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 which uses fossil energy. However, these firms can adopt a clean technology which uses renewable energy having a lower unit cost. Interestingly, opening markets to international competition increases the per-unit emission-tax and decreases the per-unit production subsidy. The socially optimal adoption date under a common market better internalizes transboundary pollution than that under autarky. In autarky (resp. a common market), firms adopt the clean technology earlier (resp. later) than what is socially optimal and, therefore, regulators induce clean technology adoption at the socially optimal adoption date by giving firms postpone (resp. speed up) adoption subsidies. Opening markets to international trade, speeds up socially optimal adoption dates and reduces the global flow of pollution.

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

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

1 Introduction

This paper investigates the relation that might 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 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 might 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. These questions have not been tackled by previous literature.

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 which uses fossil energy. However, these firms can adopt a new and clean production technology by incurring an investment cost. This clean technology does not pollute at all, uses renewable energy and therefore has a lower unit production cost. Each non-cooperating regulator looks for static and dynamic social optimalities. A per-unit emission-tax is used when a firm uses the polluting technology, a per-unit production subsidy, which can be considered as a fiscal incentive, is used when a firm uses the clean technology, and an adoption subsidy is used to induce the firm to adopt the clean technology at the socially optimal adoption date. Before the beginning of the game, at date -1, regulators announce their per-unit emission-tax and subsidy, and their adoption subsidies. Then, at date 0, firms choose their instantaneous production quantities and adoption dates. We study and compare the case where each firm operates in a separate home market, and the case where there is international trade and firms compete in the same market formed by 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 model's parameters to avoid the complicated case where firms adopt the clean technology at different dates, and we show that clean technology 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 because it is naturally expected that, to give a competitive advantage to its domestic firm, each regulator is tempted to reduce the per-unit emission-tax and to increase the per-unit production subsidy, when markets are opened to international trade. We do not get such expected results because regulators look for static (and dynamic) social optimality, i.e., first-best outcome.

Interestingly, the socially optimal adoption date under a common market better internalizes transboundary pollution than that under autarky. This result is of great interest because this paper is the first attempt linking the adoption of clean technologies with transboundary pollution.

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

The instantaneous social welfare gain from the adoption of the clean technology increases with market opening, leading to an earlier socially optimal adoption date under a common market. Consequently, international trade leads to less global flow of pollution. 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.

Our paper enrich the previous literature on renewable energies and clean technologies by providing a theoretical study on the effect of international trade on both clean technology adoption and transboundary pollution. Indeed, many theoretical studies have been concerned with renewable energies and clean technologies such as those of Wirl and Withagen (2000), Fischer et al. (2004), Soest (2005), Nasiri and Zaccour (2009) and Fujiwara (2011). Dosi and Moretto (1997) studied the regulation of a firm that 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 stimulates the innovation by subsidies and by reducing the uncertainty concerning the profitability of the clean technology by appropriate announcements. Moreover, 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. 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 it later than what is socially optimal. The regulator can induce the monopoly to adopt the clean technology at the socially optimal date by a postpone adoption subsidy. 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 also been interested in clean technologies (Whitehead and Cherry 2007, Varun et al. 2009, Li et al. 2009, Caspary 2009, Pillai and Banerjee 2009).

Let us notice that many papers, not concerned with renewable energies, have studied the impact of international trade on pollution (Péchoux and Pouyet 2003, Cremer and Gahvari 2004). Copeland and Taylor (1995) showed that uncoordinated regulation of pollution at the national level and free trade do not necessarily raise welfare.

Other studies, not concerned with renewable energies, have been interested in transboundary pollution (Hoel 1997, Zagonari 1998, Ben Youssef 2009, 2011).

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 and at the same time reaching the first best.

There is a rich literature on the timing of adoption of new technologies characterized by a lower production cost. We can cite Riordan (1992), Dutta et al. (1995), Hoppe (2000) and Milliou and Petrakis (2011). Reinganum (1981) 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. Making less severe conditions on the payoffs of firms than Reinganum (1981), Fudenberg and Tirole (1985) showed that under certain conditions there is diffusion of new technology adoption, whereas under other conditions firms adopt the new technology simultaneously. Since non-simultaneous adoption is not the principal focus of the present paper, we have imposed conditions on model's parameters to eliminate the complicated case of non-simultaneous adoption of the new and clean technology.

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 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 cost of domestic pollution and $\beta > 0$ is the marginal damage cost of foreign pollution. Thus, we use a simple and linear damage function. However, we think that our main results remain valid with a non-linear and convex damage function.

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

[1]In what follows, the subscripts d and c refer to the polluting and clean technologies,

Each firm i behaves for an infinite horizon of time and can adopt a new and clean production technology within a period of time τ_i. This clean technology does not pollute at all, uses renewable energy and therefore has a lower unit cost of production c verifying $0 < c < d$. For example, we can consider that the polluting technology uses fossil energy, whereas the clean technology uses solar energy. The per-unit energy-production cost for the clean technology is for maintaining the solar production technology, and we can reasonably assume that it is lower than the per-unit energy-production cost when a fossil energy is used. Thus, the profit of firm i is $\Pi^a_{ic} = p_i(q_i)q_i - cq_i$.

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

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

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

$$S^a_i(q_i, q_j) = CS^a_i(q_i) - D_i(q_i, q_j) + \Pi^a_i(q_i) \tag{2}$$

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]

As many studies (Fudenberg and Tirole 1985, Hoppe 2000, Milliou and Petrakis 2011), we assume that the current cost of adoption decreases overtime at a decreasing rate due to technical progress, i.e., $(V(\tau_i)e^{r\tau_i})' < 0$ and $(V(\tau_i)e^{r\tau_i})'' > 0$.

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

Before the beginning of the game, at date -1, regulators announce their per-unit emission-tax when the polluting technology is used, their per-unit production subsidy when the clean technology is used, and their adoption subsidy to push firms adopting the clean technology at the socially optimal adoption date. Then, at date 0, firms choose their instantaneous production quantities before and after the adoption of the clean technology, and their adoption date.

respectively. The superscripts a and cm refer to the autarky and common market cases, respectively.

[2] This assumption is necessary to obtain a decreasing current adoption cost function. Moreover, it guarantees that the optimal adoption dates are positive and the second-order conditions are verified (see the Appendix).

2.1 Instantaneous regulation

Being regional monopolies, 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 these socially optimal production quantities in each country.

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

$$S_{idd}^{a}(q_i, q_j) = CS_i^a(q_i) - D_i(q_i, q_j) + \Pi_{idd}^{a}(q_i) \tag{4}$$

Maximizing the expression given by (4) with respect to q_i gives the socially optimal production level with the polluting technology for each regulator $i = 1, 2$:

$$\hat{q}_{idd}^{a} = \frac{a - d - \alpha e}{2} \tag{5}$$

We assume the first inequality of the following condition to get positive production quantities. 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 (6):

$$d + \alpha e < a < 2d - c \tag{6}$$

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. With the polluting technology there are two market failures, which are monopoly and environmental externalities. As the levels of pollution and production are proportional, an emission-tax per-unit of pollution t_{idd}^{a} is sufficient to correct the two market failures and induce the socially optimal levels of production and pollution.

The instantaneous net profit of firm i is:

$$U_{idd}^{a}(q_i) = \Pi_{idd}^{a}(q_i) - t_{idd}^{a} E_i(q_i) \tag{7}$$

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

$$t_{idd}^{a} = \frac{a - d - 4\hat{q}_{idd}^{a}}{e} \tag{8}$$

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

$$t_{idd}^{a} > 0 \Longleftrightarrow a < d + 2\alpha e \tag{9}$$

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. Therefore, the emission-tax, which is used to correct monopoly and environmental externalities market failures, is positive when environmental externalities are high and is negative when environmental externalities are low.

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

$$S^a_{icc}(q_i) = CS^a_i(q_i) + \Pi^a_{icc}(q_i) \tag{10}$$

Maximizing the expression given by (10) with respect to q_i gives the socially optimal production level with the clean technology for regulator i:

$$\hat{q}^a_{icc} = \frac{a-c}{2} > 0 \tag{11}$$

We have $\hat{q}^a_{icc} > \hat{q}^a_{idd}$ because $d > c$. Therefore, the clean technology enables to produce more without polluting the environment.

With the clean technology, there is only one market failure (monopoly), which is corrected by a subsidy s^a_{icc} for each unit produced. This latter can be considered as a fiscal incentive to encourage the use of the clean technology. One may think about the production of electricity. A per-unit production subsidy can be given by a regulator when the production process is clean (using solar energy, for example). 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 sector.

This per-unit subsidy is chosen to induce the socially optimal level of production. Indeed, the instantaneous net profit of firms i is:

$$U^a_{icc}(q_i) = \Pi^a_{icc}(q_i) + s^a_{icc} q_i \tag{12}$$

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

$$s^a_{icc} = c - a + 4\hat{q}^a_{icc} > 0 \tag{13}$$

If we consider the case in which one of the two firms, for example firm 1, has adopted the clean technology, whereas firm 2 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 regulators 1 and 2 are:

$$S^a_{1cd}(q_1, q_2) = CS^a_1(q_1) + \Pi^a_{1cd}(q_1) - D_1(q_2), \tag{14}$$

$$S^a_{2cd}(q_1, q_2) = CS^a_2(q_2) + \Pi^a_{2cd}(q_2) - D_2(q_2) \tag{15}$$

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

$$\hat{q}^a_{1cd} = \frac{a-c}{2} > 0, \quad \hat{q}^a_{2cd} = \frac{a-d-\alpha e}{2} > 0 \tag{16}$$

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

Since $\hat{q}^a_{1cd} = \hat{q}^a_{1cc}$, regulator 1 can induce firm 1 to produce the socially optimal production quantity by an appropriate subsidy $s^a_{1cd} = s^a_{1cc}$. As $\hat{q}^a_{2cd} = \hat{q}^a_{2dd}$, a per-unit emission-tax $t^a_{2cd} = t^a_{2dd}$ is needed to induce firm 2 to produce the socially optimal quantity.

In the Appendix's subsection 6.1.2, we show that:

$$0 < S^a_{1cd} - S^a_{1dd} < U^a_{1cd} - U^a_{1dd} \tag{17}$$

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 firm than for its regulator, when a per-unit emission-tax and a production subsidy are used.*

Indeed, under autarky, because of the monopoly power, the instantaneous net profit of a firm is very high even when it uses the polluting technology. Moreover, when a firm adopts the clean technology, it no longer pays a pollution tax, receives production subsidies and its unit production cost decreases. This increases significantly its instantaneous net profit. The instantaneous social welfare level increases due to the absence of local environmental damage and the lower production cost. However, this increase in instantaneous social welfare is lower than the increase in instantaneous net profit.

2.2 Optimal adoption dates

In this section, we will determine the optimal adoption dates. We still suppose that, in case where firms adopt the clean technology 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 $\hat{q}^a_{1cd} = \hat{q}^a_{1cc}$ and $\hat{q}^a_{2cd} = \hat{q}^a_{2dd}$, then $U^a_{1cd} = U^a_{1cc}$ and $U^a_{2cd} = U^a_{2dd}$. This implies that the intertemporal net profit of firm i can be written as depending only on τ_i. However, as $S^a_{1cd} \neq S^a_{1cc}$ and $S^a_{2cd} \neq S^a_{2dd}$ because of crossborder pollution, the 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 firm chooses the optimal adoption date that maximizes its intertemporal net profit.

The intertemporal social welfare of regulators 1 and 2, and the intertemporal net profit of firm i are, respectively:

$$IS_1^a(\tau_1,\tau_2) = \int_0^{\tau_1} S_{1dd}^a e^{-rt}dt + \int_{\tau_1}^{\tau_2} S_{1cd}^a e^{-rt}dt + \int_{\tau_2}^{+\infty} S_{1cc}^a e^{-rt}dt - \theta e^{-mr\tau_1} \quad (18)$$

$$IS_2^a(\tau_1,\tau_2) = \int_0^{\tau_1} S_{2dd}^a e^{-rt}dt + \int_{\tau_1}^{\tau_2} S_{2cd}^a e^{-rt}dt + \int_{\tau_2}^{+\infty} S_{2cc}^a e^{-rt}dt - \theta e^{-mr\tau_2} \quad (19)$$

$$IU_i^a(\tau_i) = \int_0^{\tau_i} U_{idd}^a e^{-rt}dt + \int_{\tau_i}^{+\infty} U_{icc}^a e^{-rt}dt - \theta e^{-mr\tau_i} \quad (20)$$

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:[3]

$$0 < U_{icc}^a - U_{idd}^a < \theta mr \quad (21)$$

The above condition means that the cost of immediate adoption of the clean technology θ is sufficiently high. It prevents firms to immediately adopt (at date 0) the clean technology.

In the Appendix's subsection 6.1.3, we determine the optimal adoption dates which show that firms adopt the clean technology simultaneously:

$$\hat{\tau}^a = \frac{1}{(1-m)r} \ln\left(\frac{S_{1cd}^a - S_{1dd}^a}{\theta mr}\right) > 0 \quad (22)$$

$$\tau^{*a} = \frac{1}{(1-m)r} \ln\left(\frac{U_{icc}^a - U_{idd}^a}{\theta mr}\right) > 0 \quad (23)$$

Inequality (17) and the fact that $m > 1$, enable us to make the following ranking:

$$0 < \tau^{*a} < \hat{\tau}^a \quad (24)$$

We can state the following proposition:

Proposition 2 *Under autarky, the optimal adoption date for firms is earlier than socially optimal.*

The above proposition shows that socially optimal instantaneous regulation may not be dynamically optimal relatively to the adoption of clean technologies. This is due to the greater adoption incentives for firms compared to those for regulators, under autarky. This is clearly demonstrated by the inequalities in

[3]Notice that the left expression of (21) is independent of parameters θ, m and r.

(17). This result is similar to that established by Ben Youssef (2010) who used a model comprising one regulator and a monopolistic firm.

Paradoxically, to incite firms to delay their adoption to the socially optimal adoption date, regulators must compensate firms for the losses incurred. If the intertemporal net profits of 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:

$$\hat{g}^a = IU_i(\tau^{*a}) - IU_i(\hat{\tau}^a) > 0 \tag{25}$$

3 Common market

When markets are opened to international trade (competition), the inverse demand function of the perfect substitute goods produced by firms becomes $P = a - (q_i + q_j)$. The size of the common 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 consumers' surplus, minus damages plus the profit of the domestic firm:

$$S_i^{cm}(q_i, q_j) = CS_i^{cm}(q_i, q_j) - D_i(q_i, q_j) + \Pi_i^{cm}(q_i, q_j) \tag{26}$$

3.1 Instantaneous regulation

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

$$S_{idd}^{cm}(q_i, q_j) = CS_i^{cm}(q_i, q_j) + \Pi_{idd}^{cm}(q_i, q_j) - D_i(q_i, q_j) \tag{27}$$

Maximizing the expression given by (27) with respect to q_i gives the socially optimal production level with the polluting technology for regulator i:

$$\hat{q}_{idd}^{cm} = \frac{a - d - \alpha e}{2} > 0 \tag{28}$$

Since firm i constitutes a duopoly with firm j and produces 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:

$$U_{idd}^{cm}(q_i, q_j) = \Pi_{idd}^{cm}(q_i, q_j) - t_{idd}^{cm} E_i \tag{29}$$

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

$$t_{idd}^{cm} = \frac{a - d - 3\hat{q}_{idd}^{cm}}{e} > 0 \tag{30}$$

Therefore, under a common market, the emission-tax, which is used to correct duopoly and environmental externalities market failures, is always positive because the duopoly market failure is less important than the environmental externalities market failure.

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

$$S_{icc}^{cm}(q_i, q_j) = CS_i^{cm}(q_i, q_j) + \Pi_{icc}^{cm}(q_i, q_j) \tag{31}$$

Maximizing the expression given by (31) with respect to q_i gives the socially optimal production level with the clean technology for each regulator i:

$$\hat{q}_{icc}^{cm} = \frac{a - c}{2} > 0 \tag{32}$$

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:

$$U_{icc}^{cm}(q_i, q_j) = \Pi_{icc}^{cm}(q_i, q_j) + s_{icc}^{cm} q_i \tag{33}$$

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

$$s_{icc}^{cm} = 3\hat{q}_{icc}^{cm} + c - a > 0 \tag{34}$$

Considering that firm 1 has adopted the clean technology and firm 2 still produces using the polluting technology, the instantaneous social welfare of regulators 1 and 2 are, respectively:

$$S_{1cd}^{cm}(q_1, q_2) = CS_1^{cm}(q_1, q_2) - D_1(q_2) + \Pi_{1cd}^{cm}(q_1, q_2) \tag{35}$$

$$S_{2cd}^{cm}(q_1, q_2) = CS_2^{cm}(q_1, q_2) - D_2(q_2) + \Pi_{2cd}^{cm}(q_1, q_2) \tag{36}$$

Maximizing the expressions given by (35) and (36) respectively with respect to q_1 and q_2 gives:

$$\hat{q}^{cm}_{1cd} = \frac{2a + d - 3c + \alpha e}{4} > 0 \tag{37}$$

$$\hat{q}^{cm}_{2cd} = \frac{2a + c - 3d - 3\alpha e}{4} < 0 \tag{38}$$

Because of the second inequality of (6) and the first inequality of (1), $\hat{q}^{cm}_{2cd} < 0$. This suggests a boundary solution with $\hat{q}^{cm}_{2cd} = 0$. Thus, considering non-simultaneous adoption, will lead to one active firm and one inactive firm. This latter, will never choose non-simultaneous adoption, and the two firms will adopt simultaneously the clean technology. Let's notice that we have assumed the first inequality and the second inequality of conditions (1) and (6), respectively, 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 when adoption is non-simultaneous, their comparison is very difficult in the common market case. Moreover, studying the case of non-simultaneous adoption is not the principal focus of the present paper. Non-simultaneous adoption of new and less-costly production technologies has been extensively studied by the industrial organization literature (Reinganum 1981, Fudenberg and Tirole 1985, Hoppe 2000).

In the Appendix's subsection 6.2.2, we show that:

$$0 < U^{cm}_{icc} - U^{cm}_{idd} < S^{cm}_{icc} - S^{cm}_{idd} \tag{39}$$

These inequalities enable us to establish the following proposition:

Proposition 3 *Under a common market, the instantaneous gains from using the clean technology are greater for regulators than for firms, when a per-unit emission-tax and a production subsidy are used.*

The reasons explaining the benefit from the clean technology are the same than for the autarky case. However, when 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. This result is different from that obtained under autarky because the monopoly power induces that the instantaneous net profit of a firm is higher than under a common market where we have a duopoly. This holds whether firms use the polluting or the clean technology.[4]

3.2 Optimal adoption dates

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

[4]By using (7), (8), (12), (13), (29), (30), (33) and (34), we can easily verify that $\mathrm{U}^{a}_{idd} > \mathrm{U}^{cm}_{idd}$ and $\mathrm{U}^{a}_{icc} > \mathrm{U}^{cm}_{icc}$.

$$IS_i^{cm}(\tau) = \int_0^{\tau} S_{idd}^{cm} e^{-rt} dt + \int_{\tau}^{+\infty} S_{icc}^{cm} e^{-rt} dt - \theta e^{-mr\tau} \quad (40)$$

$$IU_i^{cm}(\tau) = \int_0^{\tau} U_{idd}^{cm} e^{-rt} dt + \int_{\tau}^{+\infty} U_{icc}^{cm} e^{-rt} dt - \theta e^{-mr\tau} \quad (41)$$

In the Appendix's subsection 6.2.3, we determine the socially optimal adoption date for regulators and the optimal adoption date for firms, which are respectively:

$$\hat{\tau}^{cm} = \frac{1}{(1-m)r} \ln\left(\frac{S_{icc}^{cm} - S_{idd}^{cm}}{\theta mr}\right) > 0 \quad (42)$$

$$\tau^{*cm} = \frac{1}{(1-m)r} \ln\left(\frac{U_{icc}^{cm} - U_{idd}^{cm}}{\theta mr}\right) > 0 \quad (43)$$

Inequality (39) and the assumption $m > 1$, enable us to make the following ranking:

$$0 < \hat{\tau}^{cm} < \tau^{*cm} \quad (44)$$

Thus, we can state the following proposition:

Proposition 4 *When markets are opened to competition, the socially optimal adoption date is earlier than the optimal adoption date for firms.*

The above proposition shows that, even in a common market, socially optimal instantaneous regulation may not be dynamically optimal relatively to the adoption of clean technologies. This is due to the fact that, under a common market, the incentives to adopt the clean technology are greater for regulators than for firms. This is clearly demonstrated by the inequalities in (39).

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

$$\hat{g}^{cm} = IU_i(\tau^{*cm}) - IU_i(\hat{\tau}^{cm}) > 0 \quad (45)$$

4 Autarky versus common market

Looking to expressions (22) and (42), we can show that:

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

The above expression relative to the autarky case does not comprise the parameter β explaining transboundary pollution. Thus, the socially optimal adoption date under autarky does not completely internalize transboundary pollution. However, the above expression relative to the common market case comprises the parameter β, and shows that, under a common market, the socially optimal adoption date internalizes transboundary pollution. This is due to the fact that our damage function is linear with respect to total pollution. Indeed, socially optimal productions do not completely internalize transboundary pollution.[5] This result is of great interest because this paper is the first attempt to link the adoption of clean technologies with transboundary pollution. Using a very different model than the present one, 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. Moreover, the investment in absorptive R&D help non-cooperating countries to better internalize transboundary pollution (Ben Youssef 2011). We can state the following proposition:

Proposition 5 *The socially optimal adoption date under a common market better internalizes transboundary pollution than that under autarky.*

Let us notice that if there is no transfrontier pollution between countries, i.e., $\beta = 0$, then from expressions (54) and (55), we deduce that the optimal adoption date for firms and the socially optimal adoption date coincide under a 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 firms. However, under autarky, the optimal adoption date for firms still remains earlier than that socially optimal because this latter does not internalize transboundary pollution.

The socially optimal productions are the same under the two market regimes ($\hat{q}^{cm}_{idd} = \hat{q}^{a}_{idd}$, $\hat{q}^{cm}_{icc} = \hat{q}^{a}_{icc}$) because they maximize the instantaneous social welfare independently whether firms compete or not. Competition between firms on the common market incites them to overproduce with the polluting technology compared to what is socially optimal, and this pushes regulators to increase their emission-tax ($t^{cm}_{idd} > t^{a}_{idd}$). With the clean technology and under autarky, the optimal production for firms is lower and very far from the socially optimal production, implying a great production subsidy; when markets are opened to

[5] 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. We think that our main analytical results will not change.

international competition, the optimal production for firms increases and the subsidy decreases ($s^a_{icc} > s^{cm}_{icc}$). These results are interesting 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. Our results are different because regulators look for first-best outcome. Ben Youssef (2009) found similar results with a different model in which regulatory instruments are a per-unit emission-tax and a per-unit R&D subsidy, and has showed that international trade increases the per-unit emission-tax and decreases the per-unit R&D subsidy.

Proposition 6 *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's subsection 6.3, we show that the instantaneous social welfare gain from using the clean technology is greater under a common market than under autarky. Thus, opening markets to international trade speeds up the socially optimal adoption date ($\hat{\tau}^{cm} < \hat{\tau}^a$). This is due to the fact that the socially optimal adoption date, under a common market, better internalizes transboundary pollution than that under autarky. Consequently, we have less flow of pollution with market opening.

Proposition 7 *International competition increases the instantaneous social welfare gain from using the clean technology, leading to an acceleration of the socially optimal adoption date and a reduction in the global flow of pollution.*

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.

Let us notice that if there is no transfrontier pollution between countries, i.e., $\beta = 0$, then from expressions (46) and (54), we deduce that the socially optimal adoption dates are the same under both market regimes ($\hat{\tau}^{cm} = \hat{\tau}^a$).

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. This clean technology uses renewable energy and therefore has a lower per-unit production cost. Non-cooperating regulators look for static and dynamic social optimalities. A per-unit emission-tax is used when a firm uses the polluting technology. A per-unit production subsidy, which can be considered as a fiscal incentive, is used when a firm uses the clean production technology. An adoption subsidy is used to induce the firm to adopt the clean technology at the socially optimal adoption date. We 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 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. These results are interesting because one may expect that, with market opening, each regulator is tempted to give a competitive advantage to its domestic firm by reducing the emission-tax and increasing the production subsidy.

In autarky both firms adopt the clean technology simultaneously due to our symmetric model. However, in a common market, because of the competition between firms, non-simultaneous adoption may occur. We impose conditions on the model's parameters to avoid the complicated case where firms adopt the clean technology at different dates, and we show that this adoption is simultaneous. Indeed, although the determination of optimal adoption dates is possible, their comparison is theoretically very difficult when adoption is not simultaneous.

Under autarky, the instantaneous gain from using the clean technology is greater for firms than for regulators. Consequently, firms adopt earlier than what is socially optimal. Therefore, in autarky, regulators 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 firms. Consequently, the socially optimal adoption date is earlier than the optimal adoption date for firms. Therefore, in a common market, regulators induce firms to adopt the clean technology at the socially optimal adoption date by giving them speed up adoption subsidies. Interestingly, the socially optimal adoption date under a common market better internalizes transboundary pollution than that under autarky.

Finally, the instantaneous social welfare benefit from the adoption of the clean technology is greater under a common market, implying an earlier socially optimal adoption date compared with that under autarky. Consequently, with market opening, we have less global flow of pollution.

Let us notice that some of our interesting results are not due to pollution and can be added to the rich literature relative to industrial organization which considered that the new technology is characterized by a lower per-unit production cost. However, some other important results are due to pollution and /or transboundary pollution: *i)* the comparison of the per-unit emission-taxes in the two market regimes, *ii)* the better internalization of transboundary pollution by the socially optimal adoption date under a common market, *iii)* the socially optimal adoption date is lower under a common market than under autarky. It is also lower compared with the optimal adoption date for firms.

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6 Appendix

6.1 Autarky

6.1.1 Instantaneous gains from using the clean technology

i) Social optimum

Using expressions (4) and (14): $S^a_{1cd} - S^a_{1dd} = [a - (\hat{q}^a_{1cd} + \hat{q}^a_{1dd}) - c] (\hat{q}^a_{1cd} - \hat{q}^a_{1dd}) + (d-c)\,\hat{q}^a_{1dd} + \alpha e \hat{q}^a_{1dd}$

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

$$S^a_{1cd} - S^a_{1dd} = \frac{d-c+\alpha e}{2} (\hat{q}^a_{1cd} + \hat{q}^a_{1dd}) > 0 \tag{46}$$

Using expressions (10) and (15): $S^a_{2cc} - S^a_{2cd} = [a - (\hat{q}^a_{2cd} + \hat{q}^a_{2cc}) - c] (\hat{q}^a_{2cc} - \hat{q}^a_{2cd}) + (d-c)\hat{q}^a_{2cd} + \alpha e \hat{q}^a_{2cd}$

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

$$S^a_{2cc} - S^a_{2cd} = \frac{d-c+\alpha e}{2} (\hat{q}^a_{2cd} + \hat{q}^a_{2cc}) > 0 \tag{47}$$

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

$$S^a_{1cd} - S^a_{1dd} = S^a_{2cc} - S^a_{2cd} \tag{48}$$

ii) Regulated firms

Since $\hat{q}^a_{icc} = \hat{q}^a_{1cd}$, then by using expressions (7) and (12):

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

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:

$$U^a_{1cd} - U^a_{1dd} = U^a_{icc} - U^a_{idd} = 2[(\hat{q}^a_{icc})^2 - (\hat{q}^a_{idd})^2] = (d-c+\alpha e)(\hat{q}^a_{icc} + \hat{q}^a_{idd}) > 0 \tag{49}$$

6.1.2 Comparison of instantaneous gains

Using expressions (49) and (46), we have:

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

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

$$0 < S^a_{1cd} - S^a_{1dd} < U^a_{1cd} - U^a_{1dd} \tag{50}$$

The instantaneous gain from using the clean technology is higher for the first adopter firm than for its regulator.

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) Regulated firms

Firm i maximizes its intertemporal net profit $IU^a_i(\tau_i)$ given by (20) with respect to τ_i:

$$\frac{\partial IU^a_i(\tau_i)}{\partial \tau_i} = \left(U^a_{idd} - U^a_{icc}\right) e^{-r\tau_i} + \theta m r e^{-mr\tau_i} = 0 \tag{51}$$

Equation (51) is equivalent to:

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

Because of $m > 1$ and condition (21), $\tau^{*a} > 0$.

We have: $\frac{\partial^2 IU^a_i(\tau_i)}{\partial \tau_i^2} = r\left(U^a_{icc} - U^a_{idd}\right) e^{-r\tau_i} - \theta(mr)^2 e^{-mr\tau_i}$.

Using the first-order condition given by (51), we get:

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

The second-order condition of optimality is verified.

ii) Social optimum

Each regulator maximizes his intertemporal social welfare function $IS^a_1(\tau_1, \tau_2)$ and $IS^a_2(\tau_1, \tau_2)$, given by (18) and (19), with respect to τ_1 and τ_2, respectively:

$$\frac{\partial IS^a_1(\tau_1, \tau_2)}{\partial \tau_1} = \left(S^a_{1dd}(\hat{q}^a_{1dd}) - S^a_{1cd}(\hat{q}^a_{1cd})\right) e^{-r\tau_1} + \theta m r e^{-mr\tau_1} = 0 \tag{52}$$

$$\frac{\partial IS^a_2(\tau_1, \tau_2)}{\partial \tau_2} = \left(S^a_{2cd}(\hat{q}^a_{2cd}) - S^a_{2cc}(\hat{q}^a_{2cc})\right) e^{-r\tau_2} + \theta m r e^{-mr\tau_2} = 0 \tag{53}$$

Equations (52) and (53) are respectively equivalent to:

$$\begin{aligned} S^a_{1dd}(\hat{q}^a_{1dd}) - S^a_{1cd}(\hat{q}^a_{1cd}) + \theta m r e^{(1-m)r\tau_1} &= 0 \Longleftrightarrow \hat{\tau}^a_1 = \frac{1}{(1-m)r} \ln\left(\frac{S^a_{1cd}(\hat{q}^a_{1cd}) - S^a_{1dd}(\hat{q}^a_{1dd})}{\theta m r}\right) \\ S^a_{2cd}(\hat{q}^a_{2cd}) - S^a_{2cc}(\hat{q}^a_{2cc}) + \theta m r e^{(1-m)r\tau_2} &= 0 \Longleftrightarrow \hat{\tau}^a_2 = \frac{1}{(1-m)r} \ln\left(\frac{S^a_{2cc}(\hat{q}^a_{2cc}) - S^a_{2cd}(\hat{q}^a_{2cd})}{\theta m r}\right) \end{aligned}$$

Because of $m > 1$, condition (21), inequalities (50), equalities (48) and (49), we get $\hat{\tau}_1^a > 0$ and $\hat{\tau}_2^a > 0$.

We have:

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

Using first-order conditions given by (52) and (53), we get:

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

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

Because of equality (48), we have: $\hat{\tau}_1^a = \hat{\tau}_2^a = \hat{\tau}^a$.

6.1.4 Comparison of adoption dates

Inequality (50), the fact that $U_{1cd}^a - U_{1dd}^a = U_{icc}^a - U_{idd}^a$ and $m > 1$, enable us to make the following ranking:

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

Under autarky, firms adopt earlier than what is socially optimal.

6.2 Common market

6.2.1 Instantaneous gains from using the clean technology

i) Social optimum

Using expressions (27) and (31):

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

By using the 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:

$$S_{icc}^{cm} - S_{idd}^{cm} = \frac{d-c+\alpha e}{2}(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) + \beta e\hat{q}_{idd}^{cm} > 0 \tag{54}$$

ii) Regulated firms

Using expressions (29) and (33):

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

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:

$$U_{icc}^{cm} - U_{idd}^{cm} = \frac{d-c+\alpha e}{2}(\hat{q}_{icc}^{cm} + \hat{q}_{idd}^{cm}) > 0 \tag{55}$$

6.2.2 Comparison of instantaneous gains

Using expressions (54) and (55), we obtain:
$S_{icc}^{cm} - S_{idd}^{cm} - (U_{icc}^{cm} - U_{idd}^{cm}) = \beta e \hat{q}_{idd}^{cm} > 0$
Thus, we have the following ranking:

$$0 < U_{icc}^{cm} - U_{idd}^{cm} < S_{icc}^{cm} - S_{idd}^{cm} \tag{56}$$

Under a common market, the instantaneous gain from using the clean technology is more important for regulators than for firms.

6.2.3 Optimal adoption dates

i) Regulated firms

Each firm i maximizes its intertemporal net profit $IU_i^{cm}(\tau)$ given by (41) with respect to τ :

$$\frac{\partial IU_i^{cm}(\tau)}{\partial \tau} = (U_{idd}^{cm} - U_{icc}^{cm})e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{57}$$

Equation (57) 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 (**??**) and (21), $\tau^{*cm} > 0$.
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 (57), 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.

ii) Social optimum

Each regulator i maximizes his intertemporal social welfare $IS_i^{cm}(\tau)$ given by (40) with respect to τ:

$$\frac{\partial IS_i^{cm}(\tau)}{\partial \tau} = (S_{idd}^{cm} - S_{icc}^{cm})e^{-r\tau} + \theta mre^{-mr\tau} = 0 \tag{58}$$

Equation (58) is equivalent to:

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

Using expressions (54) and (49), 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:

$$S_{icc}^{cm} - S_{idd}^{cm} < U_{icc}^{a} - U_{idd}^{a} \tag{59}$$

Because of $m > 1$, inequalities (59) and (21), $\hat{\tau}^{cm} > 0$.

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 (58), 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 (46) and (54), we show that:

$$S_{1cd}^{a} - S_{1dd}^{a} < S_{icc}^{cm} - S_{idd}^{cm} \tag{60}$$

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

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