows:

$$\pi^*_\emptyset = \begin{cases} \frac{(a-bt)^2}{4b(1+b\delta)}, & if \quad 0 < t < \frac{a}{b} \\ \\ 0, & otherwise \end{cases}$$

Maximizing $B(v, f)$ with respect to v and f gives $v^* = 0$[7] and $f^* = (1-\alpha)(\Pi^{Ind}_{eop} - \pi^*_\emptyset)$. Yielding

The monopoly profit in this case is $\pi^*_{eop/\emptyset} = \pi^*_\emptyset + \alpha(\Pi^{ind}_{eop} - \pi^*_\emptyset)$ and can be

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

developped as follows:

$$\pi^*_{eop/\emptyset} = \begin{cases} \pi^*_\emptyset + \alpha\frac{t^2}{4\gamma}, & if \quad 0 < t < \frac{a\gamma}{1+b(\delta+\gamma)} \\ \pi^*_\emptyset + \alpha(\frac{a^2}{4b(1+b(\delta+\gamma))} - \frac{(a-bt)^2}{4b(1+b\delta)}), & if \quad \frac{a\gamma}{1+b(\delta+\gamma)} \leq t < \frac{a}{b} \\ \alpha\frac{a^2}{4b(1+b(\gamma+\delta))}, & if \quad \frac{a}{b} \leq t \end{cases}$$

We can easily see that the end of pipe solution dominates the no-abatement one because $\Pi^{ind}_{eop} - \pi^*_\emptyset > 0$ in the three sub-cases.

Profit with integrated technology as the monopoly's outside option

When the polluter decides to develop the integrated technology, the Nash product of bargaining is given by

$$B(v, f) = (\pi^*_{eop/i} - \pi^*_i)^\alpha(\pi^{up*}_{eop/i})^{(1-\alpha)}.$$

where the polluter's its outside option π^*_i is equal to $\frac{a^2}{4b(1+b\lambda} - r$.

Resolving the stage of maximizing of $B(v, f)$ with respect to v and f gives $v^* = 0$ too and

$$\begin{cases} \pi^*_{eop/i} = \pi^*_i + \alpha(\Pi^{Ind}_{eop} - \pi^*_i - r) \\ \pi^{up*}_{eop/i} = f^* = (1-\alpha)(\Pi^{Ind}_{eop} - \pi^*_i - r) \end{cases}$$

Here the profit of the polluting monopoly is composed by the profit of its outside option, and the part α of potential gain or loss that remains. If Π^{Ind}_{eop} is higher (lower) than $\pi^*_i - r$, the polluting firm will adopt end of pipe (integrated) technology.

Developping $\bar{A} = \Pi_{eop}^{Ind} - \pi_i^* - r$ yields

$$\begin{cases} \frac{a^2}{4b(1+b\delta)} - \frac{bt^2}{4(1+b\delta)} - t(\frac{a}{2(1+b\delta)} - \frac{bt}{2(1+b\delta)}) + t\frac{t}{2\gamma} - \gamma(\frac{t}{2\gamma})^2 - \frac{a^2}{4b(1+b\lambda)} & if \quad t < \frac{a\gamma}{1+b(\delta+\gamma)} \\ \\ \frac{a^2}{4b(1+b(\delta+\gamma))} - \frac{a^2}{4b(1+b\lambda)}, & otherwise \end{cases}$$

Note that, when $t < \frac{a\gamma}{1+b(\delta+\gamma)}$, Π_{eop}^{Ind} can be decomposed in many parts. The first one $\frac{a^2}{4b(1+b\delta)}$ is the profit of the industry before the tax enforcement. $\frac{bt^2}{4(1+b\delta)}$ reflects the loss in the profit due to the tax (transalated by an increase of the price and a fall in the demand). The third term is none other than the tax times the demand that the monopolist have to pay if it doesn't use any technology. However this amount can be lowred by $t\frac{t}{2\gamma}$ which is the abatement profit due to the use of the end of pipe technology ω^* minus the adoption cost $\gamma(\frac{t}{2\gamma})^2$.
When $t > \frac{a\gamma}{1+b(\delta+\gamma)}$, Π_{eop}^{Ind} and so is $\bar{A}$ doesn't depend on the tax but only on the technologies' costs: the higher the clean technology's cost is or/and the lower end of pipe technology's costs are, the higher $\bar{A}$ is[8].

So $\bar{A}$ is positive and so is $\pi_{eop/i}^* > \pi_i^*$, only if:

$$\begin{cases} \lambda \geq \delta + \gamma \\ \\ \delta < \lambda < \delta + \gamma \qquad and \qquad 0 < t < \frac{a\gamma}{1+b(\delta+\gamma)} - \frac{\sqrt{a^2\gamma(1+b\delta)(\gamma+\delta-\lambda)(1+b\lambda)}}{(1+b(\gamma+\delta))(1+b\lambda)} \end{cases}$$

It is not surprising that the derivatives of $\bar{A}$ with respect to t, δ and γ are negative ie the higher these parameters are the less advantages due to the use of the end of pipe compared to the integrated technology is. The inverse happens when we derivate with respect to δ.
To sum up, the monopoly compares its profits under the different regimes to choose wich strategy to adopt in the second stage. It develops the integrated technology if and only if $\pi_i^* > \pi_\emptyset^*$ and $r < \frac{1-\alpha}{\alpha}(\pi_i^* - \pi_\emptyset^*)$. In this case the monopoly use the integared technology if $\pi_i^* > \pi_{enp/i}^*$ or use it as an outside option to improve its powerment against the supplier if $\pi_i^* < \pi_{enp/i}^*$.

[8]If $\lambda < \delta$ so $\bar{A} < 0$ and in this sub-case, the monopoly will always choose to use the clean technology rather than the end of pipe one.

However, if $\pi_i^* < \pi_\emptyset^*$ or $r > \frac{1-\alpha}{\alpha}(\pi_i^* - \pi_\emptyset^*)$ the monopoly doesn't develop the integrated technology and always use the end of pipe to abate some or all the pollution rather than paying the tax on all the production emissions.

So far, we have solved the last three stages of the game according to values of various parameters. Now, lets move on to the resolution of the first stage, the optimal tax.

4 Environmental regulation

The regulator's choice of taxation is based on an evaluation of the welfare function with environmental damage included. Environmental damage depends, as detailed above, on technology choice in equilibrium. Note that under integrated technology there are no emissions, so that taxation generates no revenue for the government. However, the level of the tax will play an important role as it makes the polluter switch from the integrated regime to the bargaining situation[9].

4.1 Welfare under integrated technology

The welfare function is given by the following equation:

$$W_i^* = \int_{p_i^*}^{\frac{a}{b}} D(p)\,\mathrm{d}p + D_i^* p_i^* - \lambda D_i^{*2} - r$$

yielding

$$W_i^* = \frac{a^2(3 + 2b\lambda)}{8b(1 + b\lambda)^2} - r.$$

As mentioned above, there are no environmental damages imposed on society and hence no tax revenue.

4.2 Welfare under end-of-pipe technology

Since the monopoly profit function is discontinuous, we need to calculate separately the welfare under the two situations: total and partial abatement.

[9] We don't calculate the welfare with no abatement technology since this situation is dominated by the end of pipe one. In other words, monopoly will use, regardless of the level of tax, end of pipe technology because it increases its profit.

Situation 1: With total abatement

Like the preceding case, there is no tax revenue hence there are no environmental damages. But the level of taxation plays indirectly an important role since it influences the abatement level chosen by the monopoly: if the tax is relatively high ($t > \frac{a\gamma}{1+b(\delta+\gamma)}$), the monopoly will abate all emissions. The welfare is given by:

$$\begin{cases} W^{TA*}_{eop/\emptyset} = \int_{p_i^*}^{\frac{a}{b}} D(p)\,\mathrm{d}p + D^*_{eop}p^*_{eop} - \delta D^{*2}_{eop} - \gamma D^{*2}_{eop} \\ \quad\quad \textit{if no investment in R\&D in stage 2} \\ \\ W^{TA*}_{eop/i} = W^{TA*}_{eop/\emptyset} - r \quad\quad \textit{if the monopoly invests in R\&D} \end{cases}$$

yielding

$$\begin{cases} W^{TA*}_{eop/\emptyset} = \frac{a^2(3+b(\gamma+2\delta))}{2b(2+b(\gamma+2\delta))^2} \\ \\ W^{TA*}_{eop/i} = W^{TA*}_{eop/\emptyset} - r \end{cases}$$

Note that the only difference in the welfare function comes from the R&D expenditure. Total profit of polluting industry and of upstream supplier remains the same.

Situation 2: With partial abatement

In a situation with partial abatement, the welfare is given by:

$$\begin{cases} W^{PA}_{eop/\emptyset}(t) = \int_{p^*(t^*)}^{\frac{a}{b}} D(p)\,\mathrm{d}p + D^*_{eop}(t)p^*_{eop}(t) - \delta D^*_{eop}(t)^2 - \gamma\omega^*(t)^2 \\ \quad\quad \textit{if no investment in R\&D in stage 2} \\ \\ W^{PA}_{eop/i}(t) = W^{PA}_{eop/\emptyset}(t) - r \quad\quad \textit{if the monopoly invests in R\&D} \end{cases}$$

Maximizing $W^{PA}_{eop/\phi}(t)$ with respect to t yields the optimal tax (see appendix A):

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

where $E = D(p(t)) - \omega(t)$ are emissions. Obviously, the optimal tax here is not an explicit solution for t because t is on both sides of the equation.

But this formulation helps to develop a deeper understanding of the three parts composing the tax. First part is the marginal damage - Pigouvian part of taxation. This has to be adjusted by the monopoly power of the polluting firm (second part of the expression) as in **?**. The third part comes from the existence of eco-industry. If the eco-industry charges a price higher than marginal cost, a part of the regulator's effort to induce abatement is hindered by the higher price of equipment. This needs to be corrected by an even higher tax.

Lemma 1. *The optimal tax rate is*

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

It accounts for the external damage, market power of polluter and the market power of supplier.

In our case, thanks to the two part tariff, the contract is efficient and $v = 0$. This means that the optimal tax in equilibrium will consist of two well-known effects only. Solving the expression yields:

$$t^* = \frac{a\gamma(2(2 + b(\gamma + 2\delta))\Phi - \gamma)}{\gamma(4 + b(\gamma + 2b\gamma\delta + 4\delta(2 + b\delta))) + 2(2 + b(\gamma + 2\delta))^2\Phi}$$

$$W^{PA*}_{eop/\phi}(t^*) = \frac{a^2(3 + b(\gamma + 2\delta))(\gamma + 2\Phi)}{2b\gamma(4 + b(\gamma + 2b\gamma\delta + 4\delta(2 + b\delta))) + 4b(2 + b(\gamma + 2\delta))^2\Phi}$$

We assume that the environmental damage is important to justify the introduction of a tax:

Assumption 1. $t^* > 0$ if $\Phi > \frac{\gamma}{4+2b(\gamma+2\delta)}$

4.3 Optimal taxation

To set the optimal tax, the regulator compares the three welfare functions W^*_i,W^{TA*}_{eop} and W^{PA*}_{eop}[10].

$$\begin{cases} W^*_i = \frac{a^2(3+2b\lambda)}{8b(1+b\lambda)^2} - r \\ W^{TA*}_{eop/\phi} = \frac{a^2(3+b(\gamma+2\delta))}{2b(2+b(\gamma+2\delta))^2} \\ W^{PA*}_{eop/\phi} = \frac{a^2(3+b(\gamma+2\delta))(\gamma+2\Phi)}{2b\gamma(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta)))+4b(2+b(\gamma+2\delta))^2\Phi} \end{cases}$$

[10]This part is not finished yet. It will be improved in the next version.

First of all, if we compare the two welfare functions under the end of pipe regime, we find that the welfare with partial abatement at the equilibrium always dominates the one with total abatement. Therefore, under the end of pipe technology regime, the regulator will set t^* and the monopoly will partially abate its emissions. The welfare difference is proportional to the environmental damage Φ and inversely proportional to the adoption cost of the end of pipe technology γ as shown below on Figure 2.

$$Figure 2$$

Since the welfare under end of pipe regime with total abatement is always dominated by the welfare under end of pipe regime with partial abatement, the regulator will no longer consider the first option as an alternative when choosing its tax level.

Next, if we compare the welfare with partial abatement and the welfare with integrated technology, the result is not as obvious as the preceding one. Indeed, welfare with partial abatement can be higher or lower than the welfare with integrated technology as we can see on Figure 3.

$$Figure 3$$

Let us consider the first case where $W_i^* < W_{end/\phi}^*(t^*)$. While the regulator sets the optimal tax equal to t^*, the monopolist 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 are in appendix B):

- No investment in R& D in the second stage $\pi_i^*(p_i^*) < \pi_\phi^*(p_\phi^*)$:

The monopoly profit without any technology is higher than with integrated technology. In this case, the monopoly doesnt invest in R& D and uses $\pi_\phi^*(p_\phi^*)$ as an outside option to bargain with the supplier of end of pipe technology. Setting t^* is the best response of the regulation to maximize the welfare since the welfare with end of pipe is the highest and we have no loss in R& D costs.

- Investment in R& D in the second stage to boost the bargaining power $\pi_\phi^*(p_\phi^*) < \pi_i^*(p_i^*) < \pi_{eop/i}^*(t^*)$:

The society will incur the investment cost decreasing the welfare as compared to the preceding case. Indeed, the monopoly profit with integrated technology is higher than with no technology but lower than with end of pipe one. In this case, the polluting monopoly will invest in R& D in order not to use the integrated 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. Facing this situation, the regulator has two

solutions:
a) setting $t^*$and having an deadweight loss of r compared to optimal welfare $W^*_{eop/\phi}(t^*) = W^*_{eop/\phi}(t^*) - r$
b) setting the tax $\underline{t} < t^*$ such that $\pi^*_\phi = \pi^*_i + \epsilon$ and thus deterring the monopoly from R& D investment. In this case, the regulator certainly avoids the deadweight loss r but, on the other side it loses in environmental quality (as tax gets lower and so does abatement). The welfare is equal to $W_{eop/\phi}(\underline{t})$.
To sum up, the regulator compares the two welfare functions: $W^*_{eop/i}(t^*)$ and $W_{eop/\phi}(\underline{t})$ and chooses the tax that generates the highest one. The chosen welfare will be a third best since $W^*_{eop/i}(t^*)$ and $W_{eop/\phi}(\underline{t})$ are lower than $W^*_{eop/\phi}(t^*)$.

Investment in R& D in the second stage$\pi^*_{eop/i}(t^*) < \pi^*_i$:
The monopoly profit is higher with integrated technology than with end of pipe one. Like the preceding situation, regulator examines these following situations to choose the best tax: a) setting t^*, in this situation there are two cases: i) $\pi^*_{eop/i}(t^*) < \pi^*_i < \pi^*_{eop/\phi}(t^*)$: the second best is reached because the monopoly won't invest in R& D and will use the end of pipe technology
ii) having a welfare loss because the monopoly will choose the integrated technology
b) setting the tax $\underline{t}$ to avoid the investment in R& D and the use of the integrated technology. The welfare is equal to $W_{eop/\phi}(\underline{t})$. c) Setting $\widehat{t} < t^*$ such that $\pi^*_{eop} = \pi^*_i + \epsilon$ and thus inciting the monopoly to use the end of pipe technology rather than the integrated one. To sum up, as seen above, the regulator compares the three welfares W^*_i,$W_{eop/\phi}(\widehat{t})$ and $W_(eop/\phi)(\underline{t})$ and therefore chooses the tax that generates the highest one. The welfare chosen will be a second best since W^*_i,$W_{eop/\phi}(\widehat{t})$ and $W_(eop/\phi)(\underline{t})$ are lower than $W_(end/\phi)^*(t^*)$ too.

Proposition 1. In a case where end of pipe regime dominates the integrated regime in terms of welfare, under certain parameter values, the polluting industry will invest in R& D and environmentally innovate. However, the regulator may oppose such effort and set environmental policy so as to make the firm adopt existing end of pipe solution. The welfare results in the third best. second best?

Proposition 2. In a case where end of pipe regime is dominated by the integrated 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.

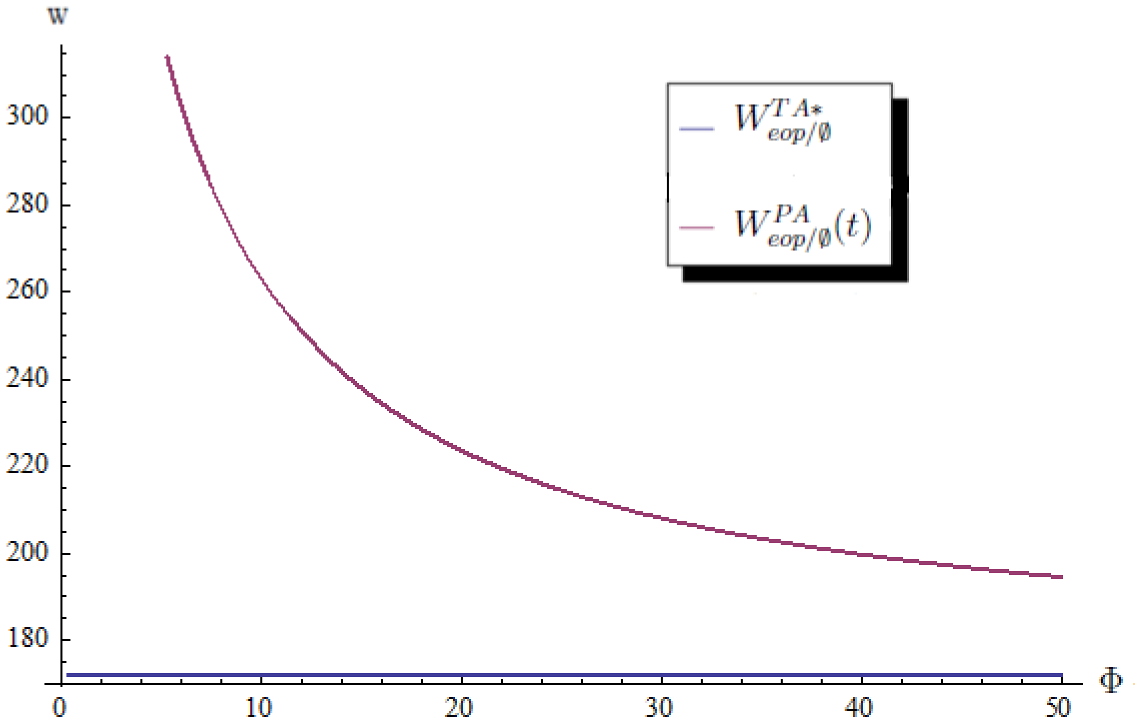
Let us move to the second case where $W_i^* < W_{end/\emptyset}^*(t^*)$ (numerical simulations are in appendix C). Three situations can occur as well: - Investment in stage 2 $\pi_{eop/i}^*(t^*) < \pi_i^*$: the monopoly profit with integrated technology is higher than the one with end of pipe technology with partial abatement. In this case the regulator sets any tax higher than $\tilde{t}$, the tax that equals $\pi_{eop}(\tilde{t})$ and π_i^*. It is the integrated technology that will be used anyway. -Forced investment in stage 2- $\pi_{eop/i}^* < \pi_i^* < \pi_{eop/i}^*(t^*)$: the monopoly profit with integrated technology is lower than the one with end of pipe technology with partial abatement but higher than with total abatement. In this case the regulator must increase the tax in order to decrease the profit of end of pipe technology (recall that profit of integrated is independent of tax). It therefore sets any $t \in [\bar{t}, +\infty[$ and thus encourages monopoly to use integrated technology. There are no welfare losses since we end up with an integrated technology and welfare independent of the tax.

Proposition 3. In a case where end of pipe regime is dominated by the integrated 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 incentivize the firm to undertake the research. The welfare is at its optimum.

5 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 they give a spur to both R& D and adoption of better abatement technologies. In this article, we have 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 have showed that, the strategic interaction between the monopoly and the 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 bigger outside option while bargaining with the end of pipe technology supplier, and therefore, a more profitable license contract. This effect may give rise to conflicts between a regulator that maximizes welfare and a firm that maximizes profits.

A. Figures



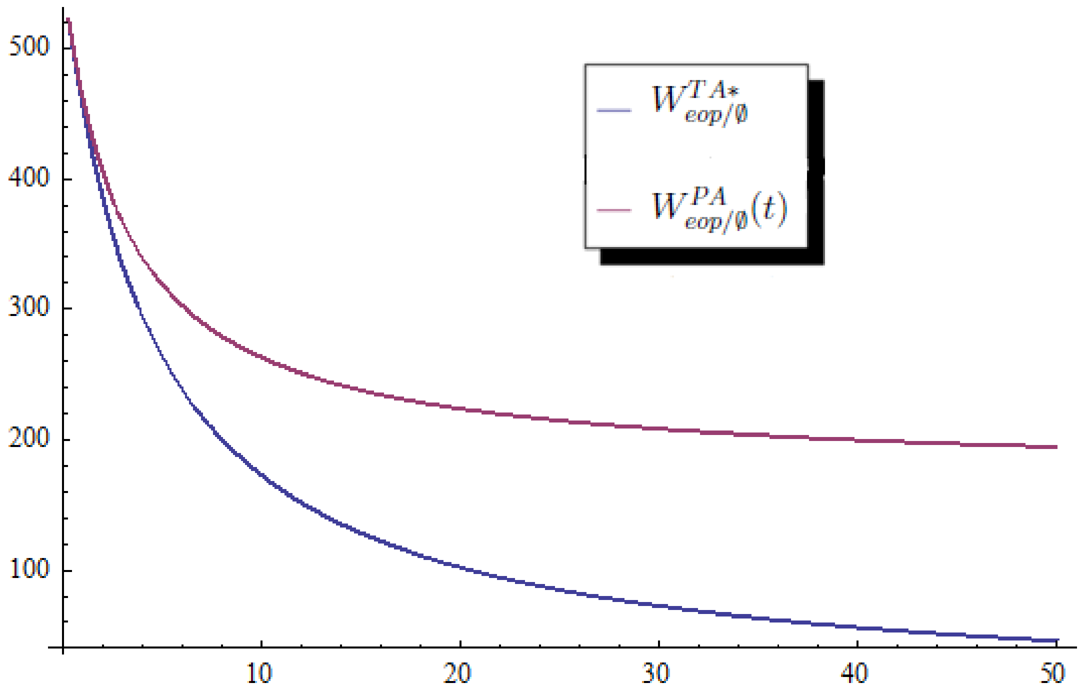


Figure 2: Welfare functions with end of pipe technology

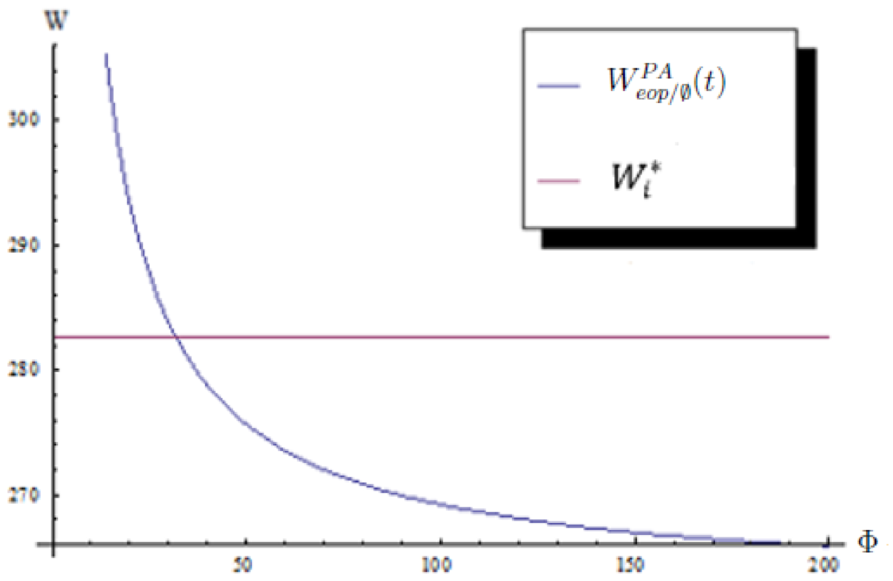


Figure 3. Welfare functions with end of pipe and integrated technology

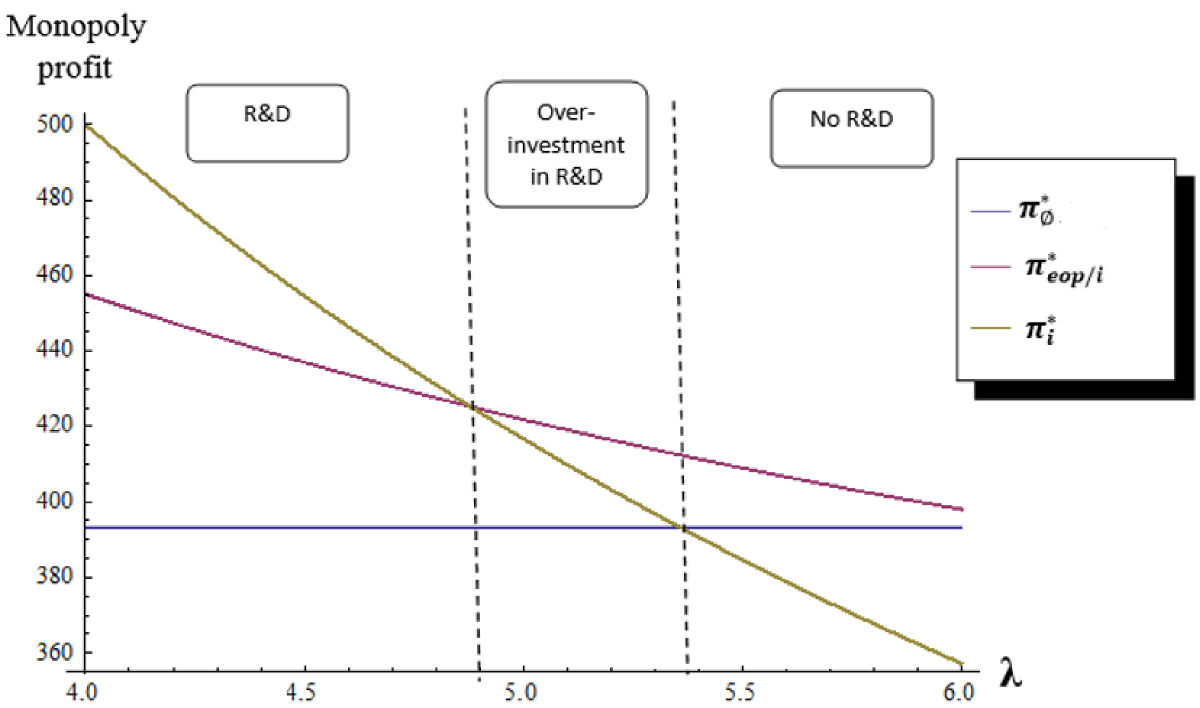


Figure 4. Investment regions under end of pipe dominating regime.

B. Appendix A- Optimal tax

Under end of pipe, the welfare is given by

$$W^*_{eop}(t) = \int_{p^*(t)}^{\frac{a}{b}} D_{eop}(p)\,dp + p^*(t)D^*_{eop}\big(p^*(t)\big) - \delta D^*_{eop}\big(p^*(t)\big)^2 - \gamma\frac{w^*(t)^2}{2} - \varphi[D^*_{eop}\big(p^*(t)\big) - w^*(t)]^2 - r$$

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

$$\frac{\partial W^*_{eop}(t)}{\partial t} = -Dp_t + Dp_t + pD_pp_t - 2\delta DD_pp_t - \gamma ww_t - 2\varphi E\big(D_pp_t - w_t\big)$$

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

$$pD_pp_t - Dp_t - pD_pp_t + tD_pp_t - w_t(t - v) - 2\varphi E\big(D_pp_t - w_t\big) = 0$$
$$-Dp_t + tD_pp_t - w_tt + w_tv - 2\varphi E\big(D_pp_t - w_t\big) = 0$$

yielding optimal tax:

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

C. Appendix B- Simulations when $\mathbf{W_i^*} < \mathbf{W^*_{end/\emptyset}}(\mathbf{t}^*)$

To illustrate our purposes, we give some numerical simulations. In the next version, this appendix will completed to illustrate all the sub-cases described.

<u>*No investment in R&D in the second stage*</u> $\pi_i^*(p_i^*) < \pi_\emptyset^*\big(p_\emptyset^*\big)$

	Parameters	Functions	Values
Variables	a		100
	b		1
	δ		4
	γ		10
	λ		6
	r		100
	φ		2
Optimal tax	t^*	$\frac{a\gamma(2(2+b(\gamma+2\delta))\varphi-\gamma)}{\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+2(2+b(\gamma+2\delta))^2\varphi}$	**20**
Monopolist profits	π_{i}^*	$\frac{a^2}{4b(1+b\lambda)} - r$	$\frac{1800}{7}$ ≈257
	$\pi_\emptyset^*(\mathrm{t}^*)$	$\frac{(a-bt)^2}{4b(1+b\delta)}$	320
	$\pi^*_{\mathrm{eop}/\emptyset}(\mathrm{t}^*)$	$\pi_\emptyset^* + \alpha\,\overline{A}$	**322**
Welfare	W_i^*	$\frac{a^2(3+2b\lambda)}{8b(1+b\lambda)^2} - r$	$\frac{13850}{49}$ ≈282
	$W^*_{eop/\emptyset}(t^*)$	$\frac{a^2(3+b(\gamma+2\delta))(\gamma+2\varphi)}{2b\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+4b(2+b(\delta+2\delta))^2\varphi}$	**420**

⇨ In this case, the regulator fix the optimal tax t^* and the monopolist will choose to use the end of pipe technology without over investing in R&D

<u>*Investment in R&D in the second stage*</u> *to* <u>*boost the bargaining power*</u> $\pi_\emptyset^*(p_\emptyset^*) < \pi_i^*(p_i^*) < \pi_{eop/i}^*(t^*)$

	Parameters	Functions	Values
Variables	a		100
	b		1
	δ		4
	γ		10
	λ		10
	r		100
	φ		350
	α		0.1
Taxes	t^*	$\frac{a\gamma(2(2+b(\gamma+2\delta))\varphi-\gamma)}{\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+2(2+b(\gamma+2\delta))^2\varphi}$	$\frac{139900}{2819} \approx$ 49.63
	$\underline{t}$	given by $\pi_\emptyset(\underline{t}) = \pi_i^*$	≈49.54
	$\overline{t}$	given by $\pi_{eop/i}(\overline{t}) = \pi_i^*$	No solution in R
	$\hat{t}$		
Monopolist profits	π_i^*	$\frac{a^2}{4b(1+b\lambda)} - r$	$\frac{1400}{11} \approx$ 127.27
	$\pi_\emptyset^*(t^*)$	$\frac{(a-bt)^2}{4b(1+b\delta)}$	≈126.89
	$\pi_\emptyset(\underline{t})$		≈127.28
	$\pi_{eop/\emptyset}^*(t^*)$	$\pi_\emptyset^* + \alpha\,\overline{A}$	≈126.89
	$\pi_{eop/\emptyset}(\underline{t})$		≈ **139.56**
	$\pi_{eop/i}^*(t^*)$	$\pi_i^* + \alpha\,\overline{A}$	≈129.55
	$\pi_{eop/i}(\overline{t})$		
Welfares	W_i^*	$\frac{a^2(3+2b\lambda)}{8b(1+b\lambda)^2} - r$	$\frac{16650}{121} \approx$ 137.60
	$W_{eop/\emptyset}^*(t^*)$	$\frac{a^2(3+b(\gamma+2\delta))(\gamma+2\varphi)}{2b\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+4b(2+b(\delta+2\delta))^2\varphi}$	$\frac{105000}{397} \approx$ 264.48
	$W_{eop/i}^*(t^*)$	$= W_{\frac{eop}{\emptyset}}^*(t^*) - r$	≈164.48
	$W_{eop/\emptyset}(\underline{t})$	$\frac{3a^2\gamma - b(2at\gamma - 2a^2\gamma\delta + t^2(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))))}{8b\gamma(1+b\delta)^2} - \varphi(\frac{a-bt}{2+2b\delta} - \frac{t}{\gamma})^2$	≈ **264.36**
	$W_{eop/i}(\overline{t})$	$\frac{3a^2\gamma-b(2at\gamma-2a^2\gamma\delta+t^2(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))))}{8b\gamma(1+b\delta)^2} - \varphi(\frac{a-bt}{2+2b\delta} - \frac{t}{\gamma})^2$-r	

⇨ In this case, the regulator will fix $\underline{t}$ ≈49.54 to avoid the deadweight loss in r an hence, it will increase the welfare from $W_{eop/i}^*(t^*)$ ≈164.48 to $W_{eop/\emptyset}(\underline{t})$ ≈ 264.36 but can't reach the best welfare available $W_{eop/\emptyset}^*(t^*)$ ≈ 264.48

Investment in R&D in the second stage- $\pi^*_{eop/i}(t^*) < \pi^*_i$:

	Parameters	Functions	Values
Variables	A		100
	b		1
	δ		4
	γ		10
	λ		6.5
	r		60
	φ		15
	α		0.1
Taxes	t^*	$\frac{a\gamma(2(2+b(\gamma+2\delta))\varphi-\gamma)}{\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+2(2+b(\gamma+2\delta))^2\varphi}$	$\frac{5900}{139} \approx$ 42.45
	$\underline{t}$	given by $\pi_\emptyset(\underline{t}) = \pi^*_i$	$\approx$26.06
	$\hat{t}$	given by $\pi_{eop/i}(\hat{t}) = \pi^*_i$	$\approx$ 21.13
Monopolist profits	π^*_i	$\frac{a^2}{4b(1+b\lambda)} - r$	$\approx$273.33
	$\pi^*_\emptyset(t^*)$	$\frac{(a-bt)^2}{4b(1+b\delta)}$	165.62
	$\pi_\emptyset(\underline{t})$	$\frac{(a-bt)^2}{4b(1+b\delta)}$	$\approx$273.33
	$\pi_\emptyset(\hat{t})$		$\approx$ 313.26
	$\pi^*_{eop/\emptyset}(t^*)$	$\pi^*_\emptyset + \alpha\,\overline{A}$	
	$\pi_{eop/\emptyset}(\underline{t})$		$\approx$276.75
	$\pi_{eop/\emptyset}(\hat{t})$		$\approx$ 311.02
	$\pi^*_{eop/i}(t^*)$	$\pi^*_i + \alpha\,\overline{A}$	$\approx$265.57
	$\pi_{eop/i}(\hat{t})$		$\approx$273.33
Welfares	W^*_i	$\frac{a^2(3+2b\lambda)}{8b(1+b\lambda)^2} - r$	$\approx$295.56
	$W^*_{eop/\emptyset}(t^*)$	$\frac{a^2(3+b(\gamma+2\delta))(\gamma+2\varphi)}{2b\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+4b(2+b(\delta+2\delta))^2\varphi}$	$\frac{42000}{139} \approx$ 302.16
	$W^*_{eop/i}(t^*)$	$= W^*_{\underset{\emptyset}{eop}}(t^*) - r$	$\approx$242.16
	$W_{eop/\emptyset}(\underline{t})$	$\frac{3a^2\gamma - b(2at\gamma - 2a^2\gamma\delta + t^2(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))))}{8b\gamma(1+b\delta)^2} - \varphi(\frac{a-bt}{2+2b\delta} - \frac{t}{\gamma})^2$	$\approx$115.55
	$W_{eop/\emptyset}(\hat{t})$	$\frac{3a^2\gamma - b(2at\gamma - 2a^2\gamma\delta + t^2(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))))}{8b\gamma(1+b\delta)^2} - \varphi(\frac{a-bt}{2+2b\delta} - \frac{t}{\gamma})^2$	-13.63

⇨ In this case, the regulator fix $t^* \approx$42.45 and the monopolist use the integrated technology thus we obtain a welfare equals to $W^*_i \approx$295.56.

D. Appendix C- Simulations when $\mathbf{W^*_i > W^*_{end/\emptyset}(t^*)}$

This appendix will be competed in the next version to illustrate all the sub-cases described.

<u>*Investment in stage 2*</u> $\pi_i^*(p_i^*) < \pi_\emptyset^*(p_\emptyset^*)$

	Parameters	Functions	Values
Variables	A		100
	B		1
	δ		4
	γ		20
	λ		8
	r		20
	φ		15
Optimal tax	t^*	$\frac{a\gamma(2(2+b(\gamma+2\delta))\varphi-\gamma)}{\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+2(2+b(\gamma+2\delta))^2\varphi}$	**53.99**
Monopolist profits	π_{i}^*	$\frac{a^2}{4b(1+b\lambda)}-r$	≈ 257.78
	$\pi_{\mathrm{eop/i}}^*(\mathrm{t}^*)$	$\pi_i^*+\alpha\,\overline{A}$	≈ 247.87
	$\pi_\emptyset^*(\mathrm{t}^*)$	$\frac{(a-bt)^2}{4b(1+b\delta)}$	≈ 105.86
	$\pi_{\mathrm{eop}/\emptyset}^*(\mathrm{t}^*)$	$\pi_\emptyset^*+\alpha\,\overline{A}$	≈113.14
Welfare	W_i^*	$\frac{a^2(3+2b\lambda)}{8b(1+b\lambda)^2}-r$	≈273.21
	$W_{eop/\emptyset}^*(t^*)$	$\frac{a^2(3+b(\gamma+2\delta))(\gamma+2\varphi)}{2b\gamma\left(4+b(\gamma+2b\gamma\delta+4\delta(2+b\delta))\right)+4b(2+b(\delta+2\delta))^2\varphi}$	≈237.73

⇨ In this case, the regulator can fix the optimal tax t^* and the monopolist will choose to use the integrated technology without over investing in R&D.

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