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Abstract: We consider a model consisting of a monopolistic firm producing a certain good with pollution. This firm can adopt a cleaner technology within a finite time by incurring an investment cost decreasing exponentially with the adoption date. At each period of time, the firm is regulated by an emission tax which induces the socially optimal pollution and production levels, and a lump sum tax on profit. The firm is induced to adopt the cleaner technology at the socially optimal date by an appropriate innovation subsidy. In the incomplete information context, the firm has private information concerning the cost of acquiring the new technology. By an appropriate contract consisting of an adoption date and a R&D subsidy depending on the value of the innovation cost parameter announced by the firm, the regulator can induce the latter to reveal the true value of its private information in compensation of a socially costly intertemporal informational rent. However, the socially optimal adoption date of incomplete information is delayed with respect to the complete information one.

Keywords: cleaner technology, adoption date, incomplete information.
JEL classification: D62, D82, H57, O32.

1. Introduction

It is widely recognized that the development and diffusion of cleaner technologies is an essential strategy for achieving environmental quality goals. By considering identical firms in a competitive industry, Milliman and Prince (1989) have evaluated the incentive effects of five environmental policy instruments, which are direct controls, emission subsidies, emission taxes, free marketable permits, and auctioned marketable permits, to promote technological change in pollution control. They showed that, on a relative basis, emission taxes and auctioned permits provide the highest firm incentives to promote technological change. Jung, Krutilla and Boyd (1996) have extended this comparative approach to a heterogeneous industry. Stranlund (1997) considered public aid to encourage the adoption of superior emission-control technologies combined with monitoring. This strategy is interesting when monitoring is difficult because the sources of pollution are widely dispersed or when emissions are not easily measured as in non-point pollution problems. Technological aid reduces the direct enforcement effort necessary for firms to reach the compliance goal. Consequently, firms adopt better control technologies, which may serve to promote further innovative activity. Carraro and Topa (1991) and Dosi and Moretto (2000) have tried to study this question in a duopolistic industry by introducing asymmetric information.

Dosi and Moretto (1997) have studied the regulation of a firm which can switch to a green technology by incurring an irreversible investment cost. This technological switch is expected to provide appropriable benefits surrounded, however, by a certain degree of uncertainty. To bridge the gap between the private and the policy-maker's desired timing of innovation, they recommended that the regulator should stimulate the innovation by subsidies and by reducing the uncertainty surrounding the profitability of the new technology through appropriate announcements. Farzin and Kort (2000) have studied the regulation of a competitive firm and examined the effect of a higher pollution tax rate on abatement investment, both under full certainty and when the timing or the size of the tax increase is uncertain. They showed the possibility that a higher pollution tax rate induces more pollution and that a credible threat to accelerate the tax increase can lead to a more abatement investment.

Our model differs from the previous literature by the fact that we study the regulation of a monopolistic firm which can adopt a cleaner technology in a finite time and may have private information about the cost of the new innovation.

We consider a model consisting of a monopolistic firm producing a certain good with pollution. This firm can adopt a cleaner technology within a finite time by incurring an investment cost decreasing exponentially with the adoption date. Since the firm is a monopoly that pollutes the environment, it is regulated. We suppose that raising public funds is socially costly. At each period of time, the firm is regulated by an emission tax, which induces the socially optimal pollution and production levels, and a lump sum tax on profit. The firm can also be induced to adopt the cleaner technology at the socially optimal date by an appropriate subsidy. Because of the positive marginal social cost of public funds, the firm has a net profit equal to zero. In the incomplete information context, the firm has private information concerning the cost of acquiring the new technology. By means of a contract consisting of an adoption date and a R&D subsidy depending on the value of the innovation cost parameter announced by the firm, the regulator can induce the latter to reveal the true value of the private information in compensation of an intertemporal informational rent. However, the socially optimal adoption date is delayed with respect to the complete information case.

The paper has the following structure. In section 2, we introduce the model and treat the full information case. In section 3, we study the incomplete information case and, in section 4, we conclude. Finally, in an appendix, we give the proofs to some results.

2. The complete information benchmark

We consider a monopolistic firm producing a certain good in quantity q sold on the market at price $p(q)=a-bq$, $a,b>0$.

The consumption of this good gives a consumer surplus equal to $CS(q) = \int_0^q p(z)\,dz - p(q)q = \frac{b}{2}q^2$.

The unit production cost is c>0 and the profit of the firm is Π(q)=p(q)q-cq.

The emission per-unit of good produced is e>0 and the pollution emitted by the firm is E=eq, which causes damages to the environment equal to D=αE, where α>0 is the marginal disutility of pollution.

At the beginning of the game i.e. at date 0, the firm uses an old production technology characterized by an emission/output ratio equal to K>0. The firm behaves for an infinite horizon of time and can adopt a new and cleaner production technology within a period of time τ, which is characterized by a lower emission/output ratio k verifying 0<k<K. The investment cost required could comprise the R&D cost and/or the cost of acquisition and installation of the new technology. Thus, we will use the terms innovation and adoption interchangeably.

We model the cost of adopting the cleaner technology at date τ actualized at date 0 as:

$$V(\tau) = \theta e^{-mr\tau} \tag{1}$$

Where θ>0 is the cost of immediate adoption of the new technology, r>0 is the discount rate, and m>1 denotes that the cost of innovation decreases more rapidly as m is greater.

Function V is decreasing because of the existence of freely-available scientific research allowing the firm to reduce the cost of innovation when it delays its adoption, and is convex as the innovation cost increases more rapidly when the firm tries to accelerate the adoption date. Let's notice that τ=+∞ means that the firm never innovates.

At each period of time, the firm is a monopoly that pollutes the environment and, therefore, should be regulated. The regulator proposes a contract (q, x), where q is the level of production and x is a monetary transfer from the regulator to the firm.

We suppose that public funds are raised through distortionary taxation and we denote the marginal social cost of public funds by λ>0, which means that collecting

1$ from a firm costs λ$ to the regulator, or equivalently, giving 1$ to the firm costs to the regulator (1+λ)$.[1]

Thus, the consumer welfare is CS(q)-D(q)-(1+λ)x, the net profit of the monopoly is U=Π(q)+x, and the social welfare W is equal to the consumer welfare plus the net profit, which can be written as W=S(q)-λU, where

$$S=CS(q)-D(q)+(1+\lambda)\Pi(q)=\frac{b}{2}q^2-\alpha eq+(1+\lambda)[(a-bq)q-cq] \quad (2)$$

Under complete information, the regulator maximizes his social welfare with respect to q and U under the rationality constraint of the firm. We allow ourselves to express the regulator's problem in function of U rather than x because these latter are one-to-one related. Since the reservation utility level of the firm is assumed to be equal to zero, the regulator chooses the monetary transfer so that the net profit of the firm is nil (U=0), then he chooses the production quantity that maximizes W or, equivalently, that maximizes S.

The socially optimal production quantities when the firm uses the old and new technology are, respectively:

$$q_o=\frac{(1+\lambda)(a-c)-\alpha K}{(1+2\lambda)b} \quad , \quad q_n=\frac{(1+\lambda)(a-c)-\alpha k}{(1+2\lambda)b} \quad (3)$$

These production quantities are positive iff:

$$(1+\lambda)(a-c)>\alpha K \quad (C.1)$$

The cleaner technology enables to increase production. We can verify that $E_n < E_o$ iff (1+λ)(a-c)> α(k+K). Therefore, when the marginal disutility of pollution is low enough, the new technology enables to produce more while reducing pollution. However, when the marginal disutility of pollution is high enough, the new technology increases pollution.

If direct quantitative regulation is not desired, at each period of time, the regulator can implement the socially optimal levels of production, pollution and social welfare by the following two instruments: a tax per-unit of pollution $t=\frac{-2bq+a-c}{e}$ and a lump sum tax on profit T=[p(q)-c-te]q>0, where q and e are, respectively, equal to q_o and K, or to q_n and k.

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[1] See Ballard et al. (1985) and Laffont (1994) for more information on this subject.

To induce the firm adopting the cleaner technology at the socially optimal date, the regulator, at date 0, proposes a contract (τ, g) where τ is the adoption date and g is the value of the innovation subsidy actualized at date 0, which will be received by the firm at date τ. Let's notice that the contract is signed at date 0, whereas the subsidy is received at date τ to prevent that the firm don't respect the signed contract after having received the innovation subsidy.

The intertemporal net profit of the firm at date 0 is IU=g-V(τ).

The intertemporal social welfare of the regulator at date 0 is equal to the instantaneous social welfare actualized at date 0, minus the innovation subsidy given to the firm weighed by (1+λ), plus the intertemporal net profit of the firm:

$$IW = \int_0^{\tau} S_o e^{-rt}\, dt + \int_{\tau}^{+\infty} S_n e^{-rt}\, dt - (1+\lambda)g + IU$$

The above expression can be written as:

$$IW = \int_0^{\tau} S_o e^{-rt}\, dt + \int_{\tau}^{+\infty} S_n e^{-rt}\, dt - (1+\lambda)V(\tau) - \lambda IU \tag{4}$$

Under complete information, the regulator sets the innovation subsidy so that the intertemporal net profit of the firm is nil. Therefore, the regulator reimburses to the firm all the cost of innovation i.e. g=V(τ).

Thus, the intertemporal social welfare is:

$$IW = \int_0^{\tau} S_o e^{-rt}\, dt + \int_{\tau}^{+\infty} S_n e^{-rt}\, dt - (1+\lambda)\theta e^{-mr\tau} \tag{5}$$

Maximizing the intertemporal social welfare given by (5) with respect to τ gives the socially optimal adoption date.

In the appendix, we show that $S_n > S_0$ meaning that the instantaneous social welfare is greater when the cleaner technology is used because innovation enables to produce more while polluting less when the marginal damage of pollution is low enough. Also, we derive the socially optimal adoption date of complete information:

$$\tau_s^C = \frac{1}{(1-m)r} \ln\left(\frac{S_n - S_o}{(1+\lambda)\theta mr}\right) \tag{6}$$

Expression (6) is positive iff:

$$\frac{S_n - S_o}{(1+\lambda)mr} < \theta \tag{C.2}$$

Therefore, the cost of immediate adoption (at date 0) is sufficiently high. This is why adoption is not immediate. What determine the socially optimal adoption date are the instantaneous gain from innovation $S_n - S_0 > 0$, and the cost of innovation which increases rapidly as adoption is accelerated. This comparison shows that the new technology is adopted within a finite and non nil time.

The natural question at this stage is what is the optimal adoption date which will be chosen by the firm without any intervention of the regulator on the innovation activity of the latter? Since the instantaneous net profit of the firm is nil, adopting the new technology at any finite date τ gives it an intertemporal net profit negative and equal to –V(τ). Thus, without an intervention of the regulator on the innovating activity of the firm, the latter will never adopt the cleaner technology.

3. The incomplete information case

Now we suppose that the firm has a private information concerning its cost of adopting the cleaner technology: θ is a private information for the firm. However, the regulator knows that $\theta \in [\underline{\theta}, \overline{\theta}]$ with the probability density function $f(\theta) = \frac{1}{\overline{\theta} - \underline{\theta}}$, and the uniform distribution *F*. The regulation of a monopoly under incomplete information and costly public funds has been very well studied by Laffont and Tirole (1986).

At each period of time, there are no informational asymmetries, and the firm is regulated as in the complete information benchmark because the lack of information of the regulator concerns the innovation abilities of the firm and does not concern its production abilities.

At date 0, the regulator proposes a contract $(\tau(\hat{\theta}), g(\hat{\theta}))$ where $\hat{\theta}$ is the value of the private information announced by the firm, $\tau(\hat{\theta})$ is the date at which it will adopt the new technology and $g(\hat{\theta})$ is the R&D subsidy, actualized at date 0, which will receive the firm from the regulator at date $\tau(\hat{\theta})$. We suppose that the regulator cannot contract on any kind of ex post information.

The instantaneous net profit of the firm is nil because there is no informational asymmetries. However, the intertemporal net profit of the firm is:

$$IU(\theta, \hat{\theta}) = g(\hat{\theta}) - V(\theta, \tau(\hat{\theta}))$$

There is a temptation for the firm to announce a higher value than the true value of its private information in order to make the regulator believe that it has high innovation cost and, accordingly, receives a higher innovation subsidy. Therefore, the contract proposed by the regulator must provide incentives to the firm to reveal the true value of θ:

$$\theta \in \arg\max_{\hat{\theta}} \left\{ g(\hat{\theta}) - V(\theta, \tau(\hat{\theta})) \right\}, \forall \theta \in \left[\underline{\theta}, \overline{\theta} \right]$$

The first order condition for the revelation problem is:

$$\left[g'(\hat{\theta}) - \tau'(\hat{\theta}) V_\tau(\theta, \tau(\hat{\theta})) \right]_{\hat{\theta}=\theta} = 0 \Leftrightarrow g'(\theta) - \tau'(\theta) V_\tau(\theta, \tau(\theta)) = 0 \tag{7}$$

At the equilibrium, the intertemporal net profit of the firm is:

$$IU(\theta) = g(\theta) - V(\theta, \tau(\theta))$$

Deriving with respect to θ the above expression, we get:

$$IU'(\theta) = g'(\theta) - V_\theta(\theta, \tau(\theta)) - \tau'(\theta) V_\tau(\theta, \tau(\theta))$$

Using (7), the first order local condition becomes:

$$IU'(\theta) = -V_\theta(\theta, \tau(\theta)) \tag{8}$$

The second order local condition is:

$$g''(\theta) - \tau''(\theta) V_\tau(\theta, \tau(\theta)) - (\tau'(\theta))^2 V_{\tau\tau}(\theta, \tau(\theta)) \leq 0$$

Using (7), we get:

$$\left[g''(\theta) - \tau''(\theta) V_\tau(\theta, \tau(\theta)) - (\tau'(\theta))^2 V_{\tau\tau}(\theta, \tau(\theta)) \right] - \tau'(\theta) V_{\theta\tau}(\theta, \tau(\theta)) = 0$$

The term between the above brackets is negative iff the other term is positive. The new second order local condition is:

$$\tau'(\theta) V_{\theta\tau}(\theta, \tau(\theta)) \leq 0 \tag{9}$$

At the equilibrium, the intertemporal social welfare is:

$$IW(\tau(\theta), g(\theta), \theta) = \int_0^{\tau(\theta)} S_o e^{-rt}\, dt + \int_{\tau(\theta)}^{+\infty} S_n e^{-rt}\, dt - (1+\lambda) g(\theta) + IU(\theta)$$

The above expression can be written as:

$$IW(\tau(\theta), g(\theta), \theta) = IS(\tau(\theta), \theta) - \lambda IU(\theta) \tag{10}$$

where

$$IS(\tau(\theta), \theta) = \int_0^{\tau(\theta)} S_o e^{-rt}\, dt + \int_{\tau(\theta)}^{+\infty} S_n e^{-rt}\, dt - (1+\lambda) V(\theta, \tau(\theta)) \tag{11}$$

The regulator maximizes the mathematical expectation of his intertemporal social welfare with respect to τ(θ) and IU(θ) under the revelation and rationality constraints of the firm.

To simplify the optimization problem of the regulator, we replace the rationality constraint (IU(θ)≥0) by $IU(\overline{\theta})=0$. This last equality seems logical since when the innovation parameter cost is equal to its higher value, the firm trying to overestimate its private information, cannot do it and, therefore, has no intertemporal informational rent. Moreover, we momentarily put aside the second order local condition. We come to the Bayesian differentiable equilibrium and we check ex post these ignored constraints as well as the positivity of the equilibrium adoption date and the global optimality of the revelation problem of the firm.

Thus, the simplified optimization problem of the regulator is:

$$\begin{aligned}&\underset{\tau(.),IU(.)}{Max}\int_{\underline{\theta}}^{\overline{\theta}} f(\theta)\big(IS(\tau(\theta),\theta)-\lambda IU(\theta)\big)d\theta\\&IU'(\theta)=-V_{\theta}(\theta,\tau(\theta))\\&IU(\overline{\theta})=0\end{aligned} \tag{12}$$

In the appendix, we derive the socially optimal adoption date of incomplete information:

$$\tau_s^I(\theta)=\frac{1}{(1-m)r}\ln\left(\frac{S_n-S_o}{\left[(1+\lambda)\theta+\lambda(\theta-\underline{\theta})\right]mr}\right) \tag{13}$$

We can verify that $\tau_s^I(\theta)>\tau_s^C(\theta)$ meaning that asymmetric information postpones the adoption of the cleaner technology.

From (8), we can calculate IU(θ), and then the innovation subsidy:

$$g(\theta)=\int_{\theta}^{\overline{\theta}} e^{-mr\tau_s^I(z)}dz+\theta e^{-mr\tau_s^I(\theta)}$$

From expression (7), we have $g'(\theta)=\left(\tau_s^I(\theta)\right)'V_{\tau}\left(\theta,\tau_s^I(\theta)\right)$. From (13), we have $\left(\tau_s^I(\theta)\right)'>0$, and since $V_{\tau}(\theta,\tau(\theta))$ <0, then g′(θ)<0: the subsidy received by the firm decreases with θ and the adoption date is delayed. This is what induces the firm to tell the true value of its private information.

4. Conclusion

We study the regulation of a monopolistic firm which can adopt a cleaner production technology in a finite time and may have private information about the cost of the new innovation. We suppose the existence of positive marginal social cost of public funds.

At each period of time, the firm is regulated by an emission tax which induces the socially optimal pollution and production levels, and a lump sum tax on profit. The firm can also be induced to adopt the cleaner technology at the socially optimal date by an appropriate innovation subsidy.

Under incomplete information, by means of a contract consisting of an adoption date and a R&D subsidy depending on the value of the innovation cost parameter announced by the firm, the regulator can induce the latter to reveal the true value of its private information in compensation of an intertemporal informational rent. However, the socially optimal adoption date is delayed with respect to the complete information case.

Our results can be extended to the case where the new technology is characterized by abatement possibilities and when abatement costs are not too high. Indeed, at each period of time, by using the new technology, pollution is lower and production is greater implying a social welfare improvement, which makes the adoption profitable. They can also be extended to the case where the new technology reduces the cost of production.

Let's notice that we deal with an infinite horizon of time thus avoiding too hard computations, but our results remain valid for a sufficiently long finite horizon.

If we extend our model to the case of n identical firms competing in quantities, the equilibrium at each period of time is determined by the total production of firms. Consequently, to support only one investment cost, the regulator will choose only one firm producing and the other will be inactive. Thus, if we want to extend this work to an interesting oligopoly case, we can consider that the marginal cost of production is not constant. The incomplete information context of such an extension is trivial if the private information parameters are perfectly correlated among firms because yardstick competition[2] enables the regulator to extract the private information at no cost and implement the full information equilibrium. Thus, what is interesting is to consider that the R&D cost parameters are independently distributed.

Appendix

A) Proof of $S_n > S_o$

Expression (2) can be written as:

$$S = -\frac{1}{2}(1+2\lambda)bq^2 + [(1+\lambda)(a-c) - \alpha e]q$$

Thus,

$$\begin{aligned} S_n - S_o &= -\frac{1}{2}(1+2\lambda)b(q_n^2 - q_o^2) + [(1+\lambda)(a-c) - \alpha k]q_n - [(1+\lambda)(a-c) - \alpha K]q_o \\ &= \left[-\frac{1}{2}(1+2\lambda)b(q_n + q_o) + (1+\lambda)(a-c)\right](q_n - q_o) + \alpha(Kq_o - kq_n) \end{aligned}$$

By using the expressions of q_o and q_n given by (3), we get:

$$S_n - S_o = \frac{\alpha}{2}(k+K)(q_n - q_o) + \alpha(Kq_o - kq_n) = \alpha\frac{K-k}{2}(q_n + q_o) > 0$$

Therefore, the instantaneous social welfare is greater when the monopoly uses the cleaner technology.

B) Derivation of the socially optimal adoption date of complete information

To get the socially optimal adoption date, the regulator maximizes his intertemporal social welfare function given by (5) with respect to τ:

$$\frac{\partial IW}{\partial \tau} = (S_o - S_n)e^{-r\tau} + (1+\lambda)\theta mre^{-mr\tau} = 0 \tag{14}$$

Equation (14) is equivalent to:

$$S_o - S_n + (1+\lambda)\theta mre^{(1-m)r\tau} = 0 \Leftrightarrow \tau_s^C = \frac{1}{(1-m)r}\ln\left(\frac{S_n - S_o}{(1+\lambda)\theta mr}\right) \tag{15}$$

Because of condition (C.2), $\tau_s^C > 0$.

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[2] See Kwerel (1977) and Shleifer (1985).

We have: $\dfrac{\partial^2 IW}{\partial \tau^2} = r(S_n - S_o)e^{-r\tau} - (1+\lambda)\theta(mr)^2 e^{-mr\tau}$.

Using (14), we get:

$$\frac{\partial^2 IW(\tau_s^C)}{\partial \tau^2} = (1+\lambda)\theta m(1-m)r^2 e^{-mr\tau_s^C} < 0$$

The second order condition of optimality is therefore verified.

C) Derivation of the socially optimal adoption date of incomplete information

The Hamiltonian of the simplified optimization problem of the regulator given by (12) is:

$$H(\tau, IU, \theta) = f(\theta)[IS(\tau,\theta) - \lambda IU] - \rho(\theta)V_\theta(\theta,\tau) \tag{16}$$

Where $\rho(\theta)$ is the multiplier of the incentive constraint.

The necessary, and sufficient due to the concavity of the Hamiltonian, Kuhn and Tucker conditions are: $\dfrac{\partial H}{\partial \tau} = 0$ and $\rho'(\theta) = -\dfrac{\partial H}{\partial IU} = \lambda f(\theta)$.

Since there is no transversality condition in $\underline{\theta}$, then $\rho(\theta) = \lambda F(\theta) = \lambda \dfrac{\theta - \underline{\theta}}{\overline{\theta} - \underline{\theta}}$.

From (16):

$$\frac{\partial H}{\partial \tau} = f(\theta)\frac{\partial IS}{\partial \tau} - \rho(\theta)V_{\theta\tau} = 0 \tag{17}$$

Using (1) and (11), we get:

$$\frac{\partial IS}{\partial \tau} = (S_o - S_n)e^{-r\tau} + (1+\lambda)\theta m r e^{-mr\tau} \tag{18}$$

Using (18) in (17) gives us the socially optimal adoption date of incomplete information:

$$\tau_s^I(\theta) = \frac{1}{(1-m)r}\ln\left(\frac{S_n - S_o}{\left[(1+\lambda)\theta + \lambda(\theta - \underline{\theta})\right]mr}\right) \tag{19}$$

Condition (C.2) guarantees that the above quantity is positive.

The intertemporal informational rent of the firm is strictly decreasing because $IU'(\theta) = -V_\theta(\theta, \tau(\theta)) = -e^{-mr\tau} < 0$, and since $IU(\overline{\theta}) = 0$, then $IU(\theta) \geq 0, \forall \theta$.

The second order local condition of the revelation problem of the firm, given by (9), is verified because $\left(\tau_s^I(\theta)\right)' > 0$ and $V_{\theta\tau} < 0$.

To verify the global optimality of the revelation problem of the firm, we consider the difference:

$$\Delta = g(\theta) - V(\theta, \tau(\theta)) - \left[g(\hat{\theta}) - V(\theta, \tau(\hat{\theta}))\right]$$
$$= \left[g(y) - V(\theta, \tau(y))\right]_{\hat{\theta}}^{\theta} = \int_{\hat{\theta}}^{\theta} g'(y) - \tau'(y) V_{\tau}(\theta, \tau(y)) dy$$

Using equation (7):

$$\Delta = \int_{\hat{\theta}}^{\theta} \tau'(y) V_{\tau}(y, \tau(y)) - \tau'(y) V_{\tau}(\theta, \tau(y))\, dy$$
$$= \int_{\hat{\theta}}^{\theta} \tau'(y)[V_{\tau}(y, \tau(y)) - V_{\tau}(\theta, \tau(y))]\, dy = \int_{\hat{\theta}}^{\theta} \tau'(y) \int_{\theta}^{y} V_{\theta\tau}(z, \tau(y))\, dz\, dy$$

Since $\left(\tau_s^I\right)'(y) > 0$ and $V_{\theta\tau} < 0$, then Δ>0, which means that the firm gets a higher intertemporal net profit when it announces the true value of its private information.

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