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The Environmental Porter Hypothesis as a Technology Adoption Problem?

Ben Kriechel* & Thomas Ziesemer†

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Abstract

The Porter Hypothesis postulates that the costs of compliance with environmental standards may be partially or even fully offset by adoption of innovations they trigger. The timing of the adoption aspect of the Porter Hypothesis has not been captured in formal theory so far. We show in this paper how the Porter Hypothesis can be approached using a model of technology adoption. In the Reinganum-Fudenberg-Tirole game of timing, a firm adopts earlier under stricter environmental taxation, and under some circumstances can credibly precommit to early adoption. We show that all times of adoption — preemption, following and joint late adoption — are earlier the higher the non-adoption tax. Under preemption the firm of the country that varies environmental taxes will adopt first with certainty indicating increased competitiveness, but get lower profits than without environmental policy. Thus the Porter Hypothesis of increasing overall profits is rejected.

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The environmental Porter Hypothesis suggests (see Porter and van der Linde, 1995) that the costs of compliance with environmental standards may be partially or even fully offset by innovations they trigger and this may even lead to absolute advantages over foreign competitors. While the general fear of trade economist was rather one of ecological dumping rather than increased environmental regulation to improve competitiveness, the article was greeted with skepticism. Nevertheless, it led economists to think seriously about the gist of the Porter Hypothesis: Is it possible that firms could gain advantage over their foreign rivals through tougher environmental regulation? While classical trade theory offers no reason to believe in the Porter Hypothesis, imperfect competition models were considered promising to find some theoretical foundations to the case study and anecdotal evidence offered by Porter and van der Linde.

Ulph (1996a) constructs a Brander-Spencer type of strategic trade model with Cournot competition. Firms can invest in technology affecting variable costs but not the accompanying pollution. He shows that the strategic interaction between producers reduces the government's incentive to loosen environmental regulation. He concludes, though, that the reduction of pollution with the lowering of the variable costs could change that result. This is the avenue that Simpson and Bradford (1996) pick up. They model the firms in a similar fashion, with the exception that R&D not only lowers marginal costs, but also the emission of the pollutant. The government uses effluent taxation to maximize the domestics firm's profits net of the environmental externalities of production. The government is able to force the firm into a Stackelberg-leader position relative to its foreign competitor. For some special cases of specifications and numerical parameter values they are able to construct a strengthening of regulation resulting in a shift of profits from foreign to domestic firms. However, they stress that this is not a general result and it is unlikely, that environmental regulation should be used as a policy device to induce industrial advantage.

Feess and Taistra (2001) model a two-period game with Cournot competition. The environmentally friendly technology is assumed to lead to a decrease of unit costs in the second period, however not in a way that reduces overall costs. Policy agencies of the foreign nation are assumed to stochastically imitate the national environmental regulation.

Bertrand-type imperfect competition models were introduced in the context of strategic environmental trade policy in the paper by Barrett (1994). In the context of cost saving research Ulph (1996b) shows both for environmental taxation and for environmental standards that firms can benefit from tighter regulation if only the governments act strategically, but firms do not.

Principal-agent models of the Porter Hypothesis are set in the context of organizational inefficiencies. In this model type incentives between principal and agent over the choice of projects are miss-aligned. Environmental regulation helps to re-align the preferences of principal and agent, hence increases the efficiency of the firm (see for example Schmutzler (2001) and Klein and Rothfels (1999)). Ambec and Barla (2002) show that, by reducing agency costs, an environmental regulation may enhance pollution-reducing innovation while at the same time increasing firms' private benefit.

Other specifications are e.g. Mohr (2002): he uses a general equilibrium framework with a large number of agents, external economies of scale in production, and discrete changes in technology. As new technologies are modelled with an industry learning curve, firms are stuck in a non-innovating equilibrium, initially. Environmental regulation enforces the adoption of 'new technology', hence allowing for subsequent learning.

Related is Hübner (2001). Using a duopoly model of a patent race, she shows that stricter environmental policy might increase the probability of a sleeping patent instead of encouraging environmental technological progress, but the reversed case is also possible: environmental policy may activate otherwise sleeping patents.

Empirical support for the Hypothesis is based on case study evidence (see Ayres (1994) Porter and van der Linde (1995)). Palmer, Oates and Portney (1995) provide empirical arguments explaining why full offsets are rather unlikely. They base their argument on information provided by entrepreneurs. A problem with both of these types of information provision is that the costs of innovation precede the returns and the returns are often stretched out over decades. Jaffe and Palmer (1997) critically evaluate the Porter Hypothesis, they attempt to empirically 'test' the Hypothesis, but find no evidence supporting it. This empirical evaluation is based on the link between the stringency of environmental regulation and R&D, but not on adoption.

Our approach differs from earlier approaches to capture the Porter Hypothesis in that we explicitly model the timing choice of both the home and foreign firm based on asymmetries in environmental taxation (regulation). The timing of adoption aspect of the Porter Hypothesis has not been captured in formal theory so far. We try to make a first attempt in this paper using the model of technology adoption of Reinganum (1981), Fudenberg and

Tirole (1985, 1987) and Tirole (1988, Chapter 10).

We will commence by using a pedagogic 'basic model' which emphasizes a crucial point we want to make: environmental policy may destroy or shorten an non-adoption equilibrium. It explains why it may be rational not to adopt, although no opportunities are overlooked. In the second section we give a profit-maximizing version of the Porter problem using a Hotelling framework. In the third section we use a model of a game of timing with a case of higher environmental taxes creating precommitment and decreasing profits providing a model of the Porter Hypothesis and a case of low environmental taxes creating the domestic firm's preemption position, but leading to lower profits as well. Thus, the Porter Hypothesis is rejected in as far as the claim is one of increasing overall profits.

1 Basic Idea: Environmental Policy Destroying Non-Adoption Equilibria

In this first part of the section we will only consider a duopoly case on a national market. Thus we assume away the effect of international competition and competitiveness to get expositional clarity. In a further step we will then consider effects of an international duopoly when firms face *different* national environmental regulation.

As in Tirole (1988, Chapter 10) we consider a process innovation that can be adopted at some cost, C, which is constant over time. It is assumed that $1 < C < (1 + r)/r$, where r is the per-period rate of interest. If none of two

Table 1: Payoff with old and new technology

Firm 1 ↓ \ Firm 2 →	New	Old
New	$\frac{(1+r)\Pi}{r} - C, \frac{(1+r)\Pi}{r} - C$	$\frac{(1+r)(\Pi+1)}{r} - C, \frac{(1+r)(\Pi-1)}{r}$
Old	$\frac{(1+r)(\Pi-1)}{r}, \frac{(1+r)(\Pi+1)}{r} - C$	$\frac{(1+r)\Pi}{r}, \frac{(1+r)\Pi}{r}$

firms adopts, the flow rent for both is $\Pi > 1$. If only one firm adopts it gets $\Pi + 1$ and the other gets $\Pi - 1$. Thus, the innovation merely transfers profits. If both firms adopt they both receive Π again. The additional flow profit of adoption when the other firm has already adopted is $1 > rC/(1+r)$. The interest on the adoption cost or net present value of the rent of adoption is $(1+r)/r > C$. Therefore an adopting firm whose action can be observed immediately will be followed by the other firm. This makes adoption for the first firm, anticipating the second adoption, unprofitable. Because of the perfect observation and reaction possibilities each firm can afford to wait and resist the temptation of adoption profit, $\Pi + 1$, which will vanish immediately after the competitors adoption anyway. In a pay-off bi-matrix the net present values of profits from adopting new or sticking to old technologies are summarized in Table 1.

Adoption of both is also an equilibrium but one with worse results than no adoption because adoption is costly. As both firms have the old technology in the beginning and both can anticipate that adoption would be followed

Table 2: Payoff with environmental taxes

Firm 1 ↓ \ Firm 2 →	New	Old
New	$\frac{(1+r)\Pi}{r} - C, \frac{(1+r)\Pi}{r} - C$	$\frac{(1+r)(\Pi+1)}{r} - C, \frac{(1+r)(\Pi-1)}{r} - T$
Old	$\frac{(1+r)(\Pi-1)}{r} - T, \frac{(1+r)(\Pi+1)}{r} - C$	$\frac{(1+r)\Pi}{r} - T, \frac{(1+r)\Pi}{r} - T$

immediately by adoption of the competitor, first adoption is self-damaging. No adoption for both is therefore the superior equilibrium for the two firms (See Tirole 1988 and Fudenberg and Tirole 1987).

Given that the new technology is not only more cost efficient, but also cleaner by assumption, the equilibrium is inferior from the consumers' point of view. "New/New" will only be an equilibrium if firms cannot observe competitors action and therefore prefer to preempt. This case of imperfect information will, however, not be considered here.

Next, suppose we have homogenous goods independent of the production technology. However, the new technology produces the good without pollution while the old one is dirty. The government punishes non-adoption with an environmental tax, T. Profits and costs are unchanged otherwise. Then, the pay-off bi-matrix changes into the one given in Table 2.

Clearly, if the environmental tax is high enough, it does not pay anymore for the two firms to stay in the non-adoption equilibrium. Formally, if $T > C$, adoption becomes profitable even disregarding the action of the other duopolist. Both adopt the new, clean technology. Without the tax, the

Table 3: International case with unilateral taxes

Firm 1 ↓ \ Firm 2 →	New	Old
New	$\frac{(1+r)\Pi}{r} - C, \frac{(1+r)\Pi}{r} - C$	$\frac{(1+r)(\Pi+1)}{r} - C, \frac{(1+r)(\Pi-1)}{r}$
Old	$\frac{(1+r)(\Pi-1)}{r} - T, \frac{(1+r)(\Pi+1)}{r} - C$	$\frac{(1+r)\Pi}{r} - T, \frac{(1+r)\Pi}{r}$

technology would never have been adopted (see Table 1).

Proposition 1.1 *Sufficiently high environmental taxes can force firms out of a non-adoption equilibrium.*

However, this argumentation so far falls short of the Porter Hypothesis in the original, strong sense which (also) implies a competitive advantage for the nation that introduces the environmental regulation. Let us assume free trade, so there is no tariff protection, and that the home country, believing in the Porter Hypothesis introduces the environmental tax or regulation at cost T. Firm 1 is located in 'Home', while firm 2 is located in 'Foreign', competing on a third market without transport costs or tariffs. Foreign does not introduce any regulation, hence the pay-out matrix looks like Table 3.

We will now derive the conditions the tax has to fulfill, in order to be effective, and also examine the effect of the tax in terms of the Porter Hypothesis. Firm 1 will adopt the new technology if the net pay-off from adopting is higher than from non-adopting. Let us examine separately the cases for a foreign firm 2 following adoption, and for a foreign firm 2 that will not adopt. Let us assume for the moment that foreign firm 2 will not adopt at all, then the best strategy for firm 1 is to adopt if:

$$\frac{(1+r)(\Pi+1)}{r} - C > \frac{(1+r)\Pi}{r} - T$$

Subtracting $\frac{\Pi(1+r)}{r}$ on both sides yields

$$\frac{(1+r)}{r} > C - T$$

and after division by $1+r$:

$$\frac{C-T}{1+r} < \frac{1}{r} \tag{1.1}$$

For $C < (1+r)/r$, as assumed above, this holds for any $T \geq 0$. This last condition states that the discounted cost minus tax should be smaller than the discounted (infinite) stream of future extra profits of the new technology (set to be equal to one in the Tirole set-up used here). However, the equation above is derived under the condition that it is not profitable for firm 2 to adopt — after all that is the case of competitive advantage even if $T = 0$. Thus the following condition should also be fulfilled. The foreign firm 2 will not adopt as long as the costs of adoption are higher than regaining the 'symmetric' adoption equilibrium:

$$\frac{(1+r)(\Pi-1)}{r} \geq \frac{(1+r)\Pi}{r} - C$$

Cancellation of the Π term yields:

$$\frac{C}{1+r} \geq \frac{1}{r} \tag{1.2}$$

This contradicts the basic assumption that

$$\frac{1+r}{r} > C > 1.$$

Hence, firm 2 will follow immediately.

Proposition 1.2 *If only one country imposes an environmental tax, non-adoption is no longer an equilibrium and both firms adopt the new technology immediately. The home firm — in contrast to the Porter Hypothesis — has no advantage.*

We will show below in a profit maximizing setting that this result is modified if adoption is delayed because later adoption is cheaper.

2 An Application to the Hotelling model

The basic idea of the previous section can easily be carried out in the Hotelling framework. In the model households are located on the unit interval [0,1] and firm 1, located at zero, has market share x and firm 2, located at point 1 of the interval, has market share $1-x$. Household x has transport cost xt if he buys from firm 1 and $(1-x)t$ if he buys from firm 2. He is indifferent between buying from any of the two firms if he has equal utility net of costs from both. A firm that does innovate offers additional utility Δs. Indicating adoption by $\delta_{1,2} = 1$ and non-adoption by $\delta_{1,2} = 0$, equality of costs net of additional utility of household x from buying from any of the two firms can be written as follows:

$$p_1 - \delta_1 \Delta s + tx = p_2 - \delta_2 \Delta s + t(1-x)$$

Table 4: Payoff matrix for Hotelling game: both firms taxed

Firm 1 $\downarrow$ \ Firm 2 $\longrightarrow$	new	old
new	$t/2 - \frac{rC}{1+r}, t/2 - \frac{rC}{1+r}$	$\frac{(t+\Delta s/3)^2}{2t-\frac{rC}{(1+r)}}, \frac{(t-\Delta s/3)^2}{2t-\tau}$
old	$\frac{(t-\Delta s/3)^2}{2t-\tau}, \frac{(t+\Delta s/3)^2}{2t-\frac{rC}{(1+r)}}$	$\frac{t}{2} - \tau, \frac{t}{2} - \tau$

Solving for x and $(1-x)$ respectively yields

$$x = [p_2 - p_1 + t - (\delta_2 - \delta_1)\Delta s]/2t \text{ and } 1 - x = [p_1 - p_2 + t + (\delta_2 - \delta_1)\Delta s]/2t$$

Taxes, τ, for non-adoption appear in a lump-sum fashion in the flow of profits of the firms where c denotes constant unit costs:

$$\Pi_i = (p_i - c)[p_j - p_i - (\delta_j - \delta_i)\Delta s + t] - (1 - \delta_i)\tau$$

Obviously, taxes do not appear in the first-order conditions of profit maximization of firms with respect to p_i, and therefore they do not appear in the reaction functions. Calculation of reaction functions, equilibrium prices and profits (see Tirole 1988, Chapter 7) yields flows of profits as summarized in Table 4.

Comparing this pay-off matrix for flow profits with that of section 2 for discounted present values shows that the relation between flow and total taxes is $T = (1 + r)\tau/r$. If $\tau > rC(1 + r)$, it is clearly better for firms to adopt.

Proposition 2.1 *Firms adopt in the Hotelling framework if the environmental tax τ is sufficiently high, i.e. $\tau > rC(1 + r)$, which yields a higher*

Table 5: Payoff matrix for Hotelling game: sales tax paid by producers

Firm 1 $\downarrow$ \ Firm 2 $\longrightarrow$	new	old
new	$t/2, t/2$	$\frac{(t+(\Delta s+\tau)/3)^2}{2t}, \frac{(t-(\Delta s+\tau)/3)^2}{2t}$
old	$\frac{(t-(\Delta s+\tau)/3)^2}{2t}, \frac{(t+(\Delta s+\tau)/3)^2}{2t}$	$t/2, t/2$

profit than non-adoption.

It may be interesting to note that other tax measures can easily fail to give an incentive for adoption. An exemption from a specific consumption tax in case of adoption ($\delta_1 = 1$), for example, leads to the following indifference condition for consumer x:

$$p_1 + (1–\delta_1)\tau - \delta_1\Delta s + tx = p_2 + (1 - \delta_2)\tau - \delta_2\Delta s + t(1 - x).$$

If both firms take the same decision, the tax term drops out in all following steps of the analysis and therefore will have no impact on the diagonal elements of the pay-off matrix. The tax exemption thus fails to provide an incentive for adoption. Next, consider an exemption from a specific sales tax paid by producers. The indifference condition is unaffected but profits are affected. The definition of profit becomes

$$\Pi_i = [p_i - (1 - \delta_i)\tau - c][p_j - p_i - (\delta_j - \delta_i)\Delta s + t]$$

Successive calculation of first-order conditions, reaction functions, equilibrium prices and profits yields the flow of profits (gross of adoption costs) given in Table 5.

Proposition 2.2 *Exemptions from consumer taxes fail to provide an incen-*

tive for adoption. An exemption from specific sales taxes on producers has an impact only in the cases of asymmetric adoption behaviour. However, asymmetric adoption behaviour is not an equilibrium outcome.

Next, consider an ad valorem sales tax exemption for firms. Profits are redefined to be

$$\Pi_i = \{p_i[1 + (1 - \delta_i)\tau] - c\}[p_j - p_i - (\delta_j - \delta_i)\Delta s + t]$$

First-order conditions can be written as

$$[1 + (1 - \delta_i)\tau][p_j - p_i - (\delta_j - \delta_i)\Delta s + t] - \{p_i[1 + (1 - \delta_i)\tau] - c\} = 0$$

Dividing this equation by $[1 + (1 - \delta_i)\tau]$ yields

$$[p_j - p_i - (\delta_j - \delta_i)\Delta s + t] - \{p_i - c/[1 + (1 - \delta_i)\tau]\} = 0$$

The production-cost term, c, did never appear in the pay-off matrix in all the cases discussed so far. Therefore the tax term will also vanish with it in this case if (non)-adoption behaviour is symmetric. This leads us to the following proposition:

Proposition 2.3 *Exemption from ad-valorem producer taxes do not affect the non-adoption equilibrium.*

All of these examples from the Hotelling model confirm a well known lesson: a tax policy must approach the problem directly. The difference with other tax and tariff lessons is that the incentive effect of x-best measures are in many other cases not zero as they are here (Bhagwati and Srinivasan 1983). Proposing indirect taxation measures for policy purposes then is tantamount to supporting the decision of the firms to avoid adoption. Therefore the definition of environmental policies which clarifies when a tax has to be paid is crucial.

3 Environmental taxes in a game of timing

In the models of the previous sections firms either both adopt or not at all even if only one country raises a tax. A less extreme distinction can be considered in a model where firms either adopt earlier or later. Reinganum (1981) and the extension by Fudenberg and Tirole (1985) provide such a model. Here we restate their model for the case of two firms and introduce an environmental non-adoption tax, τ. We show that all times of adoption — preemption, following and joint late adoption — are earlier the higher the adoption tax. Moreover, a high environmental tax ensures a precommitment position for the domestic firm but decreases profits. A low environmental tax ensures preemptive position of the domestic firm, also with lower profits.

3.1 Games of Timing: National Case

Let $\pi_0(0)$ - τ denote after-tax profits of a firm if no firm has yet adopted. $\pi_0(1)$ - τ denotes after-tax profits of a firm if only the other firm has adopted. $\pi_1(1)$ is the profit of a firm which has adopted but the other firm has not. $\pi_1(2)$ is the profit of a firm if both have adopted.[1]

There is a cost $c(t)$ associated with adoption, where c is a function of time such that early adoption is more costly ($c' < 0$). Using index 2 for the firm that is second to adopt, the follower, and index 1 for the leader, the value of the firms with adoption times T_1 and T_2 can be written as follows (the first T on the LHS denotes the firms own adoption time, the second the other firms adoption time):

[1] The number in brackets is the number of firms that has adopted: 0, 1, or 2. The lower index 1 (0) indicates that a firm has (not) adopted.

$$V^1(T_1,T_2) = \int_0^{T_1} [\pi_0(0) - \tau] e^{-rt} dt + \int_{T_1}^{T_2} \pi_1(1) e^{-rt} dt + \int_{T_2}^{\infty} [\pi_1(2)] e^{-rt} dt - c(T_1)$$

$$V^2(T_2,T_1) = \int_0^{T_1} [\pi_0(0) - \tau] e^{-rt} dt + \int_{T_1}^{T_2} [\pi_0(1) - \tau] e^{-rt} dt + \int_{T_2}^{\infty} \pi_1(2) e^{-rt} dt - c(T_2)$$

Firms only differ in two aspects. First, in the second phase firm 1 has adopted and firm 2 has not. Second, the present value of the cost of adoption, c, at different points in time are different. Assumptions made on the magnitude of the profit and cost items are the following:

1. There are decreasing returns in the rank of adoption: $\pi_1(1) > \pi_1(2)$.
2. The difference in profits from adoption, at time zero, is not larger than the decrease in the costs of adopting while waiting: $\pi_1(1) - [\pi_0(1) - \tau] \leq -c'(0)$ for all $\tau \geq 0$. Therefore immediate adoption is not profitable unless the equality part of the equation holds.
3. Second adoption always becomes profitable after some time: $\inf_t\{c(t)e^{rt}\} < \{\pi_1(2) - [\pi_0(1) - \tau]\}/r$ for all $\tau \geq 0$.
4. Current costs of adoption are falling but decreasingly so: for all t, $(c(t)e^{rt})' < 0$, $(c(t)e^{rt})'' > 0$.

If there is a precommitment on the order of adoption, the optimal adoption time for the leader, T_1, can be found from the first-order condition

$$dV^1/dT_1 = [\pi_0(0) - \tau]e^{-rT_1} - \pi_1(1)e^{-rT_1} - c'(T_1) = 0 \tag{3.1}$$

The optimal adoption time for the follower in case of a precommitment can be found from the first-order condition

$$dV^2/dT_2 = [\pi_0(1) - \tau]e^{-rT_2} - \pi_1(2)e^{-rT_2} - c'(T_2) = 0. \tag{3.2}$$

If the leader has already adopted, the second of the two equations determines the followers optimal time, T_2^*, — with and without precommitment — and allows us to calculate the impact of the environmental tax on the followers optimal adoption time. The result is:

$$\frac{dT_2^*}{d\tau} = -\frac{-e^{-rT_2}}{[\pi_0(1) - \tau](-r)e^{-rT_2} + r\pi_1(2)e^{-rT_2} - c''(T_2)} = -\frac{-e^{-rT_2}}{-rc'(T_2) - c''(T_2)} < 0 \tag{3.3}$$

The second equation has been obtained by insertion of c' from equation 3.2. Assumption (4) implies that the denominator, which is also the second-order condition of equation 3.2, has a negative sign.

The dependence of timing of the leader upon the environmental tax can be derived in a similar fashion:

$$\frac{dT_1^*}{d\tau} = -\frac{-e^{-rT_1}}{[\pi_0(0)-\tau](-r)e^{-rT_1} + r\pi_1(1)e^{-rT_1} - c''(T_1)} = -\frac{-e^{-rT_1}}{-rc'(T_1) - c''(T_1)} < 0 \tag{3.4}$$

This leads us to the following proposition:

Proposition 3.1 *The leader and the follower adopt earlier under precommitment if the environmental tax is larger.*

If there is no precommitment on the order of adoption, firms may be interested in preemption. The timing of preemption can be found as follows. The leader's payoff if she succeeds in preempting at time t is

$$L(t) = \begin{cases} V(t, T_2^*) \text{ if } t < T_2^* \\ V(t, t) \text{ if } t \geq T_2^* \end{cases}$$

The followers payoff if he is preempted at time t is:

$$F(t) = \begin{cases} V(T_2^*, t) \text{ if } t < T_2^* \\ V(t, t) \text{ if } t \geq T_2^* \end{cases}$$

If both firms adopt together the payoff for each firm is $M(T) = V(t, t)$.

If $t < T_2^*$, $L(t) > M(t)$ and $F(t) > M(t)$. Using the above definitions as in equations 3.1 and 3.2 one finds that

$$[L(t) - F(t)]' = -\pi_1(1)e^{-rT_1} - c'(T_1) + [\pi_0(1) - \tau]e^{-rT_1} = 0 \tag{3.5}$$

$$[L(t) - F(t)]'' = -rc' - c'' < 0 \tag{3.6}$$

because of assumption (4). As $L(t) - F(t)$ has a maximum, each firm would like to preempt the other. As in Fudenberg and Tirole (1985) , $L(0) < F(0)$ from assumption (2) and $L(T_2^*) = F(T_2^*)$ from the definitions of L and F and $L(T_1^*) > F(T_1^*)$ from $V^1(T_1^*, T_2^*) > V^2(T_2^*, T_1^*)$ under precommitment. Together with the monotonicity of the value functions this information implies that there must be a point in time, T_1, at which $L(T_1) = F(T_1)$ (cf. Fudenberg and Tirole, 1985, p. 386). This is the first profitable point in time for preemption. Equating the values of the firms, $V^{1,2}$, for this point in time yields

$$L(T_1) - F(T_1) = \int_{T_1}^{T_2} \pi_1(1) e^{-rt} dt - c(T_1) - \left\{ \int_{T_1}^{T_2} [\pi_0(1) - \tau] e^{-rt} dt - c(T_2) \right\} = 0 \tag{3.7}$$

Proposition 3.2 *Under preemption, the timing of preemptive adoption will be earlier if the environmental tax is higher.*

This follows from equation 3.7 which implies:

$$\frac{dT_1}{d\tau} = -\frac{\int_{T_1}^{T_2} e^{-rt} dt}{-\pi_1(1)e^{-rT_1} + [\pi_0(1) - \tau]e^{-rT_1} - c'(T_1)} < 0.$$

Now suppose that there is joint late adoption and therefore
$M = V^1 = V^2$. Insertion of the value functions given above for $T_1 = T_2$ yields

$$M = V^{1,2}(T_2, T_1) = \int_0^{T_1} [\pi_0(0) - \tau] e^{-rt} dt + \int_{T_2}^{\infty} \pi_1(2) e^{-rt} dt - c(T_2)$$

The optimal joint adoption time is found by maximization of M with respect to $T = T_1 = T_2$. The first order condition is

$$\frac{dM}{dT} = [\pi_0(0) - \tau] e^{-rT} - \pi_1(2) e^{-rT} - c'(T) = 0$$

From this we can calculate the impact of an increase in the environmental tax on the timing of joint adoption:

$$\frac{dT}{d\tau} = -\frac{-e^{-rT}}{-r[\pi_0(0) - \tau] e^{-rT} + r\pi_1(2) e^{-rT} - c''(T)} < 0$$

Proposition 3.3 *Joint late adoption takes place earlier under a higher environmental tax.*

3.2 Games of Timing: International Case

Now let us suppose that the environmental regulation is again one-sided. The firms are located in different countries and — as in section 1 — are competing in a third market.

Table 6 summarizes the payoff for the firms. Now $\pi_0(0) - \tau$ are after-tax profits of the home firm and $\pi_0(0)$ for the foreign firm if no firm has yet adopted. $\pi_0(1) - \tau$ are after-tax profits of the home firm if only the foreign firm has adopted and $\pi_0(1)$ for the foreign firm. $\pi_1(1)$ is the profit of the home firm which has adopted but the other, foreign firm has not. $\pi_1(2)$ is

Table 6: Payoff in the game of timing

		Foreign	
		lead	follow
Home	lead	(L^h, L^f)	(L^h, F^f)
	follow	(F^h, L^f)	(F^h, F^f)

the profit of either firm if both have adopted. We use upper indices 'h' and 'f' for home and foreign respectively. Let us first examine the case in which the home firm is precommitted to be the follower. In this case:

$$F^h \equiv V_F^h(T_2^h, T_1^f) = \int_0^{T_1^f} [\pi_0(0)-\tau]e^{-rt}dt + \int_{T_1^f}^{T_2^h} [\pi_0(1)-\tau]e^{-rt}dt + \int_{T_2^h}^{\infty} \pi_1(2)e^{-rt}dt - c(T_2^h) \tag{3.8}$$

And for the foreign, precommitted leader, we have:

$$L^f \equiv V_L^f(T_1^f, T_2^h) = \int_0^{T_1^f} \pi_0(0)e^{-rt}dt + \int_{T_1^f}^{T_2^h} \pi_1(1)e^{-rt}dt + \int_{T_2^h}^{\infty} \pi_1(2)e^{-rt}dt - c(T_1^f) \tag{3.9}$$

Given that home follows, we can determine the optimal adoption time:

$$T_2^h : \frac{\partial V_F^h}{\partial T_2} = [\pi_0(1) - \tau]e^{-rT_2^H} - \pi_1(2)e^{-rT_2^H} - c'(T_2^H) = 0 \tag{3.10}$$

We can see that $T_2^H(r, \tau)$ is independent of T_1. Further, $\frac{\partial T_2^H}{\partial \tau} < 0$. Hence we can state that:

Proposition 3.4 *Home, as the follower, adopts earlier if the environmental* *tax is larger, decreasing the time that a foreign firm can reap the benefits of early adoption.*

Examining the impact of the environmental tax, τ, on the timing of the foreign leader we find:

$$T_1^f : \frac{\partial V_L^f}{\partial T_1^f} = \pi_0(0)e^{-rT_1^f} - \pi_1(1)e^{-rT_1^f} - c'(T_1^f) = 0 \tag{3.11}$$

Hence, T_1^f is independent of τ and T_2^H. The timing of foreign leadership is not affected by the tax τ imposed by the home government.

Let us now turn to the case in which home is precommitted leader and foreign is follower:

$$F^f \equiv V_F^f(T_2^f, T_1^h) = \int_0^{T_1^h} \pi_0(0)e^{-rt}dt + \int_{T_1^h}^{T_2^f} \pi_0(1)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_2^f) \tag{3.12}$$

$$L^h \equiv V_L^h(T_1^h, T_2^f) = \int_0^{T_1^h} [\pi_0(0) - \tau]e^{-rt}dt + \int_{T_1^h}^{T_2^f} \pi_1(1)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_1^h) \tag{3.13}$$

Again, we can determine the optimal timing of T_2, given that foreign is committed to follow.

$$T_2^f : \frac{\partial V_F^f}{\partial T_2^f} = \pi_0(1)e^{-rT_2^f} - \pi_1(2)e^{-rT_2^f} - c'(T_2^f) = 0 \tag{3.14}$$

Once more, the timing of the foreign firm's adoption, here T_2^f, is independent

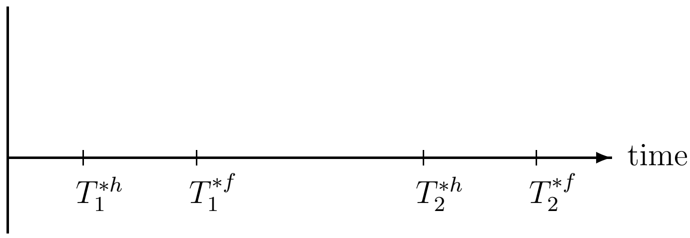


Figure 1: Timing of adoption under precommitment

of τ, but also of the timing of early adoption T_1^h. Further note that, $T_2^H < T_2^f$, because 3.10 and 3.14 differ only by τ in 3.10.

For the timing of home, as the precommitted leader, we get:

$$T_1^h : \frac{\partial V_L^h}{\partial T_1^h} = [\pi_0(0) - \tau]e^{-rT_1^h} - \pi_1(1)e^{-rT_1^h} - c'(T_1^h) = 0 \tag{3.15}$$

Note that the time of adoption is earlier the higher the environmental tax: $\frac{\partial T_1^h}{\partial \tau} < 0$. Home, as a leader, adopts faster than foreign as a leader, i.e. $T_1^h < T_1^f$ because of 3.11 and 3.15.

Proposition 3.5 *Foreign adopts slower — given that the environmental tax is smaller or equal to zero — than the home firm both as leader and follower*

Returns to Leadership and Following

We have shown above, that — under precommitment — home adopts earlier than the foreign firm, both as a leader and as a follower. Hence, we can order all timing of adoption in the following way: $T_1^h < T_1^f < T_2^h < T_2^f$, which is also depicted in Figure 1.

Table 7: Preferences of the Firm

		Foreign lead	Foreign follow
Home	lead	$L^h - F^h > 0$, $L^f - F^f > 0$	$L^h - F^h > 0$, $L^f - F^f < 0$
	follow	$L^h - F^h < 0$, $L^f - F^f > 0$	$L^h - F^h < 0$, $L^f - F^f < 0$

We have to make sure, though, that the firms actually want to be leader or follower. In order to examine this we have to examine the difference between leadership returns L and follower returns F. Table 7 summarizes the payoff, which will be specified below. Home would like to lead if $L^h - F^h \geq 0$ and follow otherwise. Subtracting the maximized value of 3.8 from 3.13 yields (see Appendix):

$$\begin{aligned} L^{*h} - F^{*h} \;=\; & \int_{T_1^{*h}(\tau)}^{T_1^{*f}} [\pi_1(1) - \pi_0(0) + \tau] e^{-rt} dt + \int_{T_1^{*f}}^{T_2^{*h}(\tau)} [\pi_1(1) - \pi_0(1) + \tau] e^{-rt} dt \\ & + \int_{T_2^{*h}(\tau)}^{T_2^{*f}} [\pi_1(1) - \pi_1(2)] e^{-rt} dt - \left[c(T_1^{*h}(\tau)) - c(T_2^{*h}(\tau)) \right] \end{aligned} \tag{3.16}$$

3.2.1 Preemption

Home will try to preempt as long as $L^{*h} - F^{*h} > 0$ and being the leader at the preemption time T yields at least the same revenue as being a follower. At this point the partial differential of equation 3.7 the first profitable time of preemption with respect to the height of the tax τ is evaluated:

$$\left.\frac{\partial T_1^h}{\partial \tau}\right|_{L^h(T_1^h)=F^h(T_2^{*h})}$$

$$= -\frac{\overbrace{-\int_0^{T_1^h} e^{-rt}dt}^{(1)} + \overbrace{\int_0^{T_1^{*f}} e^{-rt}dt}^{(2)} \overbrace{-[\pi_0(1)-\tau]e^{-rT_2^{*h}}\frac{\partial T_2^{*h}}{\partial \tau}}^{(3)} + \overbrace{\int_{T_1^{*f}}^{T_2^{*h}} e^{-rt}dt}^{(4)} \overbrace{+\pi_1(2)e^{-rT_2^{*h}}\frac{\partial T_2^{*h}}{\partial \tau}}^{(5)} \overbrace{+c'\frac{\partial T_2^{*h}}{\partial \tau}}^{(6)}}{[\pi_0(0)-\tau]e^{-rT_1^h} - \pi_1(1)e^{-rT_1^h} - c'(T_1^h)}$$

The denominator is greater than zero as $L^h - F^h = 0$ is before (in time) the maximum. We will evaluate the sign of the numerator by the parts indicated with the brackets above them: The first part (1)

$$-\left[\frac{1}{-r}e^{-rt}\right]_0^{T_1^h} = -\left[\frac{1}{-r}e^{-rT_1^h} - \frac{1}{-r}\right] < 0 \text{ as } T_1^h > 0$$

has the economic interpretation that the environmental tax reduces the profit of leadership in the first phase, and therefore the first profitable time of adoption is later.

The second part (2) is greater than zero:

$$\int_0^{T_1^{*f}} e^{-rt}dt = \left[\frac{1}{-r}e^{-rt}\right]_0^{T_1^{*f}} = \frac{1}{-r}\left[e^{-rT_1^{*f}} - 1\right] > 0 \text{ as } T_1^h > 0$$

The tax reduces the follower profit in the first phase, the company has an earlier first profitable time of adoption.

The 3rd, 5th and 6th term are all zero, as the Envelope Theorem applies to F^{*h} and therefore $\frac{\partial T_2^{h*}}{\partial \tau}$-terms sum to zero and drop out. The 4th term ensures that $\frac{\partial T_1^h}{\partial \tau} < 0$, i.e. earlier pre-emption point of time for home with higher environmental taxation. Hence, the taxation insures that the home firm always accepts earlier preemption times than foreign, because taxes guarantee lower profits as follower, and will thus win preemption games with certainty (rather than with a 50 percent chance).

Proposition 3.6 *A non-adoption tax in one country ensures that the firm in that country can preempt earlier than the firm in the other country.*

3.2.2 Joint late adoption

Another possibility is that both firms prefer to defer the investment in the new technology, yielding a joint late adoption equilibrium: $M(t) = V(t,t)$. The value function for foreign will then be:

$$M^f(t) = \int_0^{\hat{T}_1} \pi_0(0)e^{-rt}dt + \int_{\hat{T}_1}^{\infty} \pi_1(2)e^{-rt}dt - c(t)$$

The value function for the home firm mirrors that of the foreign firm, with the inclusion of the environmental tax for the non-adoption time.

$$M^h(t) = \int_0^{\hat{T}_1} [\pi_0(0) - \tau]e^{-rt}dt + \int_{\hat{T}_1}^{\infty} \pi_1(2)e^{-rt}dt - c(t)$$

The first order conditions for $c(t)$ are

$$\begin{aligned} \frac{\partial M^f}{\partial \hat{T}_1} &= \pi_0(0)e^{-r\hat{T}_1} - \pi_1(2)e^{-r\hat{T}_1} - c'(\hat{T}_1) &= 0 \\ &= (\pi_0(0) - \pi_1(2))e^{-r\hat{T}_1} - c'(\hat{T}_1) &= 0 \end{aligned}$$

$$\frac{\partial M^h}{\partial \hat{T}_1} = (\pi_0(0) - \tau - \pi_1(2))e^{-r\hat{T}_1} - c'(\hat{T}_1) = 0$$

This environmental tax destroys late adoption, as it leads to earlier adoption than the foreign firm, hence destroying the joint late adoption equilibrium.

Proposition 3.7 *Even small taxes create a precommitment against (late) joint adoption.*

3.2.3 Returns to leadership

The change of 'leadership returns' with respect to the environmental tax, τ, for home is evaluated below. Derivation with respect to T_1^h sum up to zero when the envelop theorem is applied to L^h and those with respect to T_2^h when it is applied to F^h. Therefore only the direct effects matter.

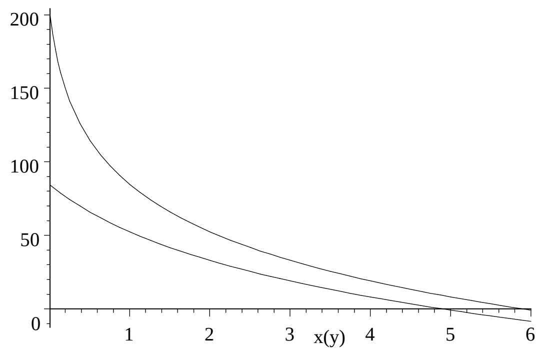
$$\begin{aligned}
\frac{\partial(L^h-F^h)}{\partial\tau} &= \int_{T_1^h(\tau)}^{T_1^f} e^{-rt}dt + \int_{T_1^f}^{T_2^h(\tau)} e^{-rt}dt \\
&= \left[-\tfrac{1}{r}e^{-rt}\right]_{T_1^h}^{T_1^f} + \left[-\tfrac{1}{r}e^{-rt}\right]_{T_1^f}^{T_2^h} \\
&= -\ \tfrac{1}{r}\left[e^{-rT_1^f} - e^{-rT_1^h}\right] - \tfrac{1}{r}\left[e^{-rT_2^h} - e^{-rT_1^f}\right] \\
&= -\ \tfrac{1}{r}\left[e^{-rT_1^h} - e^{-rT_2^h}\right] > 0
\end{aligned}$$

A higher non-adoption tax increases the desire to lead, because it reduces profits from followership, F^h, more than from leadership, L^h. Similarly, the foreign firm would like to lead if $L^f - F^f \geq 0$.

$$\begin{aligned}
L^f - F^f &= \int_{T_1^h}^{T_1^f} [\pi_0(0) - \pi_0(1)]e^{-rt}dt + \int_{T_1^f}^{T_2^h} [\pi_1(1) - \pi_0(1)]e^{-rt}dt \\
&\quad + \int_{T_2^h}^{T_2^f} [\pi_1(2) - \pi_0(1)]e^{-rt}dt - [c(T_1^f) - c(T_2^f)]
\end{aligned} \tag{3.17}$$

Now the effect of the 'home tax' on foreigns willingness to lead (or follow), is captured in the following derivative:

Figure 2: Timing of Technology Adoption under Pre-commitment



$$\frac{\partial(L^f - F^f)}{\partial\tau} = -[\pi_0(0) - \pi_0(1)]e^{-rT_1^h}\frac{\partial T_1^h}{\partial\tau} + \pi_1(1)e^{-rT_2^h}\frac{\partial T_2^h}{\partial\tau} - \pi_1(2)e^{-rT_2^h}\frac{\partial T_2^h}{\partial\tau}$$

We cannot fully sign the derivative.[2] Therefore we give a numeric simulation in the next subsection.

3.3 Simulations

The cost function in this numerical simulations will be parameterized as $c(t) = 100 \cdot e^{-\alpha t}$. The assumption of $c' < 0$ and $c'' > 0$ are then fulfilled for all economically sensible parameter values of $\alpha \in \mathbb{R}^+$. The parameter α can be interpreted as one of technological advancement lowering the cost of adoption over time.

We have parameterized the profits after innovation using an additional

[2] A large $\pi_0(1)$ makes the desire to lead weaker, because it gives a higher weight to the timing shift effect. But a larger $\pi_2(1)$ has opposing effects directly and from equation 3.3.

Table 8: Simulation Parameters and Results

Case	$\pi_0(1)$	$\pi_0(0)$	$\pi_1(2)$	$\pi_1(1)$	α	r	$z \cdot c$	Result
1	1.9	2	$2+x$	$2.2+x$	0.2	0.04	$100c$	precommit
2	1.9	2	$2+x$	$2.2+x$	0.1	0.04	$200c$	precommit
3	1.9	2	$2+x$	$3.1+x$	0.1	0.04	$100c$	preempt or precommit
4	1.9	2	$2+x$	$2.2+x$	0.1	0.04	$100c$	precommit

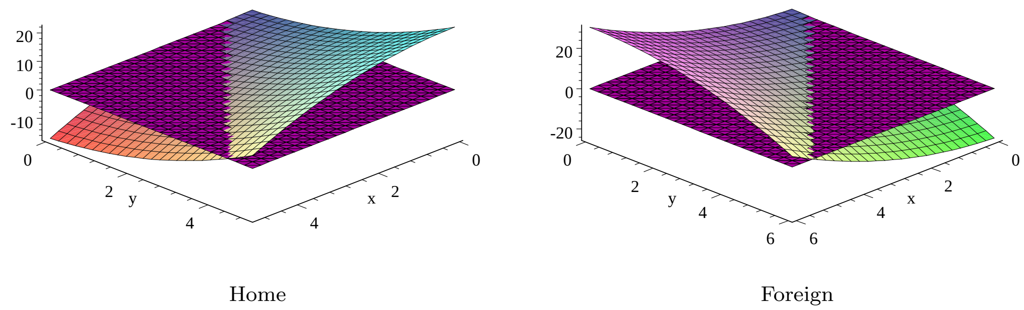
parameter x indicating the increase in profits through the new technology, denoting long-run advantage of the new technology. Note that this advantage is lasting even after the follower has also adopted. For the different parameter values that we have tried, refer to Table 8. In case 3, we find the possibilities for preemption and precommitment. In the other case there is no case of preemption because the short-run gain is too low. In the simulation that we will discuss extensively in this section, case 3, we set the interest rate to be $r = 0.04$, and the cost decrease of adopting the new technology over time to be $\alpha = 0.1$. The returns gross of adoption costs we assume are $\pi_0(1) = 1.9, \pi_0(0) = 2, \leq \pi_1(2) = 2 + x < \pi_1(1) = 3.1 + x$. In words, being a follower decreases the profits by five percent, whereas the (temporary) leader gains more than fifty percent in the short run plus some value $x = \pi_1(2) - \pi_0(0)$ gross of cost of adoption in the long run. This value of x remains after the follower has caught up and also implemented the new technology. Setting x to zero thus would indicate that — at least in terms of profits — no advantage of adoption would remain.

The timing of technology adoption can be calculated both for given (precommitted) leadership and followership according to equations (3.10, 3.11, 3.14, and 3.15). Figure 2 plots the timing of adoption for various levels of x or $y \equiv x + \tau$ for foreign and home respectively. The inner line plots the timing given a firm's precommmitment to leading, the outer line gives the optimal time of adoption given precommitment to follow.

As this figure is based on precommitment, we have to show that firms actually want to be leader or follower. If, for example, both firms would want to lead, a game of preemption will occur in which earlier points of times are chosen than those given in Figure 2. We will deal with preemption further below.

In Figure 3 we plot $L-F$ values for both home and foreign (cf. Equations 3.16 and 3.17) for various levels of x and $y \equiv x + \tau$. $L - F$ is the profit from leading minus profits from following, hence as long as it is positive, a firm will attempt to be the first to adopt. The figure graphically illustrates this situation for the home and foreign firm. The area in which the $L - F$ area is above zero home would like to lead. Areas that are overlapping between those two figures indicate regions of pre-emption. Note that x has the interpretation as above, i.e. continued gain in profits through technology, while y is defined as the sum of $x+\tau$. For the chosen parameter specification and cost functions, the 45 degree line of $x = y$, i.e. no environmental tax, is an overlapping region in which both home and foreign would like to lead. Hence, preemption would take place by each firm with fifty percent chance (Fudenberg and Tirole 1987). However, for large $\tau > 0$, i.e. $x < y = x+\tau$ we can see that both firms are pulled out of the preemption area and home will be the leader ($L - F$ is positive for the home firm) whereas foreign prefers to follow ($L - F$ is negative for the foreign firm). Only for small values of x and τ will preemption take place.

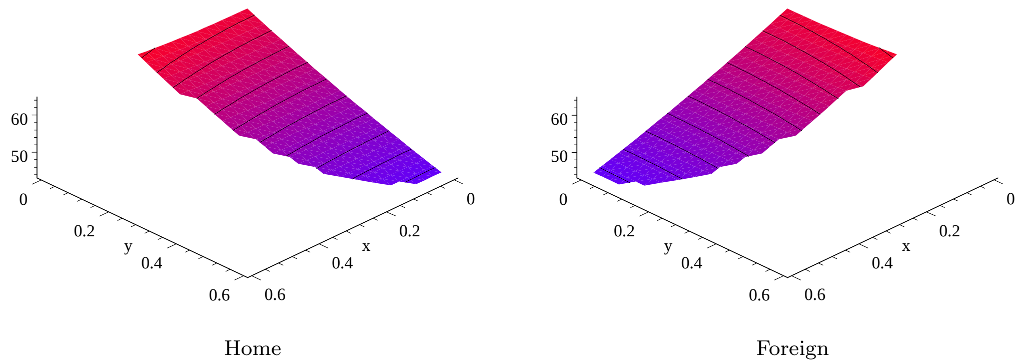
Figure 3: Willingness to lead: $L - F$



Proposition 3.8 *If the short-term gain is large enough to allow for a preemption case, low environmental taxes induce a preemption game which is certainly won by home. High non-adoption taxes induce a precommitment for home to be the leader.*

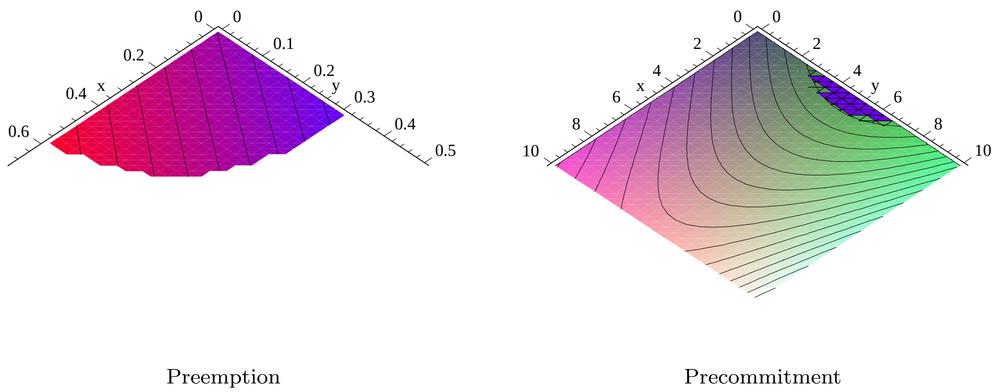
In Figure 4 the "height" gives the first profitable time T of preemption. Note that the points of time are decreasing for home with the y-axis while they are decreasing for foreign along the x-axis. Preemption should result with low τ and precommitment with high environmental taxes τ. In the case of a preemption game, the lower x is (along the 45 degree line) and the higher τ (moving parallel to the y-axis), within the preemption range, the later will be the first profitable point of preemption for the foreign firm. For home, higher environmental taxes lead to earlier profitable points of preemption. Hence, home will have an earlier profitable preemption point of time for any $\tau > 0$, therefore, it will preempt just before foreign's first profitable point of preemption (which yields higher profits than home's first

Figure 4: Preemption Point of Time



profitable point, and is sufficient to be the first one to preempt). We can then calculate the profits of preemption as a function of x and τ. Increasing τ leads to lower preemption profits. Figure 5 summarizes the profits of home as a function of x and $y = x + \tau$. The left figure gives the profits as a function of x and $y = x + \tau$. Profits are increasing along the 45 degree line and an increase in τ will lower the profits of the firm. This implies that environmental taxation does *not* lead to higher profits of the firms in games of preemption, contradicting the Porter Hypothesis. The reason is that the earlier preemption opportunitiy of home is influenced by lower gains as a follower which is induced by the environmental tax. The right part of Figure 5 gives the profits under precommitment: For small values of x (and τ) an increase in environmental taxation will lead to lower profits. Under high levels this is reversed. Only in this last case, the Porter Hypothesis would be supported. However, these high values of y imply negative adoption times and therefore have to be excluded, which one can show by cutting off the

Figure 5: Home's Profits for Preemption and Precommitment



graph at the value of y at which there is immediate adoption.

Proposition 3.9 *(Anti-Porter): Profits under preemption are lower the larger the non-adoption tax and profits under precommitment are lower for higher taxes.*

For all other numerical values which do not violate the assumptions of the model we found results that are qualitatively identical.

We have shown in this last section that environmental regulation can be beneficial in the strategic games of timing, to allow the home firm to lead and avoid preemption. One should bear in mind that this numerical example was contrived and is specific to the parameter values at hand. Many other scenarios can be thought might be just as compelling. Nevertheless, we have shown that environmental tax allows for a quicker adoption, and a longer time of 'leadership' under precommitment and a shorter time of followership in general. Profits of the firm, however, are not higher: Higher taxes decrease the profits in the first phase of (3.13), induce a longer second phase (T_2^f is unaffected by τ) and a shorter first phase and higher adoption costs. The net effect is negative.

Corollary 3.10 *It follows from propositions 3.8 and 3.9 that in the case of preemption a small tax leads to a small decrease in ex-post profits but also to an increase of the chance of pre-emption from 50% to 100%.*

In essence we have constructed an example of the weak version of the Porter Hypothesis, as firms – maximizing their profits – are pulled out of an equal chance preemption equilibrium in such a way that the firm constrained by the environmental regulation adopts earlier with certainty. Competitiveness in the sense of winning a preemption game is enhanced. Non-environmental as well as environmental welfare is enhanced for consumers of home, as they get higher quality and cleaner products earlier.

4 Conclusion

Given the prominent role of innovation offsets in the Porter Hypothesis we did prefer to model it using a framework of technology adoption by Fudenberg and Tirole in which non-adoption is an equilibrium outcome although firms are profit maximizing.

In the static version of the model we did show that a non-adoption equilibrium can be destroyed by an environmental non-adoption tax. However, as the foreign firm follows there is, in contrast to the Porter Hypothesis, no advantage for the home firm . This result also holds in the Hotelling version of the static model. Moreover, we show that taxes not directly targeting the non-adoption problem may fail to have an adoption incentive on the firms.

In a dynamic version of the model early adoption is more costly than late adoption. By implication, immediate adoption cannot be expected and an equilibrium with time periods where a new technology is not adopted by profit maximizing firms is a rational outcome. In the *national case*, under precommitment on the order of adoption, the leader and the follower adopt earlier if the environmental tax is larger. Under preemption, the timing of preemptive adoption will be earlier if the environmental tax is higher. Joint late adoption takes place earlier under a higher environmental tax.

In the *international case*, the home country raises a tax but the foreign country does not. Under precommitment on the order of adoption, if home is the follower it adopts earlier if the environmental tax is larger, decreasing the time that a foreign firm can reap the benefits of early adoption. Comparing behavior as follower, foreign adopts slower than home, because in foreign there is no environmental tax by assumption. If there is a preemption game, a non-adoption tax in one country ensures that the firm in that country can preempt earlier than the firm in the other country. The home firm preempts just before the foreign firm would do. The chance of preemption jumps from 50/50 to 100% for the home country if there is an environmental tax. The case of preemption will exist under a low environmental tax only if the temporary gains of first adoption are high relative to the temporary losses of second adoption. Under high non-adoption taxes or low temporary gains and losses there is a precommitment for home to be the leader. Ex-post profits of the home firm are lower under preemption and under precommitment the larger the tax is, in contrast to the Porter Hypothesis. In sum, a tax introduces a reduction in ex-post profits but also a jump from 50% to a 100% chance of preemption. In this sense competitiveness is increased but profits are decreased.

A Derivations of L-F function

– Not for Publication –

$$
\begin{aligned}
L^h - F^h &= V_L^h(T_1^h, T_2^f) - V_F^h(T_2^h, T_1^f) \\
&= \int_0^{T_1^h} [\pi_0(0) - \tau]e^{-rt}dt + \int_{T_1^h}^{T_2^f} \pi_1(1)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_1^h) \\
&\quad - \left[\int_0^{T_1^f} [\pi_0(0) - \tau]e^{-rt}dt + \int_{T_1^f}^{T_2^h} [\pi_0(1) - \tau]e^{-rt}dt + \int_{T_2^h}^{\infty} \pi_1(2)e^{-rt}dt - c(T_2^h)\right] \\
&= \int_0^{T_1^h} [\pi_0(0) - \tau]e^{-rt}dt + \int_{T_1^h}^{T_1^f} \pi_1(1)e^{-rt}dt + \int_{T_1^f}^{T_2^h} \pi_1(1)e^{-rt}dt + \int_{T_2^h}^{T_2^f} \pi_1(1)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_1^h) \\
&\quad - \left[\int_0^{T_1^h} [\pi_0(0) - \tau]e^{-rt}dt + \int_{T_1^h}^{T_1^f} [\pi_0(0) - \tau]e^{-rt}dt + \int_{T_1^f}^{T_2^h} [\pi_0(1) - \tau]e^{-rt}dt + \int_{T_2^h}^{T_2^f} \pi_1(2)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_2^h)\right] \\
&= \int_{T_1^h}^{T_1^f} [\pi_1(1) - \pi_0(0) + \tau]e^{-rt}dt + \int_{T_1^f}^{T_2^h} [\pi_1(1) - \pi_0(1) + \tau]e^{-rt}dt + \int_{T_2^h}^{T_2^f} [\pi_1(1) - \pi_1(2)]e^{-rt}dt - \left[c(T_1^h) - c(T_2^h)\right]
\end{aligned}
$$

From (3.9) and (3.12) we get:

$$
\begin{aligned}
L^f - F^f &= V_L^f(T_1^f, T_2^h) - V_F^f(T_2^f, T_1^h) \\
&= \int_0^{T_1^f} \pi_0(0)e^{-rt}dt + \int_{T_1^f}^{T_2^h} \pi_1(1)e^{-rt}dt + \int_{T_2^h}^{\infty} \pi_1(2)e^{-rt}dt - c(T_1^f) \\
&\quad - \left[\int_0^{T_1^h} \pi_0(0)e^{-rt}dt + \int_{T_1^h}^{T_2^f} \pi_0(1)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_2^f)\right] \\
&= \int_0^{T_1^h} \pi_0(0)e^{-rt}dt + \int_{T_1^h}^{T_1^f} \pi_0(0)e^{-rt}dt + \int_{T_1^f}^{T_2^h} \pi_1(1)e^{-rt}dt + \int_{T_2^h}^{T_2^f} \pi_1(2)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_1^f) \\
&\quad - \left[\int_0^{T_1^h} \pi_0(0)e^{-rt}dt + \int_{T_1^h}^{T_1^f} \pi_0(1)e^{-rt}dt + \int_{T_1^f}^{T_2^h} \pi_0(1)e^{-rt}dt + \int_{T_2^h}^{T_2^f} \pi_0(1)e^{-rt}dt + \int_{T_2^f}^{\infty} \pi_1(2)e^{-rt}dt - c(T_2^f)\right] \\
&= \int_{T_1^h}^{T_1^f} [\pi_0(0) - \pi_0(1)]e^{-rt}dt + \int_{T_1^f}^{T_2^h} [\pi_1(1) - \pi_0(1)]e^{-rt}dt + \int_{T_2^h}^{T_2^f} [\pi_1(2) - \pi_0(1)]e^{-rt}dt - [c(T_1^f) - c(T_2^f)]
\end{aligned}
$$

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