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Abstract: We consider a monopolistic firm producing a good while polluting and using a fossil energy. This firm can adopt a clean technology by incurring an investment cost decreasing exponentially with the adoption date. This clean technology does not pollute and has a lower production cost because it uses a renewable energy. We determine the optimal adoption date for the firm in the cases where it is regulated at each period of time and when it is not regulated. Interestingly, the regulated firm adopts the clean technology earlier than what is socially-optimal. However, the non-regulated firm adopts later than what is socially desired. The regulator can compensate the regulated firm for the loss incurred if he wants that it delays its adoption date to the socially-optimal one. Nevertheless, the regulator may be interested in letting the firm adopts earlier to encourage the diffusion of the use of green technologies in other industries.

Keywords: regulation, clean technology, renewable energy, adoption date.
JEL classification: D62, H57, Q42, Q55.

1. Introduction

Encouraging the use of renewable energy, such as solar energy or wind energy, in place of fossil energy is one of the most stimulating debates of the recent years. Indeed, countries are more conscious that fossil energy is becoming scarce and they are now experiencing the effects of climate change. Moreover, petrol multinationals have gained too much money in the last decade and are now ready to invest in the promotion of renewable energies.

Dosi and Moretto (1997) 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 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. Soest (2005) analyzed the impact of environmental taxes and quotas on the timing of adoption when the rate at which improved energy-efficient technologies become available is uncertain, and when the investment decision is irreversible. He found that neither policy instrument is unambiguously preferred to the other. Nasiri and Zaccour (2009) proposed a game-theoretic approach to model and analyze the process of utilizing biomass for power generation. They considered three players: distributor, facility developer, and participating farmer. They characterized the subgame-perfect Nash equilibrium and discussed its features. Ben Youssef (2010) considered a monopolistic firm that can adopt a cleaner technology within a finite time by incurring an investment cost. He showed that the socially-optimal adoption date of incomplete information is delayed with respect to the complete information one.

Whitehead and Cherry (2007) estimated the annual benefits of the regional amenities associated with a green energy program in North Carolina. Varun, Prakash and Bhat (2009) found that wind and small hydro are the most sustainable source for the electricity generation. Li *et al.* (2009) estimated how much US households would be willing to pay annually to support increased energy R&D activities designed to replace fossil fuels. Caspary (2009) assessed the likely competitiveness of different forms of renewable energy in Colombia over the next 25 years. The key conclusion is that while solar Photovoltaic (PV) will likely remain uncompetitive under any future cost scenario, cost paths for small hydro, modern biomass or geothermal are already close enough to being competitive. Thus, appropriate government intervention may make the decisive difference in making these technologies competitive with conventional energy technologies. Pillai and Banerjee (2009) reviewed the status and potential of different renewables (except biomass) in India and have established a diffusion model as a basis for setting targets.

The most important features of this work is that the clean technology has a lower production cost than the polluting one. Moreover, we compare the socially-optimal adoption date to the optimal one for the instantaneous regulated and non-regulated firm.

We consider a monopolistic firm producing a good using a dirty (polluting) technology. We can think about a producer of electricity like société tunisienne d’éléctricité et du gaz (STEG) which has a monopoly power of producing and distributing electricity in Tunisia. This polluting production uses fossil energy. This firm can adopt a clean technology within a finite time by incurring an investment cost decreasing exponentially as the adoption is delayed. The new and green production technology is characterized by no pollution emission and by a lower production cost because it uses a renewable energy. We consider the situation where the firm is regulated at each period of time by an emission-tax when it uses the dirty technology, and by a production subsidy when it uses the green technology. We also consider the situation where the monopoly is not regulated.

Surprisingly, the regulated firm adopts the green technology in a finite time and earlier than what is socially desired. The regulator can compensate the firm for the losses incurred so that it delays its adoption to the socially-optimal adoption date. Nonetheless, the non-regulated firm adopts the clean technology in a finite time but later than what is socially desired.

Indeed, when the regulated firm switch to the green technology, it no longer pays a pollution tax, receives a production subsidy and its production cost decrease.

Consequently, its instantaneous net profit increases importantly and that's why it adopts the clean technology very soon. In the same time, the instantaneous social welfare level increases because there are no environmental damages and production costs are lower. However, this instantaneous benefit of society from the green technology is less important than that of the firm. For this reason the firm adopts the clean technology earlier than what is socially optimal. When the non-regulated firm adopts the green technology, its production cost decreases. Consequently, its instantaneous net profit increases, but not importantly, and less than the increase of the instantaneous social welfare. Thus, the adoption date of the non-regulated firm is higher than what is socially desired.

Our main result contradicts with the one in Ben Youssef (2010) where, because of the positive marginal social cost of public funds, the instantaneous net profit of the regulated firm is nil, and that's why the firm never adopts the cleaner technology unless it receives an innovation subsidy. Also, in Dosi and Moretto (1997), the regulator objective is the abandonment of the polluting technology and adoption of the green one before a ''critical'' date, whereas in the present paper the regulator maximizes his intertemporal social welfare function. Moreover, they have not considered the case where the firm is instantaneously regulated.

The paper is structured as follows. Section 2 introduces the model. Section 3 studies the instantaneous regulated firm and Section 4 studies the non-regulated firm. In Section 5, we derive the optimal adoption dates and compare them. Section 6 concludes and an Appendix contains some proofs.

2. The model

We consider a monopolistic firm producing a 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 $CS(q)=\int_0^q p(z)\,dz-p(q)q=\frac{b}{2}q^2$.

At the beginning of the game i.e. at date *0*, the firm uses an old and polluting production technology using fossil fuels and characterized by a positive emission/output ratio $e>0$.

Therefore, the pollution emitted by the firm is $E=eq$, which causes damages to the environment equal to $D=\alpha E$, where $\alpha>0$ is the marginal disutility of pollution. Let us point out here that we suppose that damages caused to the environment are due to the flow of emissions and not to the stock of pollution.

With the polluting technology, the unit production cost is $d>0$ and the profit of the firm[1] is $\Pi_d = p(q)q - dq$.

The firm behaves for an infinite horizon of time and can adopt a new and clean production technology within a period of time τ. This clean technology does not pollute at all, uses a renewable energy (solar energy for instance) and therefore has a lower unit production cost c verifying $0<c<d$. Thus, the profit of the firm is $\Pi_c = p(q)q - cq$.

An investment cost is necessary to get the new technology. This investment cost could comprise the R&D cost and/or the cost of acquisition and installation of the green technology. Thus, we will use the terms innovation and adoption interchangeably.

The cost of adopting the clean technology at date τ actualized at date *0* is:

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

where $\theta>0$ is the cost of immediate adoption of the green technology, $r>0$ is the discount rate, and $m>1$ denotes that the cost of innovation decreases more rapidly when m is greater.

Function V is decreasing because of the existence of freely-available scientific research enabling the firm to reduce the cost of innovation when it delays its adoption, and is convex because the R&D cost increases more rapidly when the firm tries to accelerate the adoption date. Let's remark that $\tau=+\infty$ means that the firm never innovates.

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[1] In what follows, the subscripts d and c will refer to the dirty (polluting) and clean technologies, respectively.

3. Regulated firm

In this section, we study the case where the firm is regulated at each period of time. Rather than directly looking to the socially-optimal regulatory instruments, we will determine the socially-optimal production quantities. Next, we determine the regulatory instruments.

When the firm uses the dirty technology, the instantaneous social welfare is:

$$S_d = CS(q) - D(q) + \Pi_d(q) \tag{2}$$

Maximizing the expression given by (2) with respect to q gives the socially-optimal production level with the polluting technology:

$$\hat{q}_d = \frac{a - d - \alpha e}{b} \tag{3}$$

We assume the following condition so that production quantities are positive:

$$a > d + \alpha e \tag{4}$$

Therefore, the maximum willingness to pay for the good must be higher than the marginal cost of production plus the marginal damage of production.

Since the firm is a polluting monopoly, it is regulated. An emission-tax per-unit of pollution t is sufficient to induce the socially-optimal level of production.

Indeed, the instantaneous net profit of the firm is:

$$U_d = \Pi_d(q) - tE(q) \tag{5}$$

The socially-optimal per-unit emission-tax that induces the firm to produce $\hat{q}_d$ is:

$$t = \frac{a - d - 2b\hat{q}_d}{e} \tag{6}$$

Using the expression of $\hat{q}_d$, we can show that:

$$t > 0 \Leftrightarrow a < d + 2\alpha e \tag{7}$$

Therefore, the emission-tax is positive when the marginal damage of pollution is high enough. Otherwise, it is negative meaning that the regulator subsidizes production to deal with the monopoly distortion.

When the firm uses the clean technology, the instantaneous social welfare is:

$$S_c = CS(q) + \Pi_c(q) \tag{8}$$

Maximizing the expression given by (8) with respect to *q* gives the socially-optimal production level with the green technology:

$$\hat{q}_c = \frac{a-c}{b} \tag{9}$$

It is to verify that $\hat{q}_c > \hat{q}_d$. Therefore, the clean technology enables to produce more and without pollution.

Since the monopoly has tendency to under-produce, it is regulated by a subsidy per-unit of production *s* to induce the socially-optimal level of production.

Indeed, the instantaneous net profit of the firm is:

$$U_c = \Pi_c(q) + sq \tag{10}$$

The socially-optimal per-unit subsidy that induces the firm to produce $\hat{q}_c$ is:

$$s = 2b\hat{q}_c + c - a \tag{11}$$

Using the expression of $\hat{q}_c$, we can show that $s>0$.

4. Non-regulated firm

In this section, we will study the case where the monopoly is not regulated even when it uses the dirty technology.

When it uses the old technology, the firm maximizes it profit Π_d to get the optimal level of production:[2]

$$q_d^n = \frac{a-d}{2b} \tag{12}$$

When it uses the green technology, the firm maximizes it profit Π_c to get the optimal level of production:

$$q_c^n = \frac{a-c}{2b} \tag{13}$$

It is easy to verify that the firm produces more with the clean technology because of its lower production cost $\left(q_c^n > q_d^n\right)$.

We can establish that:

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[2] The superscript *n* refers to the non-regulation case.

$$\hat{q}_d > q_d^n \Leftrightarrow a - d > 2\alpha e \tag{14}$$

Indeed, with the polluting technology, the socially-optimal production takes into account both environmental damages and the monopoly distortion, and is higher than the monopoly level only when the marginal damage is low enough. However, with the clean technology, there is no pollution, and we always have $\hat{q}_c > q_c^n$ as it is commonly known.

5. Optimal adoption dates

The intertemporal social welfare, intertemporal net profit of the regulated firm and non-regulated firm are, respectively:

$$IS = \int_0^{\tau} S_d(\hat{q}_d) e^{-rt}\,dt + \int_{\tau}^{+\infty} S_c(\hat{q}_c) e^{-rt}\,dt - \theta e^{-mr\tau} \tag{15}$$

$$IU = \int_0^{\tau} U_d(\hat{q}_d) e^{-rt}\,dt + \int_{\tau}^{+\infty} U_c(\hat{q}_c) e^{-rt}\,dt - \theta e^{-mr\tau} \tag{16}$$

$$IU^n = \int_0^{\tau} \Pi_d(q_d^n) e^{-rt}\,dt + \int_{\tau}^{+\infty} \Pi_c(q_c^n) e^{-rt}\,dt - \theta e^{-mr\tau} \tag{17}$$

In order to have positive adoption dates, we need the following condition, which can be always verified by choosing θ and/or m high enough:

$$U_c(\hat{q}_c) - U_d(\hat{q}_d) < \theta mr \tag{18}$$

The regulator and the firm maximize their intertemporal payoff functions with respect to τ to get the optimal adoption date. In the Appendix, we determine the socially-optimal adoption date, the optimal adoption date for the regulated firm and for the non-regulated firm, which are respectively:

$$\hat{\tau} = \frac{1}{(1-m)r} \ln\left(\frac{S_c(\hat{q}_c) - S_d(\hat{q}_d)}{\theta mr} \right) > 0 \tag{19}$$

$$\tau^* = \frac{1}{(1-m)r} \ln\left(\frac{U_c(\hat{q}_c) - U_d(\hat{q}_d)}{\theta mr} \right) > 0 \tag{20}$$

$$\tau^{n*} = \frac{1}{(1-m)r} \ln\left(\frac{\Pi_c(q_c^n) - \Pi_d(q_d^n)}{\theta mr} \right) > 0 \tag{21}$$

Proposition 1. *We have the following ranking for the optimal adoption dates:*

$$0 < \tau^* < \hat{\tau} < \tau^{n*} \tag{22}$$

Therefore, the optimal adoption date for the regulated firm is earlier than the socially-optimal one. However, the optimal adoption date for the non-regulated firm is later than the socially-optimal one.

Proof. See the Appendix.

The above results are due to the fact that the incentives to innovate are, in order, greater for the regulated firm, the society and the non-regulated firm. This is clearly established by the inequalities in (29). Indeed, when the regulated firm uses the clean technology, its instantaneous net profit importantly increases because it no longer pays a pollution tax, receives a production subsidy and has a lower production cost. Consequently, the regulated firm adopts the green technology very early. For the society, the clean technology prevents environmental damages and reduces production costs. That's why adoption is socially desired. The non-regulated firm has less incentive because the unique advantage of the new technology is the reduction of its unit production cost. Nonetheless, the non-regulated firm adopts the green technology within a finite time.

Paradoxically, if the regulator desires that the regulated firm delays its adoption to the socially-optimal adoption date, he has to compensate the firm for the losses it incurs by this delay of adoption.

If the intertemporal net profits of the regulated firm are $IU(\tau^*)$ and $IU(\hat{\tau})$ when the adoption dates are τ^* and $\hat{\tau}$, respectively, then the innovation subsidy (compensation) is:

$$g = IU(\tau^*) - IU(\hat{\tau}) > 0 \tag{23}$$

Proposition 2. *The regulator can push the regulated firm to delay its adoption of the clean technology by giving it an innovation subsidy that compensates the firm for the losses it incur when it delays its optimal adoption date to the socially-optimal one.*

6. Conclusion

In this paper, we consider a monopolistic firm producing a good using a dirty technology. However, this firm can adopt a clean technology within a finite time by incurring an investment cost decreasing exponentially as the adoption is delayed. The green production technology is characterized by no pollution emission and by a lower production cost because it uses a renewable energy. We consider the situation where the firm is regulated at each period of time by an emission-tax when it uses the dirty technology, and by a production subsidy when it uses the green one. We also consider the situation where the monopoly is not regulated.

When the regulated firm switch to the green technology, it no longer pays a pollution tax, receives a production subsidy and its unit production cost decrease. Consequently, its instantaneous net profit increases significantly. In the same time, the instantaneous social welfare level increases because there are no environmental damages and production costs are lower. However, this instantaneous benefit of society from the green technology is less important than that of the firm. When the non-regulated firm adopts the green technology, its unit production cost decreases. Consequently, its instantaneous net profit increases, but not importantly, and less than the increase of the instantaneous social welfare. From these results we deduce the following.

The non-regulated firm adopts the clean technology in a finite time but later than what is socially-optimal. Interestingly, the regulated firm adopts the green technology in a finite time and earlier than what is socially desired. The regulator can compensate the firm for the losses incurred if he desires that the firm delays its adoption to the socially-optimal adoption date. However, the regulator may be interested in letting the firm adopts earlier to encourage the diffusion of the use of clean technologies in other industries.

Appendix

A) Instantaneous gains from the green technology

$$* S_c(\hat{q}_c) - S_d(\hat{q}_d) = \left[a - \frac{b}{2}(\hat{q}_d + \hat{q}_c) - c\right](\hat{q}_c - \hat{q}_d) + (d-c)\hat{q}_d + \alpha e \hat{q}_d$$

By using the expressions of $\hat{q}_d$ and $\hat{q}_c$, the above bracketed expression is equal to $\frac{d-c+\alpha e}{2}$. Therefore, we have:

$$S_c(\hat{q}_c) - S_d(\hat{q}_d) = \frac{d-c+\alpha e}{2}(\hat{q}_c + \hat{q}_d) > 0 \tag{24}$$

$$*U_c(\hat{q}_c) - U_d(\hat{q}_d) = [a - b(\hat{q}_c + \hat{q}_d)](\hat{q}_c - \hat{q}_d) + (s-c)\hat{q}_c + d\hat{q}_d + te\hat{q}_d$$

By changing the emission tax t and the production subsidy s by their expressions in function of $\hat{q}_d$ and $\hat{q}_c$, we obtain:

$$U_c(\hat{q}_c) - U_d(\hat{q}_d) = b(\hat{q}_c^2 - \hat{q}_d^2) > 0 \tag{25}$$

$$* \Pi_c(q_c^n) - \Pi_d(q_d^n) = [a - b(q_c^n + q_d^n)](q_c^n - q_d^n) + dq_d^n - cq_c^n$$

By replacing q_c^n and q_d^n between the above brackets by their values, we get:

$$\Pi_c(q_c^n) - \Pi_d(q_d^n) = \frac{d-c}{2}(q_c^n + q_d^n) > 0 \tag{26}$$

Therefore, the clean technology improves the instantaneous social welfare when production levels are the socially-optimal ones. It also increases the instantaneous net profit of both the regulated firm and non-regulated firm.

B) Comparison of the instantaneous gains

*By using expressions (24) and (25), we have:

$$\left(U_c(\hat{q}_c) - U_d(\hat{q}_d)\right) - \left(S_c(\hat{q}_c) - S_d(\hat{q}_d)\right) = \left[b(\hat{q}_c - \hat{q}_d) - \frac{d-c+\alpha e}{2}\right](\hat{q}_c + \hat{q}_d)$$

By using the expressions of $\hat{q}_d$ and $\hat{q}_c$ in the above bracketed expression, we obtain:

$$\left(U_c(\hat{q}_c) - U_d(\hat{q}_d)\right) - \left(S_c(\hat{q}_c) - S_d(\hat{q}_d)\right) = \frac{d-c+\alpha e}{2}(\hat{q}_c + \hat{q}_d) > 0 \tag{27}$$

*By using expressions (24) and (26), we get:

$$\left(S_c(\hat{q}_c)-S_d(\hat{q}_d)\right)-\left(\Pi_c(q_c^n)-\Pi_d(q_d^n)\right)=\frac{d-c+\alpha e}{2}(\hat{q}_c+\hat{q}_d)-\frac{d-c}{2}\left(q_c^n+q_d^n\right)$$
$$=\frac{d-c}{2}\left[\hat{q}_c+\hat{q}_d-q_c^n-q_d^n\right]+\frac{\alpha e}{2}(\hat{q}_c+\hat{q}_d)$$

By replacing $\hat{q}_d$, $\hat{q}_c$, q_c^n and q_d^n by their values in the above brackets, we obtain:

$$\left(S_c(\hat{q}_c)-S_d(\hat{q}_d)\right)-\left(\Pi_c(q_c^n)-\Pi_d(q_d^n)\right)=\frac{d-c}{2}\left[\frac{2a-c-d-2\alpha e}{2b}\right]+\frac{\alpha e}{2}(\hat{q}_c+\hat{q}_d)$$

Using condition (4) for the above bracketed term gives:

$$\left(S_c(\hat{q}_c)-S_d(\hat{q}_d)\right)-\left(\Pi_c(q_c^n)-\Pi_d(q_d^n)\right)>\frac{(d-c)^2}{4b}+\frac{\alpha e}{2}(\hat{q}_c+\hat{q}_d)>0 \tag{28}$$

Thus, we have the following ranking:

$$0<\Pi_c(q_c^n)-\Pi_d(q_d^n)<S_c(\hat{q}_c)-S_d(\hat{q}_d)<U_c(\hat{q}_c)-U_d(\hat{q}_d) \tag{29}$$

The instantaneous gain from using the clean technology is greater for the regulated firm than for the society, which benefits more than the non-regulated firm.

C) Optimal adoption dates

*To get the socially-optimal adoption date, the regulator maximizes his intertemporal social welfare function given by (15) with respect to τ:

$$\frac{\partial IS}{\partial \tau}=\left(S_d(\hat{q}_d)-S_c(\hat{q}_c)\right)e^{-r\tau}+\theta mre^{-mr\tau}=0 \tag{30}$$

Equation (30) is equivalent to:

$$S_d(\hat{q}_d)-S_c(\hat{q}_c)+\theta mre^{(1-m)r\tau}=0 \Leftrightarrow \hat{\tau}=\frac{1}{(1-m)r}\ln\left(\frac{S_c(\hat{q}_c)-S_d(\hat{q}_d)}{\theta mr}\right) \tag{31}$$

Because of *m*>*1*, condition (18) and inequality (29), $\hat{\tau}>0$.

We have: $\dfrac{\partial^2 IS}{\partial \tau^2}=r\left(S_c(\hat{q}_c)-S_d(\hat{q}_d)\right)e^{-r\tau}-\theta(mr)^2e^{-mr\tau}$.

Using the first order condition given by (30), we get:

$$\frac{\partial^2 IS(\hat{\tau})}{\partial \tau^2}=(1-m)m\theta r^2e^{-mr\hat{\tau}}<0$$

The second order condition of optimality is verified.

*The regulated firm maximizes its intertemporal net profit given by (16) with respect to τ:

$$\frac{\partial IU}{\partial \tau} = \left(U_d(\hat{q}_d) - U_c(\hat{q}_c)\right)e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{32}$$

Equation (32) is equivalent to:

$$U_d(\hat{q}_d) - U_c(\hat{q}_c) + \theta mre^{(1-m)r\tau} = 0 \Leftrightarrow \tau^* = \frac{1}{(1-m)r}\ln\left(\frac{U_c(\hat{q}_c) - U_d(\hat{q}_d)}{\theta mr}\right) \tag{33}$$

Because of $m>1$ and inequality (18), $\tau^* > 0$.

We have: $\frac{\partial^2 IU}{\partial \tau^2} = r\left(U_c(\hat{q}_c) - U_d(\hat{q}_d)\right)e^{-r\tau} - \theta(mr)^2 e^{-mr\tau}$.

Using the first order condition given by (32), we obtain:

$$\frac{\partial^2 IU(\tau^*)}{\partial \tau^2} = (1-m)m\theta r^2 e^{-mr\tau^*} < 0$$

Therefore, the second order condition of optimality is verified.

* The non-regulated firm maximizes its intertemporal net profit given by (17) with respect to τ:

$$\frac{\partial IU^n}{\partial \tau} = \left(\Pi_d(q_d^n) - \Pi_c(q_c^n)\right)e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{34}$$

The above equality implies:

$$\Pi_d(q_d^n) - \Pi_c(q_c^n) + \theta mre^{(1-m)r\tau} = 0 \Leftrightarrow \tau^{n*} = \frac{1}{(1-m)r}\ln\left(\frac{\Pi_c(q_c^n) - \Pi_d(q_d^n)}{\theta mr}\right) \tag{35}$$

Because of $m>1$, inequalities (18) and (29), $\tau^{n*} > 0$.

We have: $\frac{\partial^2 IU^n}{\partial \tau^2} = r\left(\Pi_c(q_c^n) - \Pi_d(q_d^n)\right)e^{-r\tau} - \theta(mr)^2 e^{-mr\tau}$.

Using the first order condition given by (34), we obtain:

$$\frac{\partial^2 IU^n(\tau^{n*})}{\partial \tau^2} = (1-m)m\theta r^2 e^{-mr\tau^{n*}} < 0$$

The second order condition of optimality is verified.

D) Comparison of the optimal dates

Inequalities (29) and the fact that $m>1$, enable us to make the following ranking:

$$0 < \tau^* < \hat{\tau} < \tau^{n*}$$

The regulated firm adopts sooner than what is socially desired, whereas the non-regulated firm adopts later.

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