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Timing of Adoption of Clean Technologies by Regulated Monopolies

Summary: We consider a monopoly firm producing a good and, at the same time, polluting and using fossil energy. By incurring an investment cost, this firm can adopt a lower production cost clean technology using renewable energy. We determine the optimal adoption date for the firm in the case where it is not regulated at all and in the case where it is regulated at each period. Interestingly, the regulated firm adopts the clean technology earlier than what is socially optimal, as opposed to the nonregulated firm. The regulator can induce the firm to adopt the clean technology at the socially optimal date by a postpone adoption subsidy. Nevertheless, the regulator may be interested in the earlier adoption of the firm to encourage the diffusion of the use of clean technologies in other industries.

Key words: Static regulation, Clean technology, Renewable energy, Adoption date.

JEL: D62, H57, Q42, Q55.

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Encouraging the use of renewable energies, 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 harmful 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.

We consider a monopoly firm producing a good using a polluting technology. This can be the case of a producer of electricity like Société Tunisienne d'Eléctricité et du Gaz (STEG), which has the monopoly power of producing and distributing electricity in Tunisia. This polluting production uses fossil energy. The firm can adopt a clean technology within a finite time by incurring an investment cost decreasing exponentially as the adoption is delayed. The clean production technology is characterized to be nonpolluting and having a lower production cost because it uses renewable energy (e.g. solar energy). We consider the case where the firm is not regulated. We also consider the case where the firm is regulated at each period by an emission-tax when it uses the polluting technology; when the firm uses the clean production technology, it receives a per-unit production subsidy, which can be considered as a fiscal incentive. In the latter case, the regulator looks for static social optimality.

The most important feature of the present work is that the clean technology has a lower production cost than the polluting technology. Moreover, we compare the socially optimal adoption date and the optimal adoption date of the instantaneous regulated and nonregulated firm. Theses comparisons have not been reported by previous studies. One important question to which we try to respond is whether the regulator should intervene in the adoption of clean technologies by firms, and how?

The paper is structured as follows. Section 1 is a review of the literature. Section 2 introduces the model. Section 3 studies the nonregulated firm case. Section 4 studies the instantaneous regulated firm case. In Section 5, we derive the optimal adoption dates, and we compare them. Section 6 concludes, and an Appendix contains some proofs.

1. Literature Survey

There is rich literature on the timing of adoption of new technologies characterized by a lower production cost. Jennifer F. Reinganum (1981) proved that even in the case of similar firms and complete information, there is diffusion of innovation over time because one firm innovates before the other and gains more. Drew Fudenberg and Jean Tirole (1985) suggested weaker conditions on the payoffs of firms, compared to Reinganum (1981) that showed that under certain conditions there is diffusion of new technology adoption, whereas under other conditions, firms adopt new technology simultaneously. Heidrun C. Hoppe (2000) extended the work of Fudenberg and Tirole (1985) by including uncertainty related to the profitability of new technology. She showed that there may be second-mover advantages because of informational spillovers. Prajit K. Dutta, Saul Lach, and Aldo Rustichini (1995) obtained a similar result than Hoppe (2000) by studying the case where the last innovator continues to develop technology and eventually markets a higher-quality good. Michael H. Riordan (1992) reported that, in many cases, price and entry regulations beneficially slow down technology adoption and, in some other cases, change the order in which firms adopt new technologies by speeding up one firm's adoption date and slowing down the other firm's adoption date. Chrysovalantou Milliou and Emmanuel Petrakis (2011) showed that when goods are sufficiently differentiated, the adoption of new technology occurs later than what is socially optimal.

Cesare Dosi and Michele Moretto (1997) studied the regulation of a firm, which can switch to a clean technology by incurring an irreversible investment cost. However, this technological switch is expected to provide benefits surrounded 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 stimulates the innovation by subsidies and by reducing the uncertainty surrounding the profitability of the clean technology through appropriate announcements. Dosi and Moretto (2010) extended the previous study to an oligopoly industry and studied the incentives of not being the first firm to adopt the clean technology. They showed that under network externalities and incomplete information concerning firms' switching costs, auctioning investment grants are a cost-effective way of accelerating pollution abatement.

Daan P. van Soest (2005) analyzed the impact of environmental taxes and quotas on the timing of adoption when the date at which improved energy-efficient technologies become available is uncertain and when the investment decision is irreversible. He found that no policy instrument is unambiguously preferred to the other. Fuzhan Nasiri and Georges 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. They devoted a special attention to the analysis of the effect of incentives and initial target on the equilibrium in which the biomass is part of electricity generation. Slim Ben Youssef (2010) considered a monopoly firm that can adopt a cleaner technology within a finite time by incurring an investment cost. It has been shown that the socially optimal adoption date of incomplete information is delayed compared with that of complete information.

Franz Wirl and Cees Withagen (2000) considered a model where a clean technology is available and requires costly investments but is characterized by low variable costs (e.g. solar energy or wind power). They showed that, in a competitive equilibrium, pollution-control policy is not necessarily optimal in the sense of leading to the social optimum. Carolyn Fischer, Withagen, and Michael Toman (2004) developed a model of a uniform good that can be produced by either a polluting or a clean technology. This latter is more expensive and requires investment in capacity. They showed that the optimal transition path is quite different with a clean or dirty initial environment. Kenji Fujiwara (2011) considered a dynamic model of an asymmetric oligopoly with a renewable resource and showed that increasing the number of efficient firms reduces welfare. Johanna Reichenbach and Till Requate (2012) developed a model with two types of electricity producers and showed that a first best policy requires a tax in the fossil-fuel sector and an output subsidy for the renewable energy sources sector. Reyer Gerlagh, Snorre Kverndokk, and Knut E. Rosendahl (2014) study the optimal time path for clean energy innovation policy. They find that while emission prices can be set at the Pigouvian level independently of innovation policy, the optimal level of Research and Development (R&D) subsidies and patent life time change with the stages of the climate problem. Indeed, for a given finite patent lifetime, optimal clean energy R&D subsidies are initially high, and then fall over time. However, if research subsidies are kept constant, the optimal patent lifetime should initially be long and decrease over time.

Some empirical studies have been interested in clean technologies. John C. Whitehead and Todd L. Cherry (2007) developed two approaches, *ex ante* and *ex post*, to mitigate or eliminate the overstatement of hypothetical willingness to pay. They found that willingness to pay estimates is similar when either the *ex ante* or *ex post* approach is used. Employing both approaches, they estimated the annual benefits of the regional amenities associated with a green energy program in North Carolina. Georg Caspary (2009) assessed the likely competitiveness of different forms of renewable energy in Colombia over the next 25 years. Indu R. Pillai and Rangan Banerjee (2009) reviewed the status and potential of different renewable energies (except biomass) in India and established a diffusion model as a basis for setting targets.

Nicholas Apergis and James E. Payne (2012) examined the relationship between renewable and non-renewable energy consumption and economic growth for 80 countries over the period 1990-2007. They showed the existence of short and long-run bidirectional causality between renewable energy consumption and economic growth. Mohamed S. Ben Aïssa, Mehdi Ben Jebli, and Ben Youssef (2014) explored the relationship between renewable energy consumption, international trade and gross domestic product (GDP) for 11 African countries. Their long-run estimates showed that increasing renewable energy consumption led to an increase in GDP.

Our main results are in contrast with the findings of Ben Youssef (2010) who showed that, because of the positive marginal social cost of public funds, the instantaneous net profit of the regulated firm is nil, and consequently, the firm will never adopt the cleaner technology unless it will receive an innovation subsidy. Also, in Dosi and Moretto (1997) study, the regulator objective is the abandonment of the polluting technology and the adoption of the green one before a "critical" date, whereas in the present paper, the regulator maximizes his intertemporal social welfare function for the determination of the socially optimal adoption date. Moreover, these authors did not consider the case where the firm is instantaneously regulated.

2. The Model

We consider a monopoly 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 consumers' surplus equal to $CS(q) = \int_0^q p(z)\,dz - p(q)q = \frac{b}{2}q^2$.

At the beginning, that is, at date 0, the firm uses a 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 environmental damages 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.

In what follows, the subscripts d and c refer to the polluting and clean technologies, respectively.

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

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

An investment cost is necessary to get the clean technology. This investment cost could comprise R&D cost or the cost of acquisition and installation of the clean technology.

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

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

where $\theta > 0$ is the cost of immediate adoption of the clean technology, $r > 0$ is the discount rate, and the parameter m denotes that the investment cost of adoption decreases more rapidly when it is greater. We suppose that $m > 1$, which is a necessary restriction for the optimal adoption dates to be positive. Also, it guarantees the second-order condition when determining the optimal adoption dates (see the Appendix).

Function V is decreasing because of the existence of freely available scientific research enabling the firm to reduce the investment cost of adopting the clean technology when it delays its adoption and is convex because the adoption cost increases more rapidly when the firm tries to accelerate the adoption date. Let us remark that $\tau = +\infty$ means that the firm never adopts the clean technology.

Before the beginning of the game, for instance at date *-1*, the regulator announces the per-unit emission-tax when the polluting technology is used, the per-unit production subsidy when the clean technology is used, and if he desires that the firm adopts the clean technology at the socially optimal adoption date, he also announces the adoption subsidy. Then, at date *0*, the firm chooses its instantaneous production quantities before and after the adoption of the clean technology, as well as its clean technology adoption date.

3. Nonregulated Firm

In this section, we will study the case where, at each period, the monopoly is not regulated even when it uses the polluting technology. The superscript n refers to the nonregulation case.

When it uses the polluting technology, the firm maximizes its profit Π_d to get the optimal level of production:

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

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

$$q_c^n = \frac{a-c}{2b}. \tag{3}$$

Because of condition (6), $q_d^n > 0$ and $q_c^n > 0$.

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

4. Regulated Firm

In this section, we study the case where the firm is regulated at each period. Rather than directly looking to the socially optimal regulatory instruments, we will determine the socially optimal production quantities. Next, we determine the regulatory instruments. Thus, we have a leader-follower relationship where the regulator is a leader and the monopoly is a follower.

When the firm uses the polluting technology, the instantaneous social welfare is equal to the consumers' surplus, minus damages plus the profit of the firm:

$$S_d = CS(q) - D(q) + \Pi_d(q). \tag{4}$$

Maximizing the expression given by (4) with respect to q gives the socially optimal production level with the polluting technology:

$$\hat{q}_d = \frac{a - d - \alpha e}{b}. \tag{5}$$

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

$$a > d + \alpha e. \tag{6}$$

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

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

Indeed, the instantaneous net profit of the firm is as follows:

$$U_d = \Pi_d(q) - \lambda E(q). \tag{7}$$

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

$$\lambda = \frac{a - d - 2b\hat{q}_d}{e}. \tag{8}$$

Using the expression of $\hat{q}_d$ given by (5), we can show that:

$$\lambda > 0 \Leftrightarrow a - d < 2\alpha e. \tag{9}$$

Therefore, the emission-tax is positive when the marginal production damage is high enough. Otherwise, it is negative, that is, the regulator subsidizes production to deal with the monopoly distortion. We obtain such a result because, as previously mentioned, environmental damages are due to the flow of pollution and not to the cumulative pollution.

When the firm uses the clean technology, the instantaneous social welfare is equal to the consumers' surplus plus the profit of the firm:

$$S_c = CS(q) + \Pi_c(q). \tag{10}$$

Maximizing the expression given by (10) with respect to q gives the socially optimal production level with the clean technology:

$$\hat{q}_c = \frac{a-c}{b} > 0 \cdot \tag{11}$$

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

We can establish that:

$$\hat{q}_d > q_d^n \Leftrightarrow a - d > 2\alpha e . \tag{12}$$

Indeed, with the polluting technology, the socially optimal production takes into account both environmental damages and monopoly distortion. Thus, it is higher than the optimal production level for the nonregulated firm only when the marginal production 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.

Because the production process is clean, the regulator gives the firm a subsidy s for each unit produced, which can be considered as a fiscal incentive. One may think about production of electricity. A per-unit production subsidy can be given by the regulator when the production process is clean (using solar energy, for instance). This per-unit subsidy is chosen so that it induces the socially optimal production level.

Let us notice that, in expressions (4) and (10), taxes and subsidies do not appear because they are pure transfers from the firm to the regulator. Indeed, we suppose that there is no marginal social cost of public funds and no transaction costs: the tax diminished from the firm's profit is added to the consumers' welfare, and the subsidy added to the firm's profit is diminished from the consumers' welfare.

The instantaneous net profit of the firm is:

$$U_c = \Pi_c(q) + sq . \tag{13}$$

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

$$s = 2b\hat{q}_c + c - a \cdot \tag{14}$$

Using the expression of $\hat{q}_c$ given by (11), we can show that $s > 0$.

In the Appendix, we show that:

$$0 < \Pi_c(q_c^n) - \Pi_d(q_d^n) < S_c(\hat{q}_c) - S_d(\hat{q}_d) < U_c(\hat{q}_c) - U_d(\hat{q}_d) . \tag{15}$$

The above inequalities enable us to establish the following proposition:

Proposition 1. *The instantaneous gain from using the clean technology is greater for the regulated firm than for the regulator. This latter instantaneously benefits more from the clean technology than the nonregulated firm.*

Indeed, when the regulated firm adopts the clean technology, it no longer pays a pollution tax and receives a production subsidy, and its unit production cost decreases. This increases its instantaneous net profit significantly. The instantaneous social welfare level increases because of the absence of environmental damages and the lower production cost. However, this increase in instantaneous social welfare is less important than the increase in instantaneous net profit of the regulated firm. The unique benefit of the nonregulated firm from adopting the clean technology is the reduction of its unit production cost. Consequently, its instantaneous net profit increase is less important than the increase of the instantaneous social welfare. Let us notice that Proposition 1 and the intuition behind it may remain valid even when damages are due to the stock of pollution. To confirm this, we should completely modify the model by considering that damages are due to the stock of pollution.

5. Optimal Adoption Dates

The intertemporal payoffs of the regulator or the firm are equal to the instantaneous payoffs actualized at date zero minus the investment cost of adopting the clean technology at date τ. Therefore, the intertemporal social welfare, intertemporal net profits of the regulated firm and nonregulated firm are, respectively:

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

$$IU(\tau) = \int_0^{\tau} U_d(\hat{q}_d)e^{-rt}\,dt + \int_{\tau}^{+\infty} U_c(\hat{q}_c)e^{-rt}\,dt - \theta e^{-mr\tau}, \tag{17}$$

$$IU^n(\tau) = \int_0^{\tau} \Pi_d(q_d^n)e^{-rt}\,dt + \int_{\tau}^{+\infty} \Pi_c(q_c^n)e^{-rt}\,dt - \theta e^{-mr\tau}. \tag{18}$$

To have positive adoption dates, we need the following condition, which can be always verified by choosing the parameters θ and/or m high enough because the left expression of (19) is independent of parameters θ, m and r:

$$U_c(\hat{q}_c) - U_d(\hat{q}_d) < \theta mr. \tag{19}$$

The regulator or the firm maximizes its intertemporal payoff function with respect to τ to get the optimal adoption date. In the Appendix, we determine the socially optimal adoption date, the optimal adoption dates for the regulated and nonregulated firm, which are, respectively:

$$\hat{\tau} = \frac{1}{(1-m)r}\ln\left(\frac{S_c(\hat{q}_c) - S_d(\hat{q}_d)}{\theta mr}\right) > 0, \tag{20}$$

$$\tau^* = \frac{1}{(1-m)r}\ln\left(\frac{U_c(\hat{q}_c) - U_d(\hat{q}_d)}{\theta mr}\right) > 0, \tag{21}$$

$$\tau^{n*} = \frac{1}{(1-m)r}\ln\left(\frac{\Pi_c(q_c^n) - \Pi_d(q_d^n)}{\theta mr}\right) > 0. \tag{22}$$

Proposition 2. *We have the following ranking for the optimal adoption dates:*

$$0 < \tau^* < \hat{\tau} < \tau^{n*}. \tag{23}$$

Therefore, the optimal adoption date for the regulated firm is earlier than the socially optimal adoption date, which is earlier than the optimal adoption date for the nonregulated firm. (Proof: see the Appendix.)

The above results show that socially optimal instantaneous regulation may not be dynamically optimal with respect to the adoption of clean technologies. They are due to the fact that the incentives to adopt are, in order, greater for the regulated firm, the regulator, and the nonregulated firm. This is clearly established by the inequalities in (15).

Paradoxically, if the regulator desires that the regulated firm delays its adoption to the socially optimal adoption date, he must compensate the firm for the losses it incurs by this adoption delay. If we consider our previous example where the firm is given a subsidy for each unit of electricity produced with the clean technology using solar energy, one important reason for the very early adoption by the regulated firm is the per-unit production subsidy received from the regulator; this engenders an important investment cost of adoption for the intertemporal social welfare level. To overcome this, we propose that the regulator provides a postpone adoption subsidy to the firm.

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 postpone adoption subsidy (compensation) is as follows:

$$g = IU(\tau^*) - IU(\hat{\tau}) > 0\,. \tag{24}$$

Proposition 3. *The regulator can push the regulated firm to delay its adoption of the clean technology by giving it a postpone adoption subsidy that compensates the firm for the losses it incurs when the latter delays its optimal adoption date to the socially optimal adoption date.*

6. Conclusion

In this paper, we consider a monopoly firm producing a good using a polluting technology. We assume that damages are due to the flow of emissions and not to the stock of pollution. However, this firm can adopt a clean technology characterized by no pollution emission and by a lower production cost because it uses a renewable energy. We suppose that the inverse demand function for the good remains unchanged for the two production technologies and that monetary transfers to the firm are not socially costly.

For the nonregulated and regulated firm, the quantities produced are greater with the clean technology than with that polluting one. When the regulated firm switches to the clean technology, it no longer pays a pollution tax and receives a production subsidy, and its unit production cost decreases. Consequently, its instantaneous net profit increases significantly. The instantaneous social welfare level increases because of the absence of environmental damages and the lower production costs. However, this instantaneous benefit of social welfare from the clean technology is less important than that of the regulated firm. When the nonregulated firm adopts the clean technology, its unit production cost decreases. Consequently, its instantaneous net profit increases but not significantly, and this increase is lower than the increase of the instantaneous social welfare. These results induce the following.

The nonregulated firm adopts the clean technology in a finite time but later than what is socially optimal. Interestingly, the regulated firm adopts the clean technology in a finite time and earlier than what is socially optimal. Therefore, in a dynamic setting, instantaneous regulation, which is socially optimal, may not be dynamically optimal with respect to the adoption of clean technologies. 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 by allowing the firm to adopt the clean technology earlier to encourage the diffusion of the use of clean technologies in other industries.

For future research, we propose to extend the present model to an oligopoly market structure and to consider that damages are due to the stock of pollution.

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Appendix

A) Instantaneous Gains from the Clean Technology

From expressions (4) and (10), we have:

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

By using the expressions of $\hat{q}_d$ and $\hat{q}_c$ given by (5) and (11), the above bracketed expression is equal to $\frac{d-c+\alpha e}{2}$. Therefore, we have:

$$S_c(\hat{q}_c) - S_d(\hat{q}_d) = \frac{d-c+\alpha e}{2}(\hat{q}_c + \hat{q}_d) > 0 \,. \tag{25}$$

From expressions (7) and (13), we have:

$$U_c(\hat{q}_c) - U_d(\hat{q}_d) = \left[a - b(\hat{q}_c + \hat{q}_d)\right](\hat{q}_c - \hat{q}_d) + (s-c)\hat{q}_c + d\hat{q}_d + \lambda e \hat{q}_d \,.$$

By changing the emission-tax λ and the production subsidy s by their expressions in function of $\hat{q}_d$ and $\hat{q}_c$ given by (8) and (14), we obtain:

$$U_c(\hat{q}_c) - U_d(\hat{q}_d) = b(\hat{q}_c^2 - \hat{q}_d^2) > 0 \,. \tag{26}$$

We can easily show that:

$$\Pi_c(q_c^n) - \Pi_d(q_d^n) = \left[a - b(q_c^n + q_d^n)\right](q_c^n - q_d^n) + dq_d^n - cq_c^n \,.$$

By replacing q_c^n and q_d^n between the above brackets by their values given by (2) and (3), we obtain:

$$\Pi_c(q_c^n) - \Pi_d(q_d^n) = \frac{d-c}{2}(q_c^n + q_d^n) > 0 \,. \tag{27}$$

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

B) Comparison of the Instantaneous Gains

By using expressions (25) and (26), we have:

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

By using the expressions of $\hat{q}_d$ and $\hat{q}_c$, given by (5) and (11), in the above bracketed expression, we obtain the following:

$$\left(U_c(\hat{q}_c)-U_d(\hat{q}_d)\right)-\left(S_c(\hat{q}_c)-S_d(\hat{q}_d)\right)=\frac{d-c+\alpha e}{2}(\hat{q}_c+\hat{q}_d)>0\cdot \quad (28)$$

By using expressions (25) and (27), we obtain:

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

By replacing q_d^n, q_c^n, $\hat{q}_d$, and $\hat{q}_c$, in the above brackets by their values, given by (2), (3), (5), and (11), we obtain:

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

Using condition (6) for the above bracketed term gives:

$$\left(S_c(\hat{q}_c)-S_d(\hat{q}_d)\right)-\left(\Pi_c(q_c^n)-\Pi_d(q_d^n)\right)>\frac{(d-c)^2}{4b}+\frac{\alpha e}{2}(\hat{q}_c+\hat{q}_d)>0\cdot \quad (29)$$

Thus, we have the following ranking:

$$0<\Pi_c(q_c^n)-\Pi_d(q_d^n)<S_c(\hat{q}_c)-S_d(\hat{q}_d)<U_c(\hat{q}_c)-U_d(\hat{q}_d)\cdot \quad (30)$$

The instantaneous gain from using the clean technology is greater for the regulated firm than for the regulator, which benefits from the clean technology more than the nonregulated firm.

C) Optimal Adoption Dates

To get the socially optimal adoption date, the regulator maximizes his intertemporal social welfare function given by (16) with respect to τ:

$$\frac{\partial IS}{\partial \tau} = \left(S_d(\hat{q}_d) - S_c(\hat{q}_c)\right)e^{-r\tau} + \theta m r e^{-mr\tau} = 0\,. \tag{31}$$

Equation (31) is equivalent to:

$$S_d(\hat{q}_d) - S_c(\hat{q}_c) + \theta m r e^{(1-m)r\tau} = 0 \Leftrightarrow$$
$$\hat{\tau} = \frac{1}{(1-m)r}\ln\left(\frac{S_c(\hat{q}_c) - S_d(\hat{q}_d)}{\theta m r}\right)\,. \tag{32}$$

Because of $m > 1$, condition (19) and inequality (30), $\hat{\tau} > 0$.

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

Using the first-order condition given by (31), we obtain:

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

The second-order condition of optimality is verified.

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

$$\frac{\partial IU}{\partial \tau} = \left(U_d(\hat{q}_d) - U_c(\hat{q}_c)\right)e^{-r\tau} + \theta m r e^{-mr\tau} = 0\,. \tag{33}$$

Equation (33) is equivalent to:

$$U_d(\hat{q}_d) - U_c(\hat{q}_c) + \theta m r e^{(1-m)r\tau} = 0 \Leftrightarrow$$
$$\tau^* = \frac{1}{(1-m)r}\ln\left(\frac{U_c(\hat{q}_c) - U_d(\hat{q}_d)}{\theta m r}\right)\,. \tag{34}$$

Because of $m > 1$ and inequality (19), $\tau^* > 0$.

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 (33), 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 nonregulated firm maximizes its intertemporal net profit given by (18) with respect to τ:

$$\frac{\partial IU^n}{\partial \tau} = \left(\Pi_d(q_d^n) - \Pi_c(q_c^n)\right) e^{-r\tau} + \theta m r e^{-mr\tau} = 0 . \tag{35}$$

The above equality implies the following:

$$\Pi_d(q_d^n) - \Pi_c(q_c^n) + \theta m r e^{(1-m)r\tau} = 0 \Leftrightarrow$$
$$\tau^{n*} = \frac{1}{(1-m)r} \ln\left(\frac{\Pi_c(q_c^n) - \Pi_d(q_d^n)}{\theta m r}\right). \tag{36}$$

Because of *m* > *1*, inequalities (19) and (30), $\tau^{n*} > 0$.

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 (35), we obtain:

$$\frac{\partial^2 IU^n(\tau^{n*})}{\partial \tau^2} = (1-m) m \theta r^2 e^{-mr\tau^{n*}} < 0 . \tag{37}$$

The second-order condition of optimality is verified.

D) Comparison of the Optimal Adoption Dates

Inequalities (30) and the assumption *m* > *1* enable us to make the following ranking:

$$0 < \tau^* < \hat{\tau} < \tau^{n*} . \tag{38}$$

The regulated firm adopts sooner than what is socially optimal, whereas the nonregulated firm adopts later.