Timing of adoption of clean technologies, transboundary pollution and international trade

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Abstract

We consider a symmetric model composed of two countries and a firm in each country. Firms produce the same good by means of a polluting technology that uses fossil energy. However, these firms can adopt a clean technology that uses a renewable energy and that has a lower unit cost. Surprisingly, opening markets to international competition increases the per-unit emission-tax and decreases the per-unit production subsidy. Interestingly, the socially-optimal adoption date under a common market better internalizes transboundary pollution than that under autarky, and than the optimal adoption date of regulated firms. However, the optimal adoption date of non-regulated firms completely don't internalize transboundary pollution. In autarky (resp. a common market), regulated firms adopt earlier (resp. later) than what is socially-optimal, whereas non-regulated firms adopt later than the socially-optimal adoption date and than the optimal adoption date of regulated firms. Therefore, in autarky (resp. a common market) regulators can induce firms to adopt at the socially-optimal adoption date by giving them postpone (resp. speed up) adoption subsidies. Opening markets to international trade, speeds up the socially-optimal adoption date and delays optimal adoption dates of regulated and non-regulated firms.

Keywords: Regulation, Adoption date, Renewable energy, Transboundary pollution, Common market, .

JEL *classification*: D62, F18, H57, Q42, Q55.

1 Introduction

This paper tries to study the relation that may exist between the timing of adoption of clean technologies, transboundary pollution and opening markets to international competition. Typical examples of clean production technologies are those using renewable energy such as solar energy, whereas polluting production technologies usually use fossil energy. Our research is related to at least four literature fields.

The first field deals with renewable energies and clean technologies. Dosi and Moretto (1997) studied the regulation of a firm which can switch to a clean technology by incurring an irreversible investment cost. To bridge the gap between the private and the policy-maker's desired timing of innovation, they recommended that the regulator stimulate the innovation by subsidies and by reducing the uncertainty concerning the profitability of the clean technology by appropriate announcements. Dosi and Moretto (2010) extended the previous study to oligopolistic firms and studied the incentives of not being the first firm adopting the clean technology. Soest (2005) analyzed the impact of environmental taxes and quotas on the timing of adoption and found that neither policy instrument is always preferred to the other. Nasiri and Zaccour (2009) proposed a game-theoretic model and analyzed the process of utilizing biomass for power generation. They considered three players: distributor, facility developer, and participating farmer, characterized the subgame-perfect Nash equilibrium and discussed its features. Wirl and Withagen (2000) showed that pollution-control policy is not necessarily optimal in the sense of giving the social optimum. Fischer, Withagen and Toman (2004) developed a model of a uniform good that can be produced by either a polluting or a clean technology, and showed that the optimal transition path is quite different with a clean or polluting initial environment. Ben Youssef (2010) showed that the instantaneous regulated monopoly adopts the clean technology earlier than what is socially-optimal, while the non-regulated monopoly adopts later than what is socially-optimal. The regulator can induce the monopoly to adopt at the socially-optimal date by a postpone adoption subsidy. Fujiwara (2011) developed a dynamic game model of an asymmetric oligopoly with a renewable resource and showed that increasing the number of efficient firms reduces welfare. Reichenbach and Requate (2012) considered 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.

Many empirical studies have been interested in clean technologies, among which Whitehead and Cherry (2007), Varun *et al.* (2009), Li *et al.* (2009) and Caspary (2009). For instance, Pillai and Banerjee (2009) reviewed the status and potential of different renewable energies (except biomass) in India and constructed a diffusion model as a basis for setting targets.

The second field deals with transboundary pollution. Chander and Tulkens (1992) showed that non-cooperating behavior of countries is not Pareto-optimal. Mansouri and Ben Youssef (2000) showed the necessity of cooperation between countries to effectively internalize all the transboundary pollution, while reaching the first best. Nevertheless, some studies showed that non-cooperating countries can reach the first best under some conditions (Hoel (1997), Zagonari (1998)). Ben Youssef (2009) showed that free R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transfrontier pollution. Ben Youssef (2011) established that the investment in absorptive R&D enables non-cooperating regulators to better internalize transfrontier pollution.

The third field deals with international trade. Because pollution crosses the borders, Copeland and Taylor (1995) showed that uncoordinated regulation of pollution at the national level and free trade don't necessarily raise welfare. Under incomplete information, Péchoux and Pouyet (2003) showed that firms' competition generated by the common market enables regulators to reduce the informational rents captured by firms, thereby reinforcing the need to open the markets to international trade. Using a static model with no investment possibility in cleaner production technology, Cremer and Gahvari (2004) showed that firms switch to a less polluting but more costly production technique, under economic integration.

The fourth field deals with the timing of adoption of new technologies. The diffusion of a new technology has been analyzed by Reinganum (1981). She considered an industry composed of two firms which can adopt a cost reducing technology within a period of time. She showed that even in the case of identical firms and complete information, there is diffusion of innovation over time because one firm innovates before the other and gains more. Fudenberg and Tirole (1985) made less strong conditions on the payoffs of firms and showed that under certain conditions there is diffusion, whereas under other conditions firms adopt this new technology simultaneously. Hoppe (2000) extended the work of Fudenberg and Tirole to include uncertainty regarding the profitability of the new technology. She showed that there may be second-mover advantages because of informational spillovers. Dutta *et al.* (1995) got a similar result in a context where the later innovator continues to develop the technology and eventually markets a higher-quality good. Riordan (1992) showed that price and entry regulations, in many cases, 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's. Milliou and Petrakis (2011) showed that when goods are sufficiently differentiated, the adoption of a new technology occurs later than is socially-optimal.

Our paper differs from the existing literature by the fact that we try to know how the adoption dates of clean technologies may be affected when markets are opened to international competition, and how the regulator may change his behavior with respect to firms he is regulating. Also, in the present paper, we study the relation between the adoption of clean technologies and transboundary pollution.

We consider a symmetric model composed of two countries and a monopolistic firm operating in each country. Firms produce the same homogeneous good by using a polluting technology that uses fossil energy. However, these firms can adopt a new and clean production technology by incurring an investment cost that decreases exponentially with the adoption date. This clean technology uses a renewable energy and therefore has a lower unit production cost. We study and compare the case where firms are not regulated at all, and the case where each firm is regulated at each period of time i.e. each non-cooperating regulator looks for static social optimality. In this latter case, a per-unit emission-tax is used when a firm uses the polluting technology, and a per-unit production subsidy, than can be considered as a fiscal incentive, is used when a firm uses the clean technology. We also study and compare the case where each firm operates in a separate home market, and the case where firms compete in the same common market formed by the consumers of the two countries.

In autarky, since our model is symmetric, firms adopt the clean technology simultaneously. However, in a common market, and because of the competition between firms, we impose a condition on parameters to avoid the complicated case where firms adopt at different dates, and we show that adoption is simultaneous.

When markets are opened to international competition, the per-unit emission-tax increases when the polluting technology is used, and the per-unit production subsidy decreases when the clean technology is used. These results are interesting and even surprising because one may think that, to give a competitive advantage to its domestic firm, each regulator reduces the per-unit emission-tax and increases the per-unit production subsidy, when markets are opened to international trade. Ben Youssef (2009) found similar results with a different model where regulatory instruments are a per-unit emission-tax and a per-unit R&D subsidy.

Interestingly, the socially-optimal adoption date under a common market better internalizes transboundary pollution than that under autarky, and than the optimal adoption date of regulated firms. However, the optimal adoption date of non-regulated firms completely don't internalize transboundary pollution. Therefore, the regulator should know how to intervene to get firms adopt at the socially-optimal dates. This result is of great interest because this paper is the first attempt linking the adoption of clean technologies with transboundary pollution. Notice that, using very different models than the present, Ben Youssef (2009) showed that R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transboundary pollution, and Ben Youssef (2011) showed that the investment in absorptive R&D help non-cooperating countries to better internalize transboundary pollution.

The intervention of regulators on how to induce firms adopting the clean technology at the socially-optimal adoption date completely changes when markets are opened to international competition. Indeed, in autarky (resp. common market), regulated firms adopt earlier (resp. later) than what is socially-optimal, whereas non-regulated firms adopt later than the socially-optimal adoption date and than the optimal adoption date of regulated firms. Therefore, in autarky, regulators can induce firms to adopt at the socially-optimal adoption date by giving them a postpone adoption subsidy. However, in common market, regulators can induce firms to adopt at the socially-optimal adoption date by giving them a speed up adoption subsidy.

International competition reduces the instantaneous gain from using the clean technology of non-regulated and regulated firms, with respect to autarky. Consequently, non-regulated and regulated firms delay the adoption of the clean technology when markets are opened to international trade. However, the instantaneous social welfare gain from the adoption of the clean technology increases with market opening, leading to an early socially-optimal adoption date under a common market. These results are new and interesting because the impact of opening markets to international competition on the timing of adoption of clean technologies has not been previously studied.

This paper is organized as follows. Section 2 deals with the autarky case. Section 3 deals with the common market case, and Section 4 compares the two market regimes. Section 5 concludes and an Appendix contains some proofs.

2 Autarky

We consider a symmetric model consisting of two countries and two firms. Firm i located in country i is a regional monopoly and produces good i in quantity q_i sold in the domestic market with the inverse demand function: $p_i = a - 2q_i$, $a > 0$.Thus, the market size of each country is $a/2$.

The consumption of q_i engenders a consumers' surplus in country i equal to:

$$CS_i^a(q_i) = \int_0^{q_i} p_i(z)dz - p_i(q_i)q_i = q_i^2$$

At the beginning of the game i.e. at date 0, firms produce goods by using an old and polluting production technology using fossil fuels and characterized by a positive emission/output ratio $e > 0$. The pollution emitted by firm i is $E_i = eq_i$.

We suppose that pollution crosses the borders and that damages in country i are due to the domestic pollution and the foreign pollution: $D_i = \alpha E_i + \beta E_j$, where $\alpha > 0$ is the marginal damage of domestic pollution and $\beta > 0$ is the marginal damage of foreign pollution.

When firm i uses the polluting technology, its unit production cost is $d > 0$ and its profit[1] is $\Pi_{id}^a = p_i(q_i)q_i - dq_i$.

Each firm i behaves for an infinite horizon of time and can adopt a clean production technology within a period of time τ_i. This clean technology does not pollute at all, uses a renewable energy and therefore has a lower unit cost of production c verifying $0 < c < d$. Thus, the profit of firm i is $\Pi_{ic}^a = p_i(q_i)q_i - cq_i$.

We suppose that the marginal damage of production αe is neither too small nor too high verifying the following condition:

$$\frac{d-c}{3} < \alpha e < d - c \tag{1}$$

[1] In what follows, the subscripts d and c refer to the polluting and clean technologies, respectively. The superscripts a and cm refer to the autarky and common market cases, respectively.

The instantaneous social welfare of country i is equal to the consumers' surplus, minus damages plus the profit of the domestic firm:

$$S_i^a(q_i, q_j) = CS_i^a(q_i) - D_i(q_i, q_j) + \Pi_i^a(q_i) \tag{2}$$

To get the new and clean production technology, an investment cost is necessary. This latter could comprise the R&D cost or the cost of acquisition and installation of the clean technology.

The cost of adopting the clean technology by firm i at date τ_i actualized at date 0 is:

$$V(\tau_i) = \theta e^{-mr\tau_i}, \tag{3}$$

with $\theta > 0$ is the cost of immediate adoption of the clean technology, $r > 0$ is the discount rate, and the parameter m denotes that the cost of adoption decreases more rapidly when it is greater. We assume that $m > 1$.[2]

Function V is decreasing due to the existence of freely-available scientific research enabling a firm to reduce the cost of adopting the clean technology when it delays its adoption, and is convex because the adoption cost increases more rapidly when a firm tries to accelerate the adoption date.

Let's remark that $\tau_i = +\infty$ means that firm i will never adopt the clean technology.

2.1 Non-regulated firms

In this section, we study the case where, at each period of time, each firm is not regulated even when it uses the polluting technology.

When both firms use the polluting technology, then each one maximizes its profit Π_{idd}^{na} to get the optimal level of production:[3]

$$q_{idd}^{na} = \frac{a-d}{4} > 0 \tag{4}$$

When both firms use the clean technology, then each one maximizes its profit Π_{icc}^{na} to get the optimal level of production:

$$q_{icc}^{na} = \frac{a-c}{4} > 0 \tag{5}$$

It is easy to verify that $q_{icc}^{na} > q_{idd}^{na}$ meaning that firms produce more with the clean technology because of its lower unit production cost.

If only firm 1 adopts the clean technology and firm 2 still uses the polluting technology, then the profits of firms are denoted by $\Pi_{1cd}^{na}(q_1)$ and $\Pi_{2cd}^{na}(q_2)$, respectively. Optimal production quantities for firms are given by:

$$q_{1cd}^{na} = \frac{a-c}{4} > 0, \quad q_{2cd}^{na} = \frac{a-d}{4} > 0 \tag{6}$$

[2] This assumption is necessary for the optimal adoption dates to be positive. Moreover, it guarantees the second-order condition when determining the optimal adoption dates (see the Appendix).

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

We can verify that $q_{1cd}^{na} = q_{1cc}^{na}$, $q_{2cd}^{na} = q_{2dd}^{na}$ and that $q_{1cd}^{na} > q_{2cd}^{na}$.Thus, the firm using the clean technology produces more than that using the polluting technology.

2.2 Regulated firms

In this section, we study the case where firms are regulated at each period of time. First, we start by determining the socially-optimal production quantities for each regulator. Then, we determine the regulatory instruments inducing the socially-optimal production quantities in each country.

When both firms use the polluting technology, the instantaneous social welfare of country i is:

$$S_{idd}^{a}(q_i, q_j) = CS_i^a(q_i) - D_i(q_i, q_j) + \Pi_{idd}^{a}(q_i) \tag{7}$$

Maximizing the expression given by (7) with respect to q_i gives the socially-optimal production level with the polluting technology for each regulator $i = 1, 2$:

$$\hat{q}_{idd}^{a} = \frac{a - d - \alpha e}{2} \tag{8}$$

We assume the first inequality of the following condition such that production quantities are positive. Also, the second inequality is assumed to avoid studying the complicated case of non-simultaneous adoption of the clean technology in the common market case. Moreover, the second inequality of (1) assures that there is no contradiction in inequality (9) :

$$d + \alpha e < a < 2d - c \tag{9}$$

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 each firm is a polluting monopoly, it is regulated. An emission-tax per-unit of pollution t_{idd}^{a} is sufficient to induce the socially-optimal levels of production and pollution.

The instantaneous net profit of firm i is:

$$U_{idd}^{a}(q_i) = \Pi_{idd}^{a}(q_i) - t_{idd}^{a} E_i(q_i) \tag{10}$$

The socially-optimal per-unit emission-tax that induces firm i to produce $\hat{q}_{idd}^{a}$ is:

$$t_{idd}^{a} = \frac{a - d - 4\hat{q}_{idd}^{a}}{e} \tag{11}$$

Using the expression of $\hat{q}_{idd}^{a}$, we can show that:

$$t_{idd}^{a} > 0 \Longleftrightarrow a < d + 2\alpha e \tag{12}$$

When $\alpha e > \frac{d-c}{2}$ i.e. the marginal damage of pollution is high enough, the above condition is always satisfied and the emission-tax is positive. When $\alpha e < \frac{d-c}{2}$ and $a < d+2\alpha e$, the emission-tax is positive. However, when $\alpha e < \frac{d-c}{2}$ and $a > d + 2\alpha e$ i.e. the marginal damage of pollution is low enough, the emission-tax is negative meaning that each regulator subsidizes production to deal with monopoly distortion.

If both firms use the clean technology, the instantaneous social welfare of country i is:

$$S^a_{icc}(q_i) = CS^a_i(q_i) + \Pi^a_{icc}(q_i) \tag{13}$$

Maximizing the expression given by (13) with respect to q_i gives the socially-optimal production level with the clean technology for regulator i:

$$\hat{q}^a_{icc} = \frac{a-c}{2} > 0 \tag{14}$$

Using the second inequality of (1), we show that $\hat{q}^a_{icc} > \hat{q}^a_{idd}$. Therefore, the clean technology enables to produce more and without polluting the environment.

We can establish that :

$$\hat{q}^a_{idd} < q^{na}_{idd} \iff a < d + 2\alpha e \tag{15}$$

When $\alpha e > \frac{d-c}{2}$ i.e. the marginal damage of pollution is high enough, or when $\alpha e < \frac{d-c}{2}$ and $a < d + 2\alpha e$, the above condition is always satisfied because regulators care about the environment whereas non-regulated firms do not care about the environment. However, when $\alpha e < \frac{d-c}{2}$ and $a > d + 2\alpha e$ i.e. the marginal damage of pollution is low enough, socially-optimal production is higher than the production of non-regulated monopolistic firms.

With the clean technology, socially-optimal production is always higher than that of non-regulated firms ($\hat{q}^a_{icc} > q^{na}_{icc}$).

Since the production process is clean, each regulator gives his firm a subsidy s^a_{icc} 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 a 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 level of production. Indeed, the instantaneous net profit of firms i is:

$$U^a_{icc}(q_i) = \Pi^a_{icc}(q_i) + s^a_{icc} q_i \tag{16}$$

The socially-optimal per-unit subsidy that induces firm i to produce $\hat{q}^a_{icc}$ is:

$$s^a_{icc} = c - a + 4\hat{q}^a_{icc} > 0 \tag{17}$$

If we consider the case in which one of the two firms, for instance firm 1, has adopted the clean technology, whereas the other still produces using the polluting technology, then the profits of firms are $\Pi^a_{1cd}(q_1)$ and $\Pi^a_{2cd}(q_2)$, respectively. The instantaneous social welfare of regulator 1 and 2 are:

$$S_{1cd}^a(q_1, q_2) = SC_1^a(q_1) + \Pi_{1cd}^a(q_1) - D_1(q_2), \tag{18}$$

$$S_{2cd}^a(q_1, q_2) = SC_2^a(q_2) + \Pi_{2cd}^a(q_2) - D_2(q_2) \tag{19}$$

Regulator i maximizes his social welfare function with respect to q_i to get the socially-optimal production quantities:

$$\hat{q}_{1cd}^a = \frac{a-c}{2} > 0, \quad \hat{q}_{2cd}^a = \frac{a-d-\alpha e}{2} > 0 \tag{20}$$

We can easily verify that $\hat{q}_{1cd}^a > \hat{q}_{2cd}^a$ meaning that it is socially preferred that the firm using the clean technology produces more than that using the polluting technology.

Since $q_{1cd}^{na} = q_{1cc}^{na} < \hat{q}_{1cd}^a = \hat{q}_{1cc}^a$, regulator 1 can induce firm 1 to produce the socially-optimal production quantities by an appropriate subsidy $s_{1cd}^a = s_{1cc}^a$.

Since $q_{2cd}^{na} = q_{2dd}^{na} > \hat{q}_{2cd}^a = \hat{q}_{2dd}^a$, a per-unit emission-tax $t_{2cd}^a = t_{2dd}^a$ is needed to induce firm 2 to produce the socially-optimal quantity.

In the Appendix, we show that:[4]

$$0 < \Pi_{1cd}^{na} - \Pi_{1dd}^{na} < S_{1cd}^a - S_{1dd}^a < U_{1cd}^a - U_{1dd}^a \tag{21}$$

Thus, we can establish the following Proposition:

Proposition 1 *Under autarky, the instantaneous gain from using the clean technology is greater for the first adopter regulated firm than for its regulator. This latter instantaneously benefits more from using the clean technology than its first adopter non-regulated firm.*

Indeed, when a regulated firm adopts the clean technology, it no longer pays a pollution tax, receives production subsidies and its unit production costs decreases. This increases its instantaneous net profit significantly. The instantaneous social welfare level increases due to the absence of local environmental damages and the lower production cost. However, this last increase is less important than that of the regulated firm. The only benefit of a non-regulated firm from adopting the clean technology is the reduction of its unit production cost. Consequently, its instantaneous net profit increase is less important than that of the instantaneous social welfare.

2.3 Optimal adoption dates

In this section, we will determine the optimal adoption dates. We still suppose that, in case where firms adopt at different dates, the first adopter is firm 1 and the second adopter is firm 2. Thus, in the following expressions, we suppose $\tau_1 \leq \tau_2$.

Since $q_{1cd}^{na} = q_{1cc}^{na}$, $q_{2cd}^{na} = q_{2dd}^{na}$, $\hat{q}_{1cd}^a = \hat{q}_{1cc}^a$ and $\hat{q}_{2cd}^a = \hat{q}_{2dd}^a$, then $\Pi_{1cd}^{na} = \Pi_{1cc}^{na}$, $\Pi_{2cd}^{na} = \Pi_{2dd}^{na}, U_{1cd}^a = U_{1cc}^a$ and $U_{2cd}^a = U_{2dd}^a$. This implies that the intertemporal

[4] Notice that, to prove the second inequality of (21), we have supposed that $\beta = \alpha$.

net profit of non-regulated and regulated firm i can be written as depending only on τ_i.However, since $S^a_{1cd} \neq S^a_{1cc}$ and $S^a_{2cd} \neq S^a_{2dd}$ because of crossborder pollution, intertemporal social welfare of regulators 1 and 2 depend on τ_1 and τ_2.

Each regulator chooses the socially-optimal adoption date that maximizes his intertemporal social welfare function. Each regulated and non-regulated firm chooses the optimal adoption date that maximizes its intertemporal net profit.

The intertemporal social welfare of regulators 1 and 2, intertemporal net profits of regulated and non-regulated firm i are, respectively:

$$IS^a_1(\tau_1,\tau_2) = \int_0^{\tau_1} S^a_{1dd} e^{-rt} dt + \int_{\tau_1}^{\tau_2} S^a_{1cd} e^{-rt} dt + \int_{\tau_2}^{+\infty} S^a_{1cc} e^{-rt} dt - \theta e^{-mr\tau_1} \tag{22}$$

$$IS^a_2(\tau_1,\tau_2) = \int_0^{\tau_1} S^a_{2dd} e^{-rt} dt + \int_{\tau_1}^{\tau_2} S^a_{2cd} e^{-rt} dt + \int_{\tau_2}^{+\infty} S^a_{2cc} e^{-rt} dt - \theta e^{-mr\tau_2} \tag{23}$$

$$IU^a_i(\tau_i) = \int_0^{\tau_i} U^a_{idd} e^{-rt} dt + \int_{\tau_i}^{+\infty} U^a_{icc} e^{-rt} dt - \theta e^{-mr\tau_i} \tag{24}$$

$$IU^{na}_i(\tau_i) = \int_0^{\tau_i} \Pi^{na}_{idd} e^{-rt} dt + \int_{\tau_i}^{+\infty} \Pi^{na}_{icc} e^{-rt} dt - \theta e^{-mr\tau_i} \tag{25}$$

In order to get positive adoption dates, we need the following condition, which can be always verified by choosing θ and/or m high enough:[5]

$$0 < U^a_{icc} - U^a_{idd} < \theta mr \tag{26}$$

In the Appendix, we determine the optimal adoption dates which show that firms adopt simultaneously the clean technology:

$$\hat{\tau}^a = \frac{1}{(1-m)r} \ln\left(\frac{S^a_{1cd} - S^a_{1dd}}{\theta mr}\right) > 0 \tag{27}$$

$$\tau^{*a} = \frac{1}{(1-m)r} \ln\left(\frac{U^a_{icc} - U^a_{idd}}{\theta mr}\right) > 0 \tag{28}$$

$$\tau^{na} = \frac{1}{(1-m)r} \ln\left(\frac{\Pi^{na}_{icc} - \Pi^{na}_{idd}}{\theta mr}\right) > 0 \tag{29}$$

Proposition 2 *Because of symmetry, when markets are separated, firms adopt the clean technology simultaneously.*

[5] Notice that the left expression of (26) is independent of parameters θ, m and r.

Inequality (21) and the fact that $m > 1$, enable us to make the following ranking:

$$0 < \tau^{*a} < \hat{\tau}^a < \tau^{na} \tag{30}$$

We can state the following Proposition:

Proposition 3 *The optimal adoption date of regulated firms is earlier than that socially-optimal. However, the optimal adoption date of non-regulated firms is later than that socially-optimal.*

The above proposition shows 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, under autarky, the incentives to adopt are, in order, greater for regulated firms, regulators and non-regulated firms. This is clearly established by the inequalities in (21). This result is similar to the one established by Ben Youssef (2010) who used a model comprising one regulator and a monopolistic firm.

Paradoxically, if regulators desire that regulated firms delay their adoption to the socially-optimal adoption date, they must compensate firms for the losses they incur by this adoption delay. If the intertemporal net profits of the regulated firm i are $IU_i(\tau^{*a})$ and $IU_i(\hat{\tau}^a)$ when the adoption dates are τ^{*a} and $\hat{\tau}^a$, respectively, then the postpone adoption subsidy (compensation) is:

$$\hat{g}^a = IU_i(\tau^{*a}) - IU_i(\hat{\tau}^a) > 0 \tag{31}$$

Proposition 4 *When markets are separated, each regulator can push his 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.*

3 Common market

When markets are opened to competition, the inverse demand function of the perfect substitute goods produced by firms becomes $P = a - (q_i + q_j)$. The size of the integrated market is a.

The total consumers' surplus is equally divided between the two symmetric countries:

$$CS_i^{cm}(q_i, q_j) = \frac{1}{2}\left[\int_0^{q_i+q_j} P(z)dz - P(q_i+q_j)(q_i+q_j)\right] = \frac{1}{4}(q_i+q_j)^2$$

The emission-tax per-unit of pollution is t_i^{cm} and the per-unit production subsidy is s_i^{cm}.

When firm i uses the polluting technology, its profit is given by $\Pi_{id}^{cm} = p(q_i, q_j)q_i - dq_i$, and when it uses the clean technology, its profit is given by $\Pi_{ic}^{cm} = p(q_i, q_j)q_i - cq_i$.

The instantaneous social welfare of country i is equal to the consumers' surplus, minus damages plus the profit of the domestic firm:

$$S^{cm}(q_i, q_j) = CS_i^{cm}(q_i, q_j) - D_i(q_i, q_j) + \Pi_i^{cm}(q_i, q_j) \tag{32}$$

3.1 Non-regulated firms

When both firms use the polluting technology, each one maximizes its profit Π_{idd}^{ncm} to get the optimal level of production:

$$q_{idd}^{ncm} = \frac{a-d}{3} > 0 \tag{33}$$

When both firms use the clean technology, each one maximizes its profit Π_{icc}^{ncm} to get the optimal level of production:

$$q_{icc}^{ncm} = \frac{a-c}{3} > 0 \tag{34}$$

As for the autarky case, the clean technology enables non-regulated firms to produce more because of its lower unit production cost $\left(q_{icc}^{ncm} > q_{idd}^{ncm}\right)$.

If only firm 1 uses the clean technology, whereas firm 2 still uses the polluting technology, then the profit of each non-regulated firm is Π_{1cd}^{ncm} and Π_{2cd}^{ncm}, respectively. The optimal productions are given by:

$$q_{1cd}^{ncm} = \frac{a+d-2c}{3} > 0, \quad q_{2cd}^{ncm} = \frac{a-2d+c}{3} < 0 \tag{35}$$

The second inequality of condition (9) shows that $q_{2cd}^{ncm} < 0$. Thus, the case where the two non-regulated firms adopt at different dates is unrealistic. From now on, we will suppose that if non-regulated firms adopt the clean technology, then this adoption is simultaneous.

3.2 Regulated firms

When both firms use the polluting technology, the instantaneous social welfare of regulator i is:

$$S_{idd}^{cm}(q_i, q_j) = CS_i^{cm}(q_i, q_j) + \Pi_{idd}^{cm}(q_i, q_j) - D_i(q_i, q_j) \tag{36}$$

Maximizing the expression given by (36) with respect to q_i gives the socially-optimal production level with the polluting technology for regulator i:

$$\hat{q}_{idd}^{cm} = \frac{a-d-\alpha e}{2} > 0 \tag{37}$$

Since firm i is a duopoly producing with pollution, it is regulated. A per-unit emission-tax is sufficient to induce the socially-optimal level of production. Indeed, the instantaneous net profit of firm i is:

$$U_{idd}^{cm}(q_i, q_j) = \Pi_{idd}^{cm}(q_i, q_j) - t_{idd}^{cm} E_i \tag{38}$$

The socially-optimal per-unit emission-tax that induces firm i to produce $\hat{q}_{idd}^{cm}$ is:

$$t_{idd}^{cm} = \frac{a - d - 3\hat{q}_{idd}^{cm}}{e} > 0 \tag{39}$$

When both firms use the clean technology, the instantaneous social welfare of country i is:

$$S_{icc}^{cm}(q_i, q_j) = CS_i^{cm}(q_i, q_j) + \Pi_{icc}^{cm}(q_i, q_j) \tag{40}$$

Maximizing the expression given by (40) with respect to q_i gives the socially-optimal production level with the clean technology for each regulator i:

$$\hat{q}_{icc}^{cm} = \frac{a - c}{2} > 0 \tag{41}$$

Let's notice that, because non-regulated firms don't take into account environmental damages, they always produce more than what is socially-optimal ($q_{idd}^{ncm} > \hat{q}_{idd}^{cm}$). However, with the clean technology and because of the duopolistic distortion, non-regulated firms always produce less than what is socially-optimal ($q_{icc}^{ncm} < \hat{q}_{icc}^{cm}$).

Since the production process is clean, each regulator gives his firm a per-unit production subsidy s_{icc}^{cm},which is chosen to induce the socially-optimal level of production. Indeed, the instantaneous net profit of firms i is:

$$U_{icc}^{cm}(q_i, q_j) = \Pi_{icc}^{cm}(q_i, q_j) + s_{icc}^{cm} q_i \tag{42}$$

The socially-optimal per-unit production subsidy that induces firm i to produce $\hat{q}_{icc}^{cm}$ is:

$$s_{icc}^{cm} = 3\hat{q}_{icc}^{cm} + c - a > 0 \tag{43}$$

Consider the case where firm 1 has adopted the clean technology, whereas firm 2 still produces using the polluting technology. The instantaneous social welfare of regulator 1 and 2 are, respectively:

$$S_{1cd}^{cm}(q_1, q_2) = CS_1^{cm}(q_1, q_2) - D_1(q_2) + \Pi_{1cd}^{cm}(q_1, q_2) \tag{44}$$

$$S_{2cd}^{cm}(q_1, q_2) = CS_2^{cm}(q_1, q_2) - D_2(q_2) + \Pi_{2cd}^{cm}(q_1, q_2) \tag{45}$$

Maximizing expressions given by (44) and (45) respectively with respect to q_1 and q_2 gives:

$$\hat{q}_{1cd}^{cm} = \frac{2a + d - 3c + \alpha e}{4} > 0 \tag{46}$$

$$\hat{q}_{2cd}^{cm} = \frac{2a + c - 3d - 3\alpha e}{4} < 0 \tag{47}$$

Because of the second inequality of (9) and the first inequality of (1), $\hat{q}_{2cd}^{cm} < 0$.We conclude that considering the case where one firm uses the clean technology and the other one uses the polluting technology is unrealistic. Let's notice that we have assumed the first inequality and the second inequality of conditions (1) and (9) to prevent the study of the complicated case where firms adopt the clean technology at different dates. Indeed, even if it is possible to determine the optimal adoption dates, comparing them is very difficult to do in the common market case.

Proposition 5 *Under common market, due to conditions assumed on parameters, firms adopt the clean technology simultaneously.*

In the Appendix, we show that:

$$0 < \Pi_{icc}^{ncm} - \Pi_{idd}^{ncm} < U_{icc}^{cm} - U_{idd}^{cm} < S_{icc}^{cm} - S_{idd}^{cm} \tag{48}$$

These inequalities enable us to establish the following Proposition:

Proposition 6 *Under common market, the instantaneous gains from using the clean technology are greater for regulators than for regulated firms. These latter instantaneously benefit more from the clean technology than non-regulated firms.*

The reasons explaining the benefit from the clean technology are the same than for the autarky case. However, when regulated firms compete in a common market, their instantaneous net profits increase, due to the adoption of the clean technology, is less important than the increase of instantaneous social welfare levels.

3.3 Optimal adoption dates

When both firms adopt the clean technology at the same date τ, the intertemporal social welfare of regulator i, intertemporal net profit of the regulated and non-regulated firm i are, respectively:

$$IS_i^{cm}(\tau) = \int_0^{\tau} S_{idd}^{cm} e^{-rt} dt + \int_{\tau}^{+\infty} S_{icc}^{cm} e^{-rt} dt - \theta e^{-mr\tau} \tag{49}$$

$$IU_i^{cm}(\tau) = \int_0^{\tau} U_{idd}^{cm} e^{-rt} dt + \int_{\tau}^{+\infty} U_{icc}^{cm} e^{-rt} dt - \theta e^{-mr\tau} \tag{50}$$

$$IU_i^{ncm}(\tau) = \int_0^{\tau} \Pi_{idd}^{ncm} e^{-rt} dt + \int_{\tau}^{+\infty} \Pi_{icc}^{ncm} e^{-rt} dt - \theta e^{-mr\tau} \tag{51}$$

In the Appendix, we determine the socially-optimal adoption date for regulators, the optimal adoption date for regulated firms and non-regulated firms, which are respectively:

$$\hat{\tau}^{cm} = \frac{1}{(1-m)r} \ln\left(\frac{S_{icc}^{cm} - S_{idd}^{cm}}{\theta mr}\right) > 0 \tag{52}$$

$$\tau^{*cm} = \frac{1}{(1-m)r} \ln\left(\frac{U_{icc}^{a} - U_{idd}^{a}}{\theta mr}\right) > 0 \tag{53}$$

$$\tau^{ncm} = \frac{1}{(1-m)r} \ln\left(\frac{\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm}}{\theta mr}\right) > 0 \tag{54}$$

Inequality (48) and the assumption $m > 1$, enable us to make the following ranking:

$$0 < \hat{\tau}^{cm} < \tau^{*cm} < \tau^{ncm} \tag{55}$$

Thus, we can state the following Proposition:

Proposition 7 *When markets are opened to competition, the socially-optimal adoption date is earlier than the optimal adoption date for regulated firms. This latter is earlier than the optimal adoption date for non-regulated firms.*

The above proposition shows that, even in a common market, socially-optimal instantaneous regulation may not be dynamically optimal with respect to the adoption of clean technologies. They are due to the fact that, under a common market, the incentives to adopt the clean technology are, in order, greater for regulators, regulated firms and non-regulated firms. This is clearly demonstrated by the inequalities in (48).

If regulators desire that regulated firms accelerate their adoption to the socially-optimal adoption date, they must compensate firms for the losses they incur by an early adoption. If the intertemporal net profits of the regulated firm i are $IU_i(\tau^{*cm})$ and $IU_i(\hat{\tau}^{cm})$ when the adoption dates are τ^{*cm} and $\hat{\tau}^{cm}$, respectively, then the early adoption subsidy (compensation) is:

$$\hat{g}^{cm} = IU_i(\tau^{*cm}) - IU_i(\hat{\tau}^{cm}) > 0 \tag{56}$$

Proposition 8 *In a common market, each regulator can push his regulated firm to accelerate its adoption of the clean technology by giving it an early adoption subsidy that compensates the firm for the losses it incurs when this latter accelerates its optimal adoption date to the socially-optimal adoption date.*

4 Autarky versus common market

Looking to expressions (27) and (52), we can show that:

$$\hat{\tau}^{a} = \frac{1}{(1-m)r}\ln\left(\frac{\frac{d-c+\alpha e}{2}(\hat{q}^{a}_{icc}+\hat{q}^{a}_{idd})}{\theta mr}\right),$$
$$\hat{\tau}^{cm} = \frac{1}{(1-m)r}\ln\left(\frac{\frac{d-c+\alpha e}{2}(\hat{q}^{cm}_{icc}+\hat{q}^{cm}_{idd})+\beta e\hat{q}^{cm}_{idd}}{\theta mr}\right)$$

The above expressions show that, under a common market, the socially-optimal adoption date internalizes transboundary pollution. However, under autarky, the socially-optimal adoption date does not internalize transboundary pollution. Moreover, under both market regimes, optimal adoption dates of regulated and non-regulated firms completely don't internalize transboundary pollution. This is due to the fact that our damage function is linear with respect to the total pollution. Indeed, production for non-regulated firms, socially-optimal production and net profit of firms completely don't internalize transboundary pollution.[6] This result is of great interest because this paper is the first attempt linking adoption of clean technologies with transboundary pollution. Notice that, using a very different model, Ben Youssef (2009) showed that R&D spillovers and the competition of firms on the common market help non-cooperating countries to better internalize transboundary pollution. Ben Youssef (2011) showed that the investment in absorptive R&D help non-cooperating countries to better internalize transboundary pollution. We can state the following Proposition:

Proposition 9 *The socially-optimal adoption date under a common market better internalizes transboundary pollution than that under autarky, and than the optimal adoption date of regulated firms. However, under both market regimes, the optimal adoption date of non-regulated firms completely don't internalize transboundary pollution.*

Let us notice that if there were no transfrontier pollution between countries, i.e. $\beta = 0$,then from expressions (69) and (71), we deduce that the optimal adoption date for regulated firms and the socially-optimal adoption date coincide under common market ($\tau^{*cm} = \hat{\tau}^{cm}$). Indeed, since the instantaneous social welfare gain from using the clean technology internalizes transboundary pollution causing a speedup in technology adoption, the absence of transboundary pollution delays the socially-optimal adoption date to the optimal adoption date for regulated firms. Nonetheless, under autarky, the optimal adoption date of regulated firms still remains earlier than that socially-optimal because this latter does not internalize transboundary pollution.

[6] If damage functions were not linear with respect to total pollution nor separable with respect to the pollution remaining at home and the one received from other countries, then transboundary pollution would be partially internalized by socially-optimal production quantities.

The comparison of optimal production quantities shows that the competition on the common market pushes non-regulated firms to increase their production ($q_{idd}^{ncm} > q_{idd}^{na}, q_{icc}^{ncm} > q_{icc}^{na}$).However, socially-optimal productions are the same under the two market regimes ($\hat{q}_{idd}^{cm} = \hat{q}_{idd}^{a}, \hat{q}_{icc}^{cm} = \hat{q}_{icc}^{a}$).Consequently, when the polluting technology is used, the per-unit emission-tax is greater under common market ($t_{idd}^{cm} > t_{idd}^{a}$). When the clean technology is used, the per-unit production subsidy is greater under autarky ($s_{icc}^{a} > s_{icc}^{cm}$). These results are interesting and even surprising because one may think that, to give a competitive advantage to its domestic firm, each regulator reduces the per-unit emission tax and increases the per-unit production subsidy, when markets are opened to international competition. Ben Youssef (2009) found a similar result with a different model where regulatory instruments are a per-unit emission-tax and a per-unit R&D subsidy.

Proposition 10 *Opening markets to international competition increases the per-unit emission-tax when the polluting technology is used, and decreases the per-unit production subsidy when the clean technology is used.*

In the Appendix, we show that, under a common market, the instantaneous social welfare gain from using the clean technology is greater than the instantaneous social welfare gain from using the clean technology of the first adopter under autarky. Thus, opening markets to international trade speeds up the socially-optimal adoption date ($\hat{\tau}^{cm} < \hat{\tau}^{a}$). Let us notice that if there were no transfrontier pollution between countries, i.e. $\beta = 0$,then from expressions (57) and (69), we deduce that the socially-optimal optimal adoption dates are the same under both market regimes ($\hat{\tau}^{cm} = \hat{\tau}^{a}$).

We also deduce that the competition of regulated firms on a common market reduces their instantaneous gain from using the clean technology with respect to the case where markets are separated. Thus, opening markets to international competition delays the adoption of the clean technology by regulated firms ($\tau^{*a} < \tau^{*cm}$).

Finally, we show that the competition of non-regulated firms on a common market reduces their instantaneous gain from using the clean technology with respect to the case where markets are separated. Therefore, international competition delays the adoption of the clean technology by non-regulated firms ($\tau^{na} < \tau^{ncm}$).

Proposition 11 *International competition reduces the instantaneous gain from using the clean technology by both non-regulated and regulated firms, with respect to autarky. Consequently, non-regulated and regulated firms delay the adoption of the clean technology when markets are opened to international trade. However, the instantaneous social welfare gain from using the clean technology increases with market opening, leading to an acceleration of the socially-optimal adoption date.*

The above results are new and interesting because the impact of opening markets to international trade on the timing of adoption of clean technologies has not been previously studied.

5 Conclusion

In this paper, we consider two countries and a monopolistic firm operating in each country. Firms produce the same homogeneous good by using a polluting technology that uses fossil energy. These firms can adopt a new and clean production technology by incurring an investment cost that decreases with the adoption date. This clean technology uses a renewable energy and therefore has a lower per- unit production cost. We consider and compare the case where firms are not regulated at all, and the case where each firm is regulated at each period of time i.e. each regulator looks for static social optimality. When firms are instantaneously regulated, a per-unit emission-tax is used when a firm uses the polluting technology, and a per-unit production subsidy, that can be considered as a fiscal incentive, is used when a firm uses the clean production technology. We also study and compare the case where each firm operates in a separate domestic market, and the case where firms compete in the same common market formed by the consumers of the two countries.

Our results show that, contrary to what one may expect, international competition increases the per-unit emission-tax when the polluting technology is used, and decreases the per-unit production subsidy when the clean technology is used.

In autarky, because our model is symmetric, both firms adopt the clean technology simultaneously. However, in a common market, because of the competition between firms, non-simultaneous adoption may occur. We impose conditions on parameters to avoid the complicated case where firms adopt at different dates, and we show that adoption is simultaneous. Indeed, even if it is possible to determine the optimal adoption dates, comparing them in the common market case is very difficult to do if adoption is not simultaneous.

Interestingly, the socially-optimal adoption date under a common market better internalizes transboundary pollution than that under autarky, and than the optimal adoption date of regulated firms. However, the optimal adoption date of non-regulated firms completely don't internalize transboundary pollution. Therefore, regulators should know how to intervene to get firms adopting at the socially-optimal dates.

Under autarky, the instantaneous gain from using the clean technology is greater for regulated firms than for regulators. These latter instantaneously benefit more from using the clean technology than non-regulated firms. Consequently, regulated firms adopt earlier than what is socially-optimal, whereas non-regulated firms adopt later than the socially-optimal adoption date. Therefore, in autarky, regulators can induce firms to adopt at the socially-optimal adoption date by giving them postpone adoption subsidies. Interestingly, the behavior of regulators completely changes when markets are opened to international competition.

Indeed, under a common market, the instantaneous gain from using the clean technology is greater for regulators than for regulated firms. These latter instantaneously benefit more from using the clean technology than non-regulated firms. Consequently, the socially-optimal adoption date is earlier than the optimal adoption date for regulated firms. This latter is earlier than the optimal adoption date for non-regulated firms. Therefore, in a common market, regulators can induce regulated firms to adopt at the socially-optimal adoption date by giving them speed up adoption subsidies.

Finally, international competition reduces the instantaneous benefits from using the clean technology of both non-regulated and regulated firms, with respect to autarky. Consequently, non-regulated and regulated firms delay the adoption of the clean technology when markets are opened to international trade. However, the instantaneous social welfare benefit from the adoption of the clean technology is greater under common market, implying an early socially-optimal adoption date with respect to autarky.

6 Appendix

6.1 Autarky

6.1.1 Instantaneous gains from using the clean technology

i) Social optimum

*Using expressions (7) and (18): $S^a_{1cd} - S^a_{1dd} = [a - (\hat{q}^a_{1cd} + \hat{q}^a_{1dd}) - c]\,(\hat{q}^a_{1cd} - \hat{q}^a_{1dd}) + (d - c)\,\hat{q}^a_{1dd} - \alpha e \hat{q}^a_{1dd}$

By using expressions of $\hat{q}^a_{1dd}$ and $\hat{q}^a_{1cd}$, we get:

$$S^a_{1cd} - S^a_{1dd} = \frac{d - c + \alpha e}{2}\,(\hat{q}^a_{1cd} + \hat{q}^a_{1dd}) > 0 \tag{57}$$

*Using expressions (13) and (19): $S^a_{2cc} - S^a_{2cd} = [a - (\hat{q}^a_{2cd} + \hat{q}^a_{2cc}) - c]\,(\hat{q}^a_{2cc} - \hat{q}^a_{2cd}) + (d - c)\hat{q}^a_{2cd} + \alpha e \hat{q}^a_{2cd}$

By using expressions of $\hat{q}^a_{2cc}$ and $\hat{q}^a_{2cd}$, we get:

$$S^a_{2cc} - S^a_{2cd} = \frac{d - c + \alpha e}{2}\,(\hat{q}^a_{2cd} + \hat{q}^a_{2cc}) > 0 \tag{58}$$

Given that $\hat{q}^a_{icc} = \hat{q}^a_{1cd}$ and $\hat{q}^a_{idd} = \hat{q}^a_{2cd}$, we have:

$$S^a_{1cd} - S^a_{1dd} = S^a_{2cc} - S^a_{2cd} \tag{59}$$

ii**) Non-regulated firms**

*Since $q^{na}_{icc} = q^{na}_{1cd}$, then:

$$\Pi^{na}_{1cd} - \Pi^{na}_{1dd} = \Pi^{na}_{icc} - \Pi^{na}_{idd} = [a - 2(q^{na}_{icc} + q^{na}_{idd})]\,(q^{na}_{icc} - q^{na}_{idd}) + dq^{na}_{idd} - cq^{na}_{icc}$$

By replacing q^{na}_{idd} and q^{na}_{icc} between the above brackets by their values, we get:

$$\Pi^{na}_{1cd} - \Pi^{na}_{1dd} = \Pi^{na}_{icc} - \Pi^{na}_{idd} = \frac{d - c}{2}\,(q^{na}_{icc} + q^{na}_{idd}) > 0 \tag{60}$$

iii) Regulated firms

*Since $q^{na}_{icc} = q^{na}_{1cd}$, then by using expressions (10) and (16):

$$U^a_{1cd} - U^a_{1dd} = U^a_{icc} - U^a_{idd} =$$
$$\left[a - 2\left(\hat{q}^a_{icc} + \hat{q}^a_{idd}\right)\right]\left(\hat{q}^a_{icc} - \hat{q}^a_{idd}\right) + \left(s^a_{icc} - c\right)\hat{q}^a_{icc} + d\hat{q}^a_{idd} + t^a_{idd} e \hat{q}^a_{idd}$$

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

$$U^a_{1cd} - U^a_{1dd} = U^a_{icc} - U^a_{idd} = 2[(\hat{q}^a_{icc})^2 - (\hat{q}^a_{idd})^2] = (d - c + \alpha e)(\hat{q}^a_{icc} + \hat{q}^a_{idd}) > 0 \quad (61)$$

6.1.2 Comparison of instantaneous gains

*Using expressions (61) and (57), we have:

$$U^a_{1cd} - U^a_{1dd} - (S^a_{1cd} - S^a_{1dd}) = \left[2\left(\hat{q}^a_{1cd} - \hat{q}^a_{1dd}\right) - \tfrac{d-c+\alpha e}{2}\right]\left(\hat{q}^a_{1cc} + \hat{q}^a_{1dd}\right)$$

By using expressions of $\hat{q}^a_{1cd}$ and $\hat{q}^a_{1dd}$ in the above bracketed expression, we show that:

$$U^a_{1cd} - U^a_{1dd} - (S^a_{1cd} - S^a_{1dd}) > 0 \quad (62)$$

*Using expressions (57) and (60), we obtain:

$$S^a_{1cd} - S^a_{1dd} - (\Pi^{na}_{1cd} - \Pi^{na}_{1dd}) = \tfrac{d-c+\alpha e}{2}\left(\hat{q}^a_{1cc} + \hat{q}^a_{1dd}\right) - \tfrac{d-c}{2}\left(q^{na}_{1cc} + q^{na}_{1dd}\right)$$
$$= \tfrac{d-c}{2}\left[\hat{q}^a_{1cc} + \hat{q}^a_{1dd} - q^{na}_{1cc} - q^{na}_{1dd}\right] + \tfrac{\alpha e}{2}\left(\hat{q}^a_{1cc} + \hat{q}^a_{1dd}\right)$$

By replacing the expression of $\hat{q}^a_{1cc}$, $\hat{q}^a_{1dd}$, q^{na}_{1cc}, and q^{na}_{1dd} by their values in the above brackets, we obtain:

$$S^a_{1cd} - S^a_{1dd} - (\Pi^{na}_{1cd} - \Pi^{na}_{1dd}) = \frac{d-c}{2}\left[\frac{2a - c - d - 2\alpha e}{4}\right] + \frac{\alpha e}{2}\left(\hat{q}^a_{1cd} + \hat{q}^a_{1dd}\right)$$

Using the first inequality of condition (9), we can prove that $2a - c - d - 2\alpha e > 0$, then:

$$S^a_{1cd} - S^a_{1dd} - (\Pi^{na}_{1cd} - \Pi^{na}_{1dd}) > 0 \quad (63)$$

Thus, we have the following ranking:

$$0 < \Pi^{na}_{1cd} - \Pi^{na}_{1dd} < S^a_{1cd} - S^a_{1dd} < U^a_{1cd} - U^a_{1dd} \quad (64)$$

The instantaneous gain from using the clean technology is higher for the first adopter regulated firm than for its regulator, which benefits more than its non-regulated firm.

6.1.3 Optimal adoption dates

We suppose that $\tau_1 \leq \tau_2$, meaning that, in case of non-simultaneous adoption, firm 1 is the first adopter and firm 2 is the second.

i) Non-regulated firms*:*

Firm i maximizes its intertemporal net profit $IU_i^{na}(\tau_i)$ given by (25) with respect to τ_i:

$$\frac{\partial IU_i^{na}(\tau_i)}{\partial \tau_i} = \left(\Pi_{idd}^{na} - \Pi_{icc}^{na}\right) e^{-r\tau_i} + \theta m r e^{-mr\tau_i} = 0 \tag{65}$$

Equation (65) is equivalent to:

$$\Pi_{idd}^{na} - \Pi_{icc}^{na} + \theta m r e^{(1-m)r\tau_i} = 0 \Longleftrightarrow \tau_i^{na} = \tau^{na} = \frac{1}{(1-m)r} \ln\left(\frac{\Pi_{icc}^{na} - \Pi_{idd}^{na}}{\theta m r}\right)$$

Because of $m > 1$, condition (26) and inequality (64), $\tau^{na} > 0$.

We have: $\frac{\partial^2 IU_i^{na}(\tau_i^{na})}{\partial \tau_i^2} = r\left(\Pi_{icc}^{na} - \Pi_{idd}^{na}\right) e^{-r\tau_i^{na}} - \theta(mr)^2 e^{-mr\tau_i^{na}}$.

Using the first order condition given by (65), we get:

$$\frac{\partial^2 IU_i^{na}(\tau_i^{na})}{\partial \tau_i^2} = (1-m)m\theta r^2 e^{-mr\tau_i^{na}} < 0$$

Thus, the second-order condition of optimality is verified.

ii) Regulated firms:

Firm i maximizes its intertemporal net profit $IU_i^{a}(\tau_i)$ given by (24) with respect to τ_i:

$$\frac{\partial IU_i^{a}(\tau_i)}{\partial \tau_i} = \left(U_{idd}^{a} - U_{icc}^{a}\right) e^{-r\tau_i} + \theta m r e^{-mr\tau_i} = 0 \tag{66}$$

Equation (66) is equivalent to:

$$U_{idd}^{a} - U_{icc}^{a} + \theta m r e^{(1-m)r\tau_i} = 0 \Longleftrightarrow \tau_i^{*a} = \tau^{*a} = \frac{1}{(1-m)r} \ln\left(\frac{U_{icc}^{a} - U_{idd}^{a}}{\theta m r}\right)$$

Because of $m > 1$ and condition (26), $\tau^{*a} > 0$.

We have: $\frac{\partial^2 IU_i^{a}(\tau_i)}{\partial \tau_i^2} = r\left(U_{icc}^{a} - U_{idd}^{a}\right) e^{-r\tau_i} - \theta(mr)^2 e^{-mr\tau_i}$.

Using the first-order condition given by (66), we get:

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

The second-order condition of optimality is verified.

iii) Social optimum

Each regulator maximizes his intertemporal social welfare function $IS_1^a(\tau_1, \tau_2)$ and $IS_2^a(\tau_1, \tau_2)$, given by (22) and (23), with respect to τ_1 and τ_2, respectively:

$$\frac{\partial IS_1^a(\tau_1,\tau_2)}{\partial \tau_1} = \left(S_{1dd}^a(\hat{q}_{1dd}^a) - S_{1cd}^a(\hat{q}_{1cd}^a)\right)e^{-r\tau_1} + \theta mre^{-mr\tau_1} = 0 \tag{67}$$

$$\frac{\partial IS_2^a(\tau_1,\tau_2)}{\partial \tau_2} = \left(S_{2cd}^a(\hat{q}_{2cd}^a) - S_{2cc}^a(\hat{q}_{2cc}^a)\right)e^{-r\tau_2} + \theta mre^{-mr\tau_2} = 0 \tag{68}$$

Equations (67) and (68) are respectively equivalent to:

$$\begin{aligned} S_{1dd}^a(\hat{q}_{1dd}^a) - S_{1cd}^a(\hat{q}_{1cd}^a) + \theta mre^{(1-m)r\tau_1} &= 0 \Longleftrightarrow \hat{\tau}_1^a = \frac{1}{(1-m)r}\ln\left(\frac{S_{1cd}^a(\hat{q}_{1cd}^a) - S_{1dd}^a(\hat{q}_{1dd}^a)}{\theta mr}\right) \\ S_{2cd}^a(\hat{q}_{2cd}^a) - S_{2cc}^a(\hat{q}_{2cc}^a) + \theta mre^{(1-m)r\tau_2} &= 0 \Longleftrightarrow \hat{\tau}_2^a = \frac{1}{(1-m)r}\ln\left(\frac{S_{2cc}^a(\hat{q}_{2cc}^a) - S_{2cd}^a(\hat{q}_{2cd}^a)}{\theta mr}\right) \end{aligned}$$

Because of $m > 1$, condition (26), inequalities (64), equalities (59) and (61), we get $\hat{\tau}_1^a > 0$ and $\hat{\tau}_2^a > 0$.

We have:

$$\begin{cases} \frac{\partial^2 IS_1^a(\tau_1,\tau_2)}{\partial \tau_1^2} = r\left(S_{1cd}^a(\hat{q}_{1cd}^a) - S_{1dd}^a(\hat{q}_{1dd}^a)\right)e^{-r\tau_1} - \theta(mr)^2e^{-mr\tau_1} \\ \frac{\partial^2 IS_2^a(\tau_1,\tau_2)}{\partial \tau_2^2} = r\left(S_{2cc}^a(\hat{q}_{2cc}^a) - S_{2cd}^a(\hat{q}_{2cd}^a)\right)e^{-r\tau_1} - \theta(mr)^2e^{-mr\tau_2} \end{cases}$$

Using first-order conditions given by (67) and (68), we get:

$$\frac{\partial^2 IS_1^a(\hat{\tau}_1^a,\tau_2)}{\partial \tau_1^2} = (1-m)m\theta r^2e^{-mr\hat{\tau}_1^a} < 0 \; ; \; \frac{\partial^2 IS_2^a(\tau_1,\hat{\tau}_2^a)}{\partial \tau_2^2} = (1-m)m\theta r^2e^{-mr\hat{\tau}_2^a} < 0$$

Thus, the second-order condition of optimality is verified for each regulator.

Because of equality (59), we have: $\hat{\tau}_1^a = \hat{\tau}_2^a = \hat{\tau}^a$.

6.1.4 Comparison of adoption dates

Inequality (64), the fact that $\Pi_{1cd}^{na} - \Pi_{1dd}^{na} = \Pi_{icc}^{na} - \Pi_{idd}^{na}$, $U_{1cd}^a - U_{1dd}^a = U_{icc}^a - U_{idd}^a$ and $m > 1$, enable us to make the following ranking:

$$0 < \tau^{*a} < \hat{\tau}^a < \tau^{na}$$

Under autarky, regulated firms adopt earlier than what is socially-desired, while non-regulated firms adopt later.

6.2 Common market

6.2.1 Instantaneous gains from using the clean technology

i) Social optimum

*Using expressions (36) and (40):

$$S_{icc}^{cm} - S_{idd}^{cm} = [a - (\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) - c]\,(\hat{q}_{icc}^{cm} - \hat{q}_{idd}^{cm}) + (d-c)\hat{q}_{idd}^{cm} + (\alpha+\beta)e\hat{q}_{idd}^{cm}$$

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

$$S_{icc}^{cm} - S_{idd}^{cm} = \frac{d-c+\alpha e}{2}\,(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) + \beta e\hat{q}_{idd}^{cm} > 0 \tag{69}$$

ii) Non-regulated firms

$*\Pi_{icc}^{cm} - \Pi_{idd}^{cm} = [a - 2(q_{icc}^{ncm} + q_{idd}^{ncm})]\,(q_{icc}^{ncm} - q_{idd}^{ncm}) + dq_{idd}^{ncm} - cq_{icc}^{ncm}$

By replacing q_{idd}^{ncm} and q_{icc}^{ncm} between the above brackets by their values, we get:

$$\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm} = \frac{d-c}{3}\,(q_{icc}^{ncm} + q_{idd}^{ncm}) > 0 \tag{70}$$

iii) Regulated firms

*Using expressions (38) and (42):

$$U_{icc}^{cm} - U_{idd}^{cm} = [a - 2\,(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm})]\,(\hat{q}_{icc}^{cm} - \hat{q}_{idd}^{cm}) + (s_{icc}^{cm} - c)\,\hat{q}_{icc}^{cm} + d\hat{q}_{idd}^{cm} + t_{idd}^{cm}e\hat{q}_{idd}^{cm}$$

By changing the emission tax t_{idd}^{cm} and the production subsidy s_{icc}^{cm} by their expressions in function of $\hat{q}_{idd}^{cm}$ and $\hat{q}_{icc}^{cm}$, we obtain:

$$U_{icc}^{cm} - U_{idd}^{cm} = \frac{d-c+\alpha e}{2}\,(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) > 0 \tag{71}$$

6.2.2 Comparison of instantaneous gains

Using expressions (69), (70) and (71), we obtain:

$*S_{icc}^{cm} - S_{idd}^{cm} - (U_{icc}^{cm} - U_{idd}^{cm}) = \beta e\hat{q}_{idd}^{cm} > 0$

$*U_{icc}^{cm} - U_{idd}^{cm} - (\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm}) = \frac{d-c}{2}\,(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) - \frac{d-c}{3}\,(q_{icc}^{ncm} + q_{idd}^{ncm}) + \frac{\alpha e}{2}\,(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm})$

Using expressions of $\hat{q}_{icc}^{cm}$, $\hat{q}_{idd}^{cm}$, q_{icc}^{ncm},and q_{idd}^{ncm}, we get:

$$U_{icc}^{cm} - U_{idd}^{cm} - (\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm}) = \tfrac{d-c}{36}(10a - 5d - 5c - 9\alpha e) + \tfrac{\alpha e}{2}\,(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm})$$

Because of the first inequality of condition (9), we have $10a-5d-5c-9\alpha e > 0$, and:

$$U_{icc}^{cm} - U_{idd}^{cm} - (\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm}) > 0$$

Thus, we have the following ranking:

$$0 < \Pi_{icc}^{ncm} - \Pi_{idd}^{ncm} < U_{icc}^{cm} - U_{idd}^{cm} < S_{icc}^{cm} - S_{idd}^{cm} \tag{72}$$

Under common market, the instantaneous gain from using the clean technology is more important for regulators than regulated firms, which benefit more than non-regulated firms.

6.2.3 Optimal adoption dates

i) Non-regulated firms

Each non-regulated firm i maximizes its intertemporal net profit given by (51) with respect to τ:

$$\frac{\partial IU_i^{ncm}(\tau)}{\partial \tau} = (\Pi_{idd}^{ncm} - \Pi_{icc}^{ncm})e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{73}$$

Equation (73) is equivalent to:

$$\Pi_{idd}^{ncm} - \Pi_{icc}^{ncm} + \theta mre^{(1-m)r\tau} = 0 \Longleftrightarrow \tau^{ncm} = \frac{1}{(1-m)r} \ln\left(\frac{\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm}}{\theta mr}\right)$$

Because of $m > 1$, inequalities (79), (64) and (26), $\tau^{ncm} > 0$.

We have: $\frac{\partial^2 IU_i^{ncm}(\tau)}{\partial \tau^2} = r(\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm})e^{-r\tau} - \theta(mr)^2 e^{-mr\tau}$.

Using the first-order condition given by (73), we get:

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

Therefore, the second-order condition of optimality is verified.

ii) Regulated firms

Each regulated firm i maximizes its intertemporal net profit $IU_i^{cm}(\tau)$ given by (50) with respect to τ :

$$\frac{\partial IU_i^{cm}(\tau)}{\partial \tau} = (U_{idd}^{cm} - U_{icc}^{cm})e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{74}$$

Equation (74) is equivalent to:

$$U_{idd}^{cm} - U_{icc}^{cm} + \theta mre^{(1-m)r\tau} = 0 \Longleftrightarrow \tau^{*cm} = \frac{1}{(1-m)r} \ln\left(\frac{U_{icc}^{cm} - U_{idd}^{cm}}{\theta mr}\right)$$

Because of $m > 1$, inequalities (78) and (26), $\tau^{*cm} > 0$.

We have: $\frac{\partial^2 IU_i^{cm}(\tau)}{\partial \tau^2} = r(U_{icc}^{cm} - U_{idd}^{cm})e^{-r\tau} - \theta(mr)^2 e^{-mr\tau}$.

Using the first-order condition given by (74), we get:

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

Thus, the second-order condition of optimality is verified.

iii) Social optimum

Each regulator i maximizes his intertemporal social welfare $IS_i^{cm}(\tau)$ given by (49) with respect to τ:

$$\frac{\partial IS_i^{cm}(\tau)}{\partial \tau} = (S_{idd}^{cm} - S_{icc}^{cm})e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{75}$$

Equation (75) is equivalent to:

$$S_{idd}^{cm} - S_{icc}^{cm} + \theta m r e^{(1-m)r\tau} = 0 \Longleftrightarrow \hat{\tau}^{cm} = \frac{1}{(1-m)r} \ln\left(\frac{S_{icc}^{cm} - S_{idd}^{cm}}{\theta m r}\right)$$

Using expressions (69) and (61), we show that:

$$S_{icc}^{cm} - S_{idd}^{cm} - (U_{icc}^{a} - U_{idd}^{a}) = \frac{d-c+\alpha e}{2}(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) + \beta e \hat{q}_{idd}^{cm} - (d-c+\alpha e)(\hat{q}_{icc}^{a} + \hat{q}_{idd}^{a})$$

Since $\hat{q}_{icc}^{cm} = \hat{q}_{icc}^{a}$ and $\hat{q}_{idd}^{cm} = \hat{q}_{idd}^{a}$, then:

$$S_{icc}^{cm} - S_{idd}^{cm} - (U_{icc}^{a} - U_{idd}^{a}) = \frac{-(d-c+\alpha e)}{2}(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) + \beta e \hat{q}_{idd}^{cm}$$

Suppose that $\beta = \alpha$, and using the second inequality of (1), then:

$$S_{icc}^{cm} - S_{idd}^{cm} - (U_{icc}^{a} - U_{idd}^{a}) = \frac{-(d-c+\alpha e)}{2}\hat{q}_{icc}^{cm} + \frac{\alpha e + c - d}{2}\hat{q}_{idd}^{cm} < 0$$

Therefore:

$$S_{icc}^{cm} - S_{idd}^{cm} < U_{icc}^{a} - U_{idd}^{a} \qquad (76)$$

Because of $m > 1$, inequalities (76) and (26), $\hat{\tau}^{cm} > 0$.

We have: $\frac{\partial^2 IS_i^{cm}(\tau)}{\partial \tau^2} = r(S_{icc}^{cm} - S_{idd}^{cm})e^{-r\tau} - \theta(mr)^2 e^{-mr\tau}$.

Using the first-order condition given by (75), we get $\frac{\partial^2 IS_i^{cm}(\hat{\tau}^{cm})}{\partial \tau^2} = (1-m)m\theta r^2 e^{-mr\hat{\tau}^{cm}} < 0$.

Thus, the second-order condition of optimality is verified.

6.3 Autarky versus common market

*From expressions (57) and (69), we show that:

$$S_{1cd}^{a} - S_{1dd}^{a} < S_{icc}^{cm} - S_{idd}^{cm} \qquad (77)$$

This implies that $\hat{\tau}^{cm} < \hat{\tau}^{a}$.

*From expressions (61) and (71), we show that:

$$U_{icc}^{cm} - U_{idd}^{cm} < U_{icc}^{a} - U_{idd}^{a} \qquad (78)$$

Since $m > 1$,then $\tau^{*cm} > \tau^{*a}$.

*Using expressions of $q_{idd}^{na}, q_{icc}^{na}, q_{idd}^{ncm}$ and q_{icc}^{ncm} in (60) and (70), we obtain:

$$\Pi_{icc}^{ncm} - \Pi_{idd}^{ncm} < \Pi_{icc}^{na} - \Pi_{idd}^{na} \qquad (79)$$

Since $m > 1$, then $\tau^{ncm} > \tau^{na}$.

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