Strategic Environmental Policy, Clean Technologies and the Learning Curve

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Abstract

In the political discussion, it is often emphasized that the environmental industry benefits from an early and strong environmental policy. This is especially likely if the costs of production are decreasing over time due to learning curve effects. Surprisingly, the environmental industry has not been integrated into the theory of strategic environmental policy yet. Our main question is whether a national leadership in environmental policy can pay off if profits of the environmental industry are taken into account. We consider a two-period model with one firm in each country competing on a third market. Emissions can be substituted by the clean factor when deciding upon the production technology. The unit costs of producing the clean factor are a decreasing function of the quantity produced in the initial period. We derive the optimal environmental policy for both periods from a national point of view and show that the existence of the environmental industry can indeed lead to a national leadership in pollution control.

Keywords: Environmental Policy, Strategic Trade Policy, Learning Curve, Clean Technology, Infant Industry

JEL-Classification: F12, Q20

1 Introduction

It is well known that imperfect competition and global pollution problems create incentives to deviate from the first best rule of equating the emission tax with marginal damage from pollution. Building on the literature on strategic trade policy, there are many articles analyzing strategic environmental policy in different settings.[1] With Cournot competition and production for a third market, maximization of domestic welfare leads to an emission tax below marginal damage (eco-dumping) in order to shift rents from foreign countries (see Barrett (1994)). Hence, there seems to be a natural trade off between concerns about the competitiveness of industries and environmental issues.

In the meantime, many extensions including Carraro and Soubeyran (1996), Conrad (1996), A. Ulph (1996), Ulph and Ulph (1996), A. Ulph (1998), Bandyopadhyay (1997), Zigic (1998), Nannerup (1998), Althammer and Buchholz (2000), and Rege (2000) have been published. These articles consider different modes of competition, the role of demand elasticities, various environmental policy instruments, and more complicated situations with respect to technology choices. However, none of these articles integrates the environmental industry into the framework of strategic environmental policy. This is surprising, because higher emission taxes do not only affect the producing industries but also the environmental service industries providing clean technologies and input factors, since demand for these technologies is likely to rise in case of a tough environmental policy.[2] In fact, environmental industries are rapidly growing, and apparently there are considerable dynamic returns to scale in abatement production.[3] Whereas the impact of a tough environmental policy on environmental service industries is emphasized in the empirical literature and by practitioners, it has almost been completely neglected in the formal literature on strategic environmental policy.

Against this background, we analyze a two-period model of strategic environmental policy, including an environmental service sector in which the cost of producing a clean input factor is decreasing in the quantity produced in the preceding period.[4] The question we are interested in is whether a national leadership in environmental policy can pay off if the profits of the environmental service industry are factored into the social welfare function. To this end, we consider a traditional Cournot-model of strategic environmental policy where products are sold on a third market. The producing firms can substitute emissions by the clean input factor which is only produced in the "home" country. Besides the assumption that the environmental service industry is only located in one country, our model is completely symmetric. These standard assumptions are appropriate to isolate the impact of the environmental industry, and to discuss our main question whether a national leadership can be justified by the benefits for the environmental industry. Without an environmental service industry, under Cournot-competition with production for a third market, taxes of both countries would be below the Pigouvian tax (usually called "ecological dumping"), because products are strategic substitutes. We consider a completely symmetric model except the presence of an environmental industry in one country. Hence, we will interpret choosing a higher tax rate than the other country as national leadership in pollution control coming from the environmental industry.

In each period, governments first simultaneously set emission taxes. Given these taxes, both firms choose their amounts of emissions and clean input factors (their factor combination). Finally, the producing firms sell their products in Cournot fashion on a third-country market.[5] Our main findings are as follows: first, a higher tax rate does not necessarily increase the demand for the clean technology. This stems from the fact that there is a negative indirect demand effect via the reduced equilibrium quantities on the commodity market, countervailing the positive demand effect of a changed factor price ratio. Second, whenever the overall demand effect for the clean factor is positive, the home country will choose a higher tax rate than the foreign country, and will thus find the role of national leadership desirable. Third, if the effect on the profits of the environmental industry is strong enough, the optimal domestic tax rate can even be higher than the Pigouvian tax. Including the environmental industry into the analysis can thus lead to a harmonization of national welfare maximization and environmental concerns.

To the best of our knowledge, Feess and Muehlheusser (1999) is the only other paper that integrates an environmental sector into the framework of strategic environmental policy. In this model, however, it is assumed that the tax rate of the foreign environmental agency is either zero or identical to the domestic tax rate. Moreover, the model could only be developed with very special numerical specifications.

The remainder of the paper is organized as follows: The model is presented in section 2. Following the logic of backwards induction, we analyze the second period of the model in section 3. The first period is examined in section 4. We conclude in section 5. Comparative statics results and proofs are delegated to the Appendix.

2 The Model

We consider a two-period model with two countries, home h and Foreign F. Periods are denoted $i = 1, 2$. In each country there is one firm, and both firms produce identical consumption goods sold on a third-country market. During the production process a global pollutant is discharged. The firms produce with emissions and a clean input factor provided by an environmental service industry. The environmental industry is located in country h and is subject to a learning curve, meaning that costs of production are a decreasing function of the output produced in the preceding period. Domestic variables are denoted in lower case letters, foreign variables are denoted in upper case letters, variables affecting both countries equally are denoted in Greek letters. We make the following assumptions:

1. The inverse demand function for the consumption good on the third-country-market in period i is $\Pi(y_i, Y_i)$ where $i = 1, 2$. $\Pi(y_i, Y_i)$ is assumed to be linear in quantities.

2. The clean factor is provided by an environmental industry located in country h. Marginal costs of production are z_1 in period 1. Let α_i denote the total quantity of the clean factor produced and sold in period i. For marginal costs of production in period 2, we assume $z_2(\alpha_1) = z_1 - \widehat{z} \cdot k(\alpha_1)$, where $k(\alpha_1)$ is a quasi-concave function with $k(0) = 0$, and $\widehat{z} > 0$ is a parameter measuring the strength of the learning curve effect. $\widehat{z} > 0$ guarantees that the learning curve is positive, and the properties of $k(\alpha_1)$ imply that the size of the learning effect is decreasing in α_1. These are standard assumptions in the literature on learning curve effects required to get interior solutions.

3. The quantities of the clean factor demanded in countries h and F are denoted a_i and A_i, respectively. Thus, $\alpha_i = a_i + A_i$. Define λ as the factor price, and let λ^m denote the factor price that would arise in a monopoly market, that is if there were perfect competition on the demand side. We assume that λ is exogenously given, and that $z_1 < \lambda < \lambda^m$ holds, i.e. that the price is between marginal cost of production of abatement in period 1 (z_1) and the monopoly price λ^m. Furthermore, we assume that λ is the same in both periods. The convenient assumption that the factor price is exogenously given is introduced for three reasons: first, there are only two buyers in the market and one seller, so that there is no standard concept to determine the equilibrium price. Second, our focus is on the optimal strategic environmental policy with an industry producing clean input factors, and

not on analyzing a multiparty-bargaining game between the producing firms and the environmental industry. Third, λ is endogenous in Feess and Muehlheusser (1999), and this made it impossible to solve the model without numerical specifications although the structure is simple compared to the present paper.

4. The consumption good is produced according to the symmetric cost functions $c(y_i, \lambda, t_i)$ and $C(Y_i, \lambda, T_i)$. We assume the cost functions to be linear in output, and to be concave in factor prices t_i and λ, and T_i and λ, respectively. The concavity property arises because there will be substitution between emissions and the clean factor if the factor price ratios t_i/λ and T_i/λ change. As usual, these assumptions are required to rule out corner solution when determining the optimal factor input ratio.

5. Total emissions in period i are denoted by Σ_i. The damage function $\Delta(\Sigma_i)$ is assumed to be the same in both countries. Moreover, we assume that marginal damage is constant. The latter assumption gives us the Pigouvian tax equal to marginal damage independently of the quantity of the consumption good. This implies that the Pigouvian tax rate is the same in both countries, and allows us to emphasize the effects caused by the presence of the environmental service industry.

When determining the optimal tax rates, governments maximize an intertemporal national welfare function given by the difference of profits and environmental harm for each period. Note that the profits from selling abatement accrue in country h only. Without loss of generality, there is no discounting. The timing of the game is as follows:

- Period 1 includes stages 1-3 of the game. In stage 1, governments choose emission taxes t_1 and T_1. Given these tax rates, the environmental industry decides upon the quantity of the clean factor sold at price λ in stage 2. The factor-ratio follows from cost minimizing behavior of the producing firms. Hence, there is no need in modeling this as a stage of the game. In stage 3, the producing firms compete in quantities on the third country's market by choosing y_1 and Y_1.

- In period 2, the stages 4-6 are the same as the stages 1-3 in period 1.

As usual, the game is solved qua backwards induction, starting with stage 6 in period 2.

3 Second period

Output game (stage 6) In stage 6, the firms producing the consumption good simultaneously offer their quantities on the market (Cournot competition). At this stage, the price of abatement (λ) and the period 2 tax rates (t_2 and T_2) are already given. As firms minimize their unit costs of production by choosing the optimal factor combination, profit functions can be written as

$$g_2 = \Pi(y_2, Y_2) \cdot y_2 - c(y_2, \lambda, t_2) \tag{1}$$

and

$$G_2 = \Pi(y_2, Y_2) \cdot Y_2 - C(Y_2, \lambda, T_2). \tag{2}$$

The Nash-Equilibrium in quantities is implicitly defined by the following first order condition:

$$\frac{\partial \Pi(y_2, Y_2)}{\partial y_2} \cdot y_2 + \Pi(y_2, Y_2) - \frac{\partial c}{\partial y_2} = 0 \tag{3}$$

and

$$\frac{\partial \Pi(y_2, Y_2)}{\partial Y_2} \cdot Y_2 + \Pi(y_2, Y_2) - \frac{\partial C}{\partial Y_2} = 0 \tag{4}$$

From the comparative statics analysis we obtain the standard properties as known from the literature: $\frac{dy_2}{dt_2} < 0$, $\frac{dy_2}{dT_2} > 0$, $\frac{dY_2}{dt_2} > 0$, $\frac{dY_2}{dT_2} < 0$, $\frac{dy_2}{d\lambda} < 0$ and $\frac{dY_2}{d\lambda} < 0$.[6] Thus, equilibrium quantities are decreasing in the own tax rates and in the price for the clean factor due to higher unit costs. Furthermore, equilibrium quantities are increasing in the tax rate of the other country, because quantities are strategic substitutes. This means that the quantity produced in one country is ceteris paribus the higher, the lower the quantity produced in the other country.

Environmental industry (stage 5) The environmental industry sells abatement at price λ. The total cost minimizing quantity $\alpha_2 = a_2 + A_2$ purchased by the two firms producing the consumption good can be obtained by applying Shephard's lemma to the cost functions $c(y_2, \lambda, t_2)$ and $C(Y_2, \lambda, T_2)$, where $a_2 = \frac{\partial c}{\partial \lambda}$ and $A_2 = \frac{\partial C}{\partial \lambda}$.[7]

Hence, the profit of the environmental industry in period 2, denoted by b_2 is

$$b_2 = [\lambda - (z_1 - \hat{z} \cdot k(\alpha_1(t_1, T_1)))] \cdot \alpha_2 \tag{5}$$

Unit costs z_2 in period 2 depend on the quantity sold in period 1 (α_1), and hence on the tax rates in period 1 (t_1 and T_1). To express the profit per unit more conveniently, we define the vector of taxes in period 1 as $\tau_1 \equiv (t_1, T_1)$, and

$$\theta(\alpha_1(\tau_1)) \equiv \lambda - z_1 + \widehat{z} \cdot k(\alpha_1(\tau_1)) \tag{6}$$

to get

$$b_2 = \theta(\tau_1) \cdot \alpha_2. \tag{7}$$

Equation (7) shows that the environmental industry's profit in period 2 is determined by the tax rates in period 1 and the quantity bought in period 2 depending on the tax rates in period 2.[8]

Governments (stage 4) Governments simultaneously maximize national welfare, taking into consideration profits of the firms and damage caused by emissions. Again, we make use of the fact that the producing firms' cost minimizing amount of emissions can be obtained by applying Shephard's lemma to the cost functions $c(y_2, \lambda, t_2)$ and $C(Y_2, \lambda, T_2)$. This gives us total emissions $\Sigma_2 = e_2 + E_2$, where $e_2 = \frac{\partial c}{\partial t_2}$ and $E_2 = \frac{\partial C}{\partial T_2}$. Then, social welfare in the two countries is

$$\begin{aligned} w_2(\cdot) &= \Pi(y_2, Y_2) \cdot y_2 - c(y_2, \lambda, t_2) + t_2 \cdot e_2(y_2, \lambda, t_2) \\ &\quad + \theta(\tau_1) \cdot \alpha_2 - \Delta(\Sigma_2) \end{aligned} \tag{8}$$

and

$$\begin{aligned} W_2(\cdot) &= \Pi(y_2, Y_2) \cdot Y_2 - c(Y_2, \lambda, T_2) + T_2 \cdot E_2(Y_2, \lambda, T_2) \\ &\quad - \Delta(\Sigma_2), \end{aligned} \tag{9}$$

respectively. In equation (8), the first two terms express the domestic firm's profits, the third term is the tax payment received by the government, and the fourth term is environmental harm caused by total emissions. Equation (9) can be interpreted analogously. Differentiating (8) with respect to t_2 and (9) with respect to T_2 yields the following first order conditions:

$$\begin{aligned} \frac{\partial w_2(\cdot)}{\partial t_2} &= \left(\Pi' y_2 + \Pi - \frac{\partial c}{\partial y_2}\right)\frac{dy_2}{dt_2} + \Pi' \frac{dY_2}{dt_2} y_2 - \frac{\partial c}{\partial t_2} + e_2(\cdot) \\ &\quad + t_2 \cdot \left(\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial e_2}{\partial t_2}\right) + \theta(\tau_1) \cdot \left(\frac{\partial a_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial a_2}{\partial t_2} + \frac{\partial A_2}{\partial Y_2}\frac{dY_2}{dt_2}\right) \end{aligned} \tag{10}$$

$$-\Delta' \left(\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial e_2}{\partial t_2} + \frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dt_2} \right)$$
$$= 0$$

and

$$\begin{aligned} \frac{\partial W_2(\cdot)}{\partial T_2} &= \left(\Pi' Y_2 + \Pi - \frac{\partial C}{\partial Y_2} \right) \frac{dY_2}{dT_2} + \Pi' \frac{dy_2}{dT_2} Y_2 - \frac{\partial C}{\partial T_2} + E_2(\cdot) \\ &\quad + T_2 \cdot \left(\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dT_2} + \frac{\partial E_2}{\partial T_2} \right) - \Delta' \left(\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dT_2} + \frac{\partial E_2}{\partial T_2} + \frac{\partial e_2}{\partial y_2}\frac{dy_2}{dT_2} \right) \\ &= 0, \end{aligned} \tag{11}$$

where $\Delta' = \frac{\partial \Delta}{\partial \Sigma_2}$ denotes constant marginal damage from emissions.

Using (3) and (4), and recalling the definitions of e_2 and E_2, we have the optimal tax rates as implicit functions of the other country's tax rate:

$$\begin{aligned} & \Pi' \frac{dY_2}{dt_2} y_2 + (t_2 - \Delta') \cdot \left(\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial e_2}{\partial t_2} \right) \\ & + \theta(\tau_1) \cdot \left(\frac{\partial a_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial a_2}{\partial t_2} + \frac{\partial A_2}{\partial Y_2}\frac{dY_2}{dt_2} \right) - \Delta' \left(\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dt_2} \right) \\ = {} & 0 \end{aligned} \tag{12}$$

and

$$\begin{aligned} & \Pi' \frac{dy_2}{dT_2} Y_2 + (T_2 - \Delta') \cdot \left(\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dT_2} + \frac{\partial E_2}{\partial T_2} \right) - \Delta' \left(\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dT_2} \right) \\ = {} & 0 \end{aligned} \tag{13}$$

Solving (12) for t_2 reveals the structure of the optimal environmental policy for country h in period 2:

$$t_2 = \Delta' + \frac{1}{\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial e_2}{\partial t_2}} \left(\begin{array}{c} -\Pi' \frac{dY_2}{dt_2} y_2 - \theta(\tau_1) \cdot \left(\frac{\partial a_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial a_2}{\partial t_2} + \frac{\partial A_2}{\partial Y_2}\frac{dY_2}{dt_2} \right) \\ + \Delta' \left(\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dt_2} \right) \end{array} \right) \tag{14}$$

Note first that the multiplier $\frac{1}{\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dt_2}+\frac{\partial e_2}{\partial t_2}}$ is negative: $\frac{\partial e_2}{\partial y_2}\frac{dy_2}{dt_2}$ is negative, because the demand for emissions e_2 is increasing in y_2, while y_2 is decreasing in t_2. $\frac{\partial e_2}{\partial t_2}$ is also negative, because the demand for emissions is decreasing in the tax rate due to the concavity of the cost function. Then, intuitively, the optimal tax rate is distorted from marginal damage for the following reasons:

Rent shifting: $\Pi' \frac{dY_2}{dt_2} y_2$ expresses the familiar rent shifting effect from imperfect competition, measuring the impact of an increase in t_2 on the profits of the domestic producing firm. A higher t_2 leads to a decrease in y_2 and to an increase in Y_2. Since total quantity decreases, the price increases in equilibrium. As $-\Pi'$ and $\frac{dY_2}{dt_2}$ are positive, the term is positive as usual under Cournot-quantity competition. This would lead to a tax rate below marginal damage if no additional effects were taken into account.

Environmental harm: $\Delta' \left(\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dt_2}\right)$ measures the damage effect resulting from higher equilibrium quantities of the foreign firm on the consumption good market. Its sign is positive, because the foreign quantity is increasing in the domestic tax rate and emissions are increasing in quantities.

Abatement demand: $\theta(\tau_1)\cdot\left(\frac{\partial a_2}{\partial y_2}\frac{dy_2}{dt_2} + \frac{\partial a_2}{\partial t_2} + \frac{\partial A_2}{\partial Y_2}\frac{dY_2}{dt_2}\right)$ measures the effect of t_2 on marginal profits of the environmental industry. It is useful to decompose this effect into its components: $\frac{\partial a_2}{\partial y_2}\frac{dy_2}{dt_2}$ measures the decrease of domestic demand for the clean input factor resulting from a lower equilibrium quantity on the consumption good market. $\frac{\partial A_2}{\partial Y_2}\frac{dY_2}{dt_2}$ is the increase of foreign demand resulting from a higher equilibrium quantity Y_2, and $\frac{\partial a_2}{\partial t_2}$ is the increase of demand resulting from the fact that the factor price ratio has changed. This can be interpreted as the usual substitution effect.

The first term is negative, the second and the third term are positive. Our standard assumptions ensure that the total amount of consumption goods decreases in t_2, i.e. $\frac{d(y_2+Y_2)}{dt_2} < 0$ (quantity effect). It follows that the total effect is ambiguous, because an increase of the tax rate in country h can lead to a lower total demand for the clean factor if the quantity effect is greater than the substitution effect. This is expressed in

Lemma 1 *The demand for the clean factor and the profit of the environmental industry may either be increasing or decreasing in t_2.*

Proof: See Appendix.

Since its profit is increasing in total demand, it follows that the environmental service industry might either benefit or not from a higher tax rate. We restrict our attention to the case where $\frac{\partial \alpha_2}{\partial t_2} > 0$ and $\frac{\partial b_2}{dt_2} > 0$ for two reasons: first, it is obvious that the domestic tax rate will otherwise always be below marginal damage, so that the first case is the interesting one. Second, the other case can be analyzed similarly and leads to no additional insights.

The three effects identified above show that the rent shifting effect and the damage effect lead to eco-dumping as usual, but the effect on marginal profits of the environmental industry can go either way. If higher taxes lead to higher profits of the environmental industry, then the domestic tax rate will be above the foreign tax rate. Therefore, a national leadership in pollution control will emerge. Moreover, even a tax rate above marginal damage can maximize national welfare if the effect due to the presence of the environmental industry is strong enough. To see this, suppose that the costs of the environmental industry (z_2) are very low. Profits of the environmental industry b_2 would then increase for any given demand of abatement, and therefore for each emission tax. Hence, the lower λ, the higher the advantage of a high emission tax coming from the profits of the environmental industry. On the other hand, unit costs of the environmental industry do not affect the profits of the producing industry (g_2), since λ is given exogenously. It follows that the welfare maximizing emission tax is decreasing in z_2, and can be below marginal damage if z_2 is sufficiently low.[9]

Determining the optimal tax rate for country F is similar. Taking into account that there is no foreign environmental industry, T_2 is implicitly given by

$$T_2 = \Delta' + \frac{1}{\frac{\partial E_2}{\partial Y_2}\frac{dY_2}{dT_2} + \frac{\partial E_2}{\partial T_2}} \left(-\Pi' \frac{dy_2}{dT_2} Y_2 + \Delta' \left(\frac{\partial e_2}{\partial y_2} \frac{dy_2}{dT_2} \right) \right) \tag{15}$$

As there is no ambiguous effect for the foreign government, the rent shifting effect and the damage effect lead to an optimal national tax rate below marginal damage. Note that due to the learning curve effect, emission taxes in both countries depend on the taxes chosen in the former period (hence $t_2 = t_2(\tau_1)$ and $T_2 = T_2(\tau_1)$). Given our analysis, the following result holds:

Proposition 1 *In equilibrium, $t_2 > T_2$ If and only if $\frac{\partial b_2}{dt_2} > 0$. Furthermore, t_2 is increasing in the strength of the learning curve effect.*

Proof: See Appendix.

The first part of Proposition 1 expresses that the domestic tax rate is higher than the foreign tax rate whenever the profit of the environmental service industry is increasing in the tax rate. The intuition is straightforward, because the domestic government has an incentive to increase the tax rate if and only if there is an additional benefit for the environmental industry. This benefit is the higher the lower the unit costs of production, which explains the second part of Proposition 1. If the countries were asymmetric with respect to firms' costs or the damage function, it could not be excluded that $t_2 < T_2$

even if $\frac{\partial b_2}{dt_2} > 0$. If, for instance, the foreign equilibrium quantity Y_2 is small while the domestic quantity y_2 is high, we could have $t_2 < T_2$ because the domestic government would be more concerned about the profits of the firm.[10] However, the interesting question would then not be if t_2 were higher than T_2 in absolute terms, but the comparison to the situation without environmental industry. This would lead to serious formal complications, but the result that the domestic tax rate is increasing due to $\frac{\partial b_2}{dt_2} > 0$ still holds. The symmetry assumption allows to isolate the effect caused by the environmental industry in a convenient way.

Besides the comparison of t_2 and T_2, there are two questions one would be interested in: First, how changes in the price for the clean factor (λ) affect the equilibrium configuration. Second, whether the tax rates are strategic complements or substitutes. Unfortunately, these effects are highly ambiguous in our model. Since it is straightforward to derive these ambiguities by constructing counterexamples, we do not present the ambiguity statements in formal results, but prefer to elaborate the different effects causing the ambiguities instead.[11] Within our model, increasing λ has the following effects:

Environmental industry: Since we have assumed that the factor price is below the monopoly price, b_2 is increasing in λ. Profits are increasing in λ up to λ^m by definition of a monopoly price. The higher price overcompensates for the lower quantity demanded.

Producing firms: Since costs go up, equilibrium quantities and profits go down.

Environmental harm: The effect on the environment is ambiguous: On the one hand, the clean factor is substituted by emissions. On the other hand, emissions are reduced because total production decreases. Generally, either the quantity effect or the substitution effect may dominate. The lower the elasticity of substitution, the higher the increase in unit costs if λ increases, the more likely that the quantity effect dominates.

Depending on the strength of the learning curve effect, the division of the bargaining power and the demand function for output, the slopes of the reaction functions of the governments are ambiguous as well. This means that emission taxes can either be strategic complements or substitutes. If one considered a simplified model without a domestic environmental industry, the tax rates would be strategic complements as one country, h say, can raise its tax rate at "lower costs" (in terms of foregoing profits of the producing industry) if F's tax rate is high, since the equilibrium quantities are lower, reducing the detrimental impact of the rent shifting effect on h's welfare.[12] In our model, however, there are many additional strategic effects, because the change in the profit of the environmental industry if one tax rate is changed also depends on the other tax rate.

4 First period

Output Game (stage 3) With respect to period 1, note first that there are no intertemporal effects for the firms producing the consumption good. The reason is the assumption that λ is constant over time, so that the producing firms do not gain from the learning effect. It follows that the Cournot-Nash-Equilibrium in period 1 can be characterized by the usual first order conditions:

$$\frac{\partial \Pi(y_1, Y_1)}{\partial y_1} \cdot y_1 + \Pi(y_1, Y_1) - \frac{\partial c}{\partial y_1} = 0 \tag{16}$$

and

$$\frac{\partial \Pi(y_1, Y_1)}{\partial Y_1} \cdot Y_1 + \Pi(y_1, Y_1) - \frac{\partial C}{\partial Y_1} = 0 \tag{17}$$

Environmental industry (stage 2) Let $\alpha_1 = a_1 + A_1$ denote the total amount of the clean factor demanded in period 1. Again, applying Shephard's lemma yields $a_1 = \frac{\partial c}{\partial \lambda}$ and $A_1 = \frac{\partial C}{\partial \lambda}$. The profit of the environmental industry in period 1 is

$$b_1 = (\lambda - z_1) \cdot \alpha_1 \tag{18}$$

Governments (stage 1) In period 1, governments maximize intertemporal welfare. Note that the domestic government does not only care about its environmental industry, damages from pollution and shifting rents in period 1, but also about the fact that a higher demand for the clean factor in period 1 leads to higher profits for the environmental industry in period 2 via the learning curve effect. The governments' intertemporal objective functions are

$$\begin{aligned} w(\cdot) &= w_1(\cdot) + w_2(\cdot) \\ &= g_1 + t_1 \cdot e_1 + (\lambda - z_1) \cdot \alpha_1 - \Delta(\Sigma_1) + w_2(t_2(\tau_1), t_1) \end{aligned} \tag{19}$$

and

$$\begin{aligned} W(\cdot) &= W_1(\cdot) + W_2(\cdot) \\ &= G_1 + T_1 \cdot E_1 - \Delta(\Sigma_1) + W_2(T_2(\tau_1)) \end{aligned} \tag{20}$$

Differentiating (19) with respect to t_1 and (20) with respect to T_1 yield

$$
\begin{aligned}
\frac{\partial w(\cdot)}{\partial t_1} &= \frac{\partial w_1(\cdot)}{\partial t_1} + \frac{\partial w_2(\cdot)}{\partial t_2}\frac{\partial t_2}{\partial t_1} + \frac{\partial w_2(\cdot)}{\partial t_1} \\
&= \frac{\partial w_1(\cdot)}{\partial t_1} + \frac{\partial w_2(\cdot)}{\partial t_1}
\end{aligned} \tag{21}
$$

and

$$
\begin{aligned}
\frac{\partial W(\cdot)}{\partial T_1} &= \frac{\partial W_1(\cdot)}{\partial T_1} + \frac{\partial W_2(\cdot)}{\partial T_2}\frac{\partial T_2}{\partial T_1} \\
&= \frac{\partial W_1(\cdot)}{\partial T_1}
\end{aligned} \tag{22}
$$

Due to the optimization process in stage 4, the indirect impact of t_1 and T_1 on period 2's results drops out.[13] This implies that the foreign government cannot influence the outcomes in period 2 directly. Thus, there are no intertemporal impacts of T_1. In the home country, the tax rate in period 1 influences the optimal tax rate in period 2 via the learning curve effect of the environmental industry.

Using the solution of the output game in (16), rearranging terms and solving for t_1 yields

$$
t_1 = \Delta' + \frac{1}{\frac{\partial e_1}{\partial y_1}\frac{dy_1}{dt_1} + \frac{\partial e_1}{\partial t_1}} \left(\begin{array}{c} -\Pi' \frac{dY_1}{dt_1} y_1 + \Delta' \left(\frac{\partial E_1}{\partial Y_1}\frac{dY_1}{dt_1} \right) \\ -(\lambda - z_1) \cdot \left(\frac{\partial a_1}{\partial y_1}\frac{dy_1}{dt_1} + \frac{\partial a_1}{\partial t_1} + \frac{\partial A_1}{\partial Y_1}\frac{dY_1}{dt_1} \right) \\ -\frac{\partial \theta}{\partial t_1} \cdot \alpha_2 \end{array} \right) \tag{23}
$$

Comparing equations (23) and (14) shows that they differ with respect to the impact of t_1 on the environmental industry's profits in period 2 given by $-\frac{\partial \theta}{\partial t_1} \cdot \alpha_2$. All units sold in period 2 can be produced with lower costs. As in period 2, the optimal tax rate will be above marginal damages if the effect for the environmental industry is strong enough.

Since there are no intertemporal effects for the foreign government, its optimal policy is implicitly given by

$$
T_1 = \Delta' + \frac{1}{\frac{\partial E_1}{\partial Y_1}\frac{dY_1}{dT_1} + \frac{\partial E_1}{\partial T_1}} \left(-\Pi' \frac{dy_1}{dt_1} Y_1 + \Delta' \left(\frac{\partial e_1}{\partial y_1}\frac{dy_1}{dT_1} \right) \right) \tag{24}
$$

Similarly to period 2, the two terms in brackets are positive and the coefficient is negative, so that the foreign government will choose a tax rate below marginal damage.

Intuitively, one might think that the tax rate in period 1 should be higher than in period 2 to induce learning curve effects whenever the environmental service industry benefits from higher taxes. However, comparing t_1 and t_2 as derived in (23) and (14) reveals that there are again countervailing effects. Inducing higher abatement demand in period 1 has positive effects on the profits of the environmental industry in period 1 *and* in period 2. In (23), the term $\frac{\partial \theta}{\partial t_1} \cdot \alpha_2 = \widehat{z} \cdot \frac{\partial k}{\partial \alpha_1} \frac{\partial \alpha_1}{\partial t_1} \cdot \alpha_2$ indicates that additional learning affects total sales of abatement in period 2, which offers an incentive to increase the tax rate. On the other hand, in period 2, from (14) the strength of the learning effect is given and affects marginal profits of the environmental industry via $k(\alpha_1) \cdot \frac{\partial \alpha_2}{\partial t_2}$. As the sign of $\frac{\partial \theta}{\partial t_1} \cdot \alpha_2 - k(\alpha_1) \cdot \frac{\partial \alpha_2}{\partial t_2}$ is ambiguous, so is the sign of $t_2 - t_1$. If the learning curve effect is weak and demand for abatement is very elastic to tax rate changes, it can be better to choose a higher tax in period 2, because it will not pay off to weaken the producing industry too much in period 1 by imposing a high tax rate. By contrast, when analyzing infant industries as in the present context, it seems to be likely that there are still considerable gains from learning. Then, our result suggests that it would be better to implement a tough environmental policy early in order to take full advantage of the learning curve effect. For instance, this would confirm the opinion of authors arguing that one major reason for the dominance of the German environmental industry in the world market is that the German government was one of the first to implement a tough environmental policy.

5 Conclusion

We have shown that including an environmental industry producing a clean technology into the framework of strategic environmental policy might change the standard results known from the literature. Under Cournot-competition with production for a third market, taxes of two symmetric countries are identical and certainly below marginal damage if the impact on the environmental industry is neglected. In our model, the country the environmental industry is located in chooses a lower tax rate if and only if the quantity effect in the demand for the clean factor does not overcompensate the substitution effect.[14] Thus, whenever the environmental industry benefits from higher taxes, a national leadership will result. Moreover, the optimal emission tax rate in this country can exceed marginal damage. Since we assume that the production costs of the environmental industry are subject to a learning curve, there is an intertemporal effect of choosing the optimal tax rate in period 1. Our results suggest that choosing a higher tax rate in period 1 than in period 2 is optimal if there are considerable gains from learning in the environmental industry, as might be the case for infant environmental industries. This indicates that the presence of learning-by-doing in the environmental industry can make a tough policy control desirable from a national point of view. This argument would be in accordance with the so-called "Porter-Hypothesis", although he did not only refer to the environmental sector but also to the producing industry itself.[15]

As already discussed in the introduction, we assume that there is only one environmental industry, selling abatement to both producing firms at a fixed price between marginal costs of production and the monopoly price. Allowing for more than one environmental industry seems to be a natural extension, but turns out to complicate the model dramatically. Moreover, it leads away from the question we are most interested in, namely if a national leadership pays off. A possible extension is to relax the assumption that the price remains unchanged over time. When dropping this assumption, two further strategic effects arise: First, the producing firms are induced to deviate from cost minimizing demand for abatement in period 1 in order to stimulate the learning process to gain from a lower price of abatement in period 2. Second, the foreign country has in incentive to stimulate abatement demand in period 1, since a lower price of abatement in period 2 increases profits of the producing firms and, hence, foreign welfare.

Notes

[1]See Brander (1995) for a survey on strategic trade policy.

[2]Empirical studies confirm that the crucial factor determining the growth rate of the environmental industry is the intensity of (domestic) environmental policy. See e.g. the study of the Ifo-Institut (Wackerbauer (1995), p. 11-13). Also, Porter (1990, p. 47) has argued that tough environmental standards might enhance the incentives to carry out innovations, thereby increasing the long-term international competitiveness.

[3]See Baumol (1995) for an empirical overview. Due to these dynamic economies of scale, Baumol suggests to subsidize clean technologies that are internationally important.

[4]Thus, although in another context, learning-by-doing is modeled similarly to Fudenberg and Tirole (1983) and Dasgupta and Stiglitz (1988).

[5]The third market assumption allows us to abstract from consumer surplus, which facilitates isolating the effects caused by the presence of the environmental service industry.

[6]See the appendix for details.

[7]See e.g. Mas-Colell et al. (1995) for an exposition.

[8]Clearly, α_2 depends on t_2, T_2 and λ.

[9]An numerical example in which we have $t_2 > \Delta'$ in equilibrium is shown in the Appendix.

[10]We are grateful to an anonymous referee for having raised this point.

[11]One might also want to have the abatement price related to abatement demand, i.e. $\lambda(\alpha_2)$. However, this would lead to a different set of questions, and it would no longer be possible to solve our 6-stage game in a general way.

[12]This was pointed out by A. Ulph (1998).

[13]See Eqn. (10).

[14]Presupposed that countries are identical except for the environmental industry.

[15]See Stähler (1998) for a survey on the Porter hypothesis.

Appendix

Comparative statics of the output game with respect to t_i, T_i and λ .

The equilibrium quantities of the output game are given by[16]

$$\frac{\partial \Pi(y,Y)}{\partial y}\cdot y+\Pi(y,Y)-\frac{\partial c(y,\lambda,t)}{\partial y}=0$$

and

$$\frac{\partial \Pi(y,Y)}{\partial Y}\cdot Y+\Pi(y,Y)-\frac{\partial C(Y,\lambda,T)}{\partial Y}=0$$

Comparative statics analysis with respect to t and T leads to the following equation system:

$$\begin{pmatrix} \frac{\partial g(y,Y)}{\partial y^2} & \frac{\partial g(y,Y)}{\partial y \partial Y} \\ \frac{\partial G(y,Y)}{\partial Y \partial y} & \frac{\partial G(y,Y)}{\partial Y^2} \end{pmatrix} \begin{pmatrix} dy \\ dY \end{pmatrix} = \begin{pmatrix} \frac{\partial^2 c(y,\lambda,t)}{\partial y \partial t} dt \\ \frac{\partial^2 C(Y,\lambda,T)}{\partial y \partial T} dT \end{pmatrix}$$

Given concave profit functions and the assumptions about the cost functions, and assuming that cross effects do not dominate, i.e. $\begin{vmatrix} \frac{\partial g(y,Y)}{\partial y^2} & \frac{\partial g(y,Y)}{\partial y \partial Y} \\ \frac{\partial G(y,Y)}{\partial Y \partial y} & \frac{\partial G(y,Y)}{\partial Y^2} \end{vmatrix} > 0$ holds, and solving the system with Cramer's rule yields the usual results $\frac{dy}{dt} < 0$, $\frac{dY}{dt} > 0$, $\frac{dy}{dT} > 0$ and $\frac{dY}{dT} < 0$.

Similarly, for comparative statics with respect to λ, we have

$$\begin{pmatrix} \frac{\partial g(y,Y)}{\partial y^2} & \frac{\partial g(y,Y)}{\partial y \partial Y} \\ \frac{\partial G(y,Y)}{\partial Y \partial y} & \frac{\partial G(y,Y)}{\partial Y^2} \end{pmatrix} \begin{pmatrix} dy \\ dY \end{pmatrix} = \begin{pmatrix} \frac{\partial^2 c(y,\lambda,t)}{\partial y \partial \lambda} d\lambda \\ \frac{\partial^2 C(Y,\lambda,T)}{\partial y \partial \lambda} d\lambda \end{pmatrix}$$

i.e.

$$\frac{dy}{d\lambda} = \frac{\begin{vmatrix} \frac{\partial^2 c(y,\lambda,t)}{\partial y \partial \lambda} & \frac{\partial g(y,Y)}{\partial y \partial Y} \\ \frac{\partial^2 C(Y,\lambda,T)}{\partial y \partial \lambda} & \frac{\partial G(y,Y)}{\partial Y^2} \end{vmatrix}}{\begin{vmatrix} \frac{\partial g(y,Y)}{\partial y^2} & \frac{\partial g(y,Y)}{\partial y \partial Y} \\ \frac{\partial G(y,Y)}{\partial Y \partial y} & \frac{\partial G(y,Y)}{\partial Y^2} \end{vmatrix}}$$

and

$$\frac{dY}{d\lambda} = \frac{\begin{vmatrix} \frac{\partial g(y,Y)}{\partial y^2} & \frac{\partial^2 c(y,\lambda,t)}{\partial y \partial \lambda} \\ \frac{\partial G(y,Y)}{\partial Y \partial y} & \frac{\partial^2 C(Y,\lambda,T)}{\partial y \partial \lambda} \end{vmatrix}}{\begin{vmatrix} \frac{\partial g(y,Y)}{\partial y^2} & \frac{\partial g(y,Y)}{\partial y \partial Y} \\ \frac{\partial G(y,Y)}{\partial Y \partial y} & \frac{\partial G(y,Y)}{\partial Y^2} \end{vmatrix}}$$

With symmetric cost functions and again assuming that cross partial derivatives are not dominating, we obtain the intuitive results that $\frac{dy}{d\lambda} < 0$ and $\frac{dY}{d\lambda} < 0$.

Proof of Lemma 1:

Given the assumptions about the cost function $c(y_2, \lambda, t_2)$ and the comparative statics results of the output game, the derivative of abatement demand with respect to t_2 can go either way, since we have $\frac{\partial a_2}{\partial y_2}\frac{dy_2}{dt_2} < 0$, $\frac{\partial a_2}{\partial t_2} > 0$, and $\frac{\partial A_2}{\partial Y_2}\frac{dY_2}{dt_2} > 0$. Since the price for abatement is independent of the quantity demanded by assumption, the effect on the profits of the environmental industry is also ambiguous.

Proof of Proposition 1:

Part i):

We start with the comparison of t_2 and T_2 and show that the first order condition for country h is not satisfied in a symmetric equilibrium with $t_2 = T_2$. In equilibrium, the first order condition (15) must be satisfied. Let T_2^* be the maximizer of (15). Then,

$$\frac{\partial G_2}{\partial T_2^*} - \frac{\partial \Delta}{\partial T_2^*} = 0$$

From the symmetry of G_2 and g_2, it follows that at $t_2 = T_2^*$, we have

$$0 = \frac{\partial g_2}{\partial t_2} - \frac{\partial \Delta}{\partial t_2} \leq \frac{\partial g_2}{\partial t_2} - \frac{\partial \Delta}{\partial t_2} + \frac{\partial b_2}{\partial t_2},$$

since $\frac{\partial b_2}{\partial t_2} > 0$. Therefore, marginal social welfare in h is increasing at $t_2 = T_2^*$. Thus $t_2^* > T_2^*$.[17]

Part ii):

Take the first order conditions for welfare maximization (12) and (13)

$$\begin{aligned}\frac{\partial w_2(t_2, T_2)}{\partial t_2} &= 0\\ \frac{\partial W_2(t_2, T_2)}{\partial T_2} &= 0\end{aligned}$$

The Jacobian J is given by

$$J = \begin{pmatrix} \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2^2} & \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2 \partial T_2} \\ \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2 \partial t_2} & \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2^2} \end{pmatrix}$$

where

$$|J| = \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2^2} \cdot \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2^2} - \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2 \partial T_2} \cdot \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2 \partial t_2} > 0$$

is assumed to hold. This assumption simply says that cross partial derivatives are not dominating. For the comparative statics with respect to $\widehat{z}$ we get the following equation system:

$$\begin{pmatrix} \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2^2} & \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2 \partial T_2} \\ \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2 \partial t_2} & \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2^2} \end{pmatrix} \begin{pmatrix} dt_2 \\ dT_2 \end{pmatrix} = \begin{pmatrix} -k(\tau_1) d\widehat{z} \\ 0 \end{pmatrix}$$

Moreover, our assumptions ensure concavity of the welfare functions, i.e. $\frac{\partial^2 w_2(t_2,T_2)}{\partial t_2^2} < 0$ and $\frac{\partial^2 W_2(t_2,T_2)}{\partial T_2^2} < 0$. Solving for $\frac{dt_2}{d\widehat{z}}$, we get

$$\frac{dt_2}{d\widehat{z}} = \frac{\begin{vmatrix} -k(\tau_1) & \frac{\partial^2 w_2(t_2,T_2)}{\partial t_2 \partial T_2} \\ 0 & \frac{\partial^2 W_2(t_2,T_2)}{\partial T_2^2} \end{vmatrix}}{|J|} > 0. \blacksquare$$

Numerical example to generate $t_2 > md$ in equilibrium:

Consider a simplified version of our model consisting of the second period only. Since the result should hold whenever the costs of the environmental industry are sufficeintly low, we look at the simplest case where $z_2 = 0$. Moreover, the remaining parameters and functional relationships are specified as follows: $\Pi(y_2, Y_2) = 180 - y_2 - Y_2$, $c_2 = 2 \cdot (t_2 \cdot \lambda)^{0.5}$, $C_2 = 2 \cdot (T_2 \cdot \lambda)^{0.5}$, $\lambda = 20$, $\Delta(\Sigma_2) = \Sigma_2$ (i.e. marginal damage Δ' is equal to 1). In the last stage, for the equilibrium quantities, we get[18]

$$\begin{aligned} y_2 &= 60 - 5.96 \cdot {t_2}^{0.5} + 2.98 \cdot {T_2}^{0.5} \\ Y_2 &= 60 + 2.98 \cdot {t_2}^{0.5} - 5.96 \cdot {T_2}^{0.5} \end{aligned}$$

For total abatement demand we have

$$\alpha_2 = 13.41 \cdot ({t_2}^{0.5} + {T_2}^{0.5}) - 1.33 \cdot (t_2 + T_2) + 1.33 \cdot (t_2 T_2)^{0.5}$$

Thus, $b_2 = 20 \cdot \alpha_2$. Total emissions are given by

$$\Sigma_2 = 268.32 \cdot \left({t_2}^{-0.5} + {T_2}^{-0.5}\right) + 13.33 \cdot \left({t_2}^{0.5} {T_2}^{-0.5} + {T_2}^{0.5} {t_2}^{-0.5}\right) - 53.33$$

In the first stage, the first order conditions for maximization of the social welfare functions are

$$\frac{134.16}{{t_2}^{1.5}} - \frac{89.44}{{t_2}^{0.5}} - \frac{6.66}{(t_2 T_2)^{0.5}} + \frac{6.66 \cdot {T_2}^{0.5}}{{t_2}^{1.5}} + \frac{2.22 \cdot {T_2}^{0.5}}{{t_2}^{0.5}} - 17.77 = 0$$

and

$$\frac{141.47}{{T_2}^{1.5}} - \frac{241.87}{{T_2}^{0.5}} + 8.88 = 0$$

A solution to this nonlinear equation system is $t_2 \approx 1.20$ and $T_2 \approx 0.6$, leading to $y_2 \approx 55.67$, $Y_2 \approx 58.64$, $b_2 \approx 477.08$, and $\Sigma_2 \approx 565.38$. Thus we have $t_2 > \Delta' > T_2$.

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