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1. Introduction

Basically, strategic environmental policy models investigate the trade-off between two market imperfections: imperfect competition and negative externalities. The model's conventional setup comprises a duopoly spanning two countries which results in the typical consequences for quantities and prices: less quantities of the considered commodity are produced at a higher price compared to a market governed by perfect competition.[1] Furthermore, producing the commodity involves the generation of emissions which are treated as negative externalities since the ensuing pollution gives rise to unpriced and therefore unconsidered costs to society. Hence, in trying to reduce environmental damage a welfare-maximising government has to take into account that putting a price on emissions has consequences for the output quantities of the affected firm: everything that increases production costs of one firm automatically reduces its quantities and allows the other firm to increase output and profits. Consequently, a government, the negative impact of pollution on national welfare notwithstanding,[2] has a strong incentive to establish a regulatory measure below the Pigouvian level to allow the firm located under its jurisdiction to engage in rent seeking. This

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[1] Typically, the assumption of a third country market on which the goods are sold allows to ignore the impact of these imperfections on consumer surplus. Any considerations of the thusly involved detrimental effects that trade policies induce on national welfare are therefore neglected. The analytically convenient third country, however, has to cope with the impacts resulting from the market imperfections that the producers face.

[2] To be sure, one has to consider whether pollution is global or nationally bounded. That is, reductions in emissions in one country that are due to a lower output of the according firm will be (partly) offset by emissions in the other country whose firm can increase its output. In case of a global pollutant the first country will be worse off in two ways: profits of its firm decrease without adding much to environmental soundness.

implies that in case the government chooses to tax emissions the conventional result will be a tax rate which is lower than marginal damage, a constellation that is regularly referred to as ecological dumping (Rauscher, 1994).

So far different possible cures to this dilemma have been analysed by means of strategic environmental policy models. One way to extenuate this inherent offset is to grant the firm affected by an emission tax a subsidy for abatement activities. Such a policy mix proves to be more capable of addressing the externalities from pollution and imperfect competition because it allows for a higher tax rate and mitigates the detrimental rent-shifting effect (Conrad, 1993).[3]With tradable emission permits and an exogenously set permit price ecological dumping can be reversed (Antoniou et al., 2010). Another option for easing the trade-off between environmental protection and the competition for international market shares is to consider the impact of R&D on the involved externalities. Although an emission tax is conceived to establish allocative efficiency it also has a dynamic property in the sense that it induces innovation up to a point where the marginal costs of innovation equal the according marginal benefits. Such benefits are for instance captured by reductions in either marginal production costs (Simpson and Bradford, 1996) or marginal abatement costs (Ulph and Ulph, 1996). These cost reductions notwithstanding, the inclusion of an R&D stage does not suffice to alter the general policy prediction of a suboptimal tax policy.[4] However, this result may turn out to be provisional.

Although allowing for investments in R&D appears to be a more realistic approach compared to the early innovation-free two-stage games this modification lacks a foundation of what is implicitly assumed in form of the beneficial effects of induced innovation: the ongoing development of firm-level knowledge. To provide a more thorough basis for what happens in the process of induced innovation one needs to consider the three fundamental properties of knowledge: non-rivalry, non-excludability and cumulativeness (Foray, 2004). The first two properties give rise to the perception that knowledge has positive externalities in the sense that knowledge, once published, can be transferred at little or even no costs (internally and externally) and put to use by other agents other than its initial creator (Arrow, 1962a).[5]That is, the social benefits of creating knowledge are higher than the benefits the inventor may collect. Consequently, knowledge is underprovided by markets since the inventor cannot reap all the ensuing benefits but has to incur all involved costs (Jaffe et al., 2005). In this sense an emission tax offers an incentive to increase R&D expenditures that, although they primarily aim at economising on the more expensive factor, also mitigate strategic underinvestment in R&D. More important for the private investment motive, however, is the cumulativeness of knowledge. Novel knowledge builds upon the existing stock of knowledge which implies that R&D expenditures from previous periods, although they are sunk costs, are intertemporally effective. From an investment perspective, knowledge capital does not wear out from continuous utilisation but rather accumulates over time.[6] Furthermore, employing a hitherto otherwise utilised production factor to achieve a reduction of emissions implies opportunity costs amounting to the consumption foregone due to this shift. But while employing a physical production factor creates opportunity costs for each utilised factor the use of the factor knowledge engenders the same opportunity costs only once when R&D expenditures occur.[7]

The notion of a cumulative knowledge capital is also captured in the concepts of learning curves and learning by doing: the marginal costs of producing a certain good decrease with the amount of goods previously produced which is considered a solid proxy for accumulated experience (Arrow, 1962b, Argote and Apple, 1990). To our knowledge the notion of a learning curve has been applied to a strategic environmental policy model only once (Feess and Muehlheusser, 2002). In a two-period model the authors show that the inclusion of an environmental service sector that is subject to a learning process does not only prevent ecological dumping but renders a tax rate above the Pigouvian level possible. Obviously, this result is only obtainable in a model whose configuration allows for an intertemporal analysis of knowledge accumulation.[8]

Thus, the starting point of this analysis is the question whether a model setup that allows for the accumulation of knowledge still results in a lax regulation schedule. Our results show that incorporating the long-term effects of induced innovation will yield a less severe trade-off between the initial externalities. That is, improvements in abatement technology mitigate the negative external-

[3] Due to the countervailing pollution-shifting effect a government may have an incentive to displace polluting firms to other countries (Kennedy, 1994). This is of course only applicable for local emissions.

[4] Tax rates above the Pigouvian benchmark are possible for feasible but uncommon cost functions (Simpson and Bradford, 1996) and generally in case of price competition (Barrett, 1994).

[5] The non-existence of barriers to adoption and imitation imply that knowledge ultimately turns into a public good. However, measures such as the establishment of a property rights systems by granting patents exist to keep knowledge private (at least for a defined period of time). Furthermore, substantial transaction costs may impede or even preclude the transfer or diffusion of knowledge. These include the costs of comprehending novel knowledge. Finally, adopted knowledge needs to be integrated into the adopter's organisational context for which the necessary faculties might be missing.

[6] To be sure, the accumulation of knowledge may cease when parts of the stock of knowledge fall victim to obsoleteness or simply leave the firm. Furthermore, like external transfer of knowledge is subject to impediments such as transaction costs or imperfect absorptive capacities (Cohen and Levinthal, 1990) its internal transfer may be confronted with similar barriers.

[7] If one allows for a depreciation of knowledge capital maintenance costs which imply according opportunity costs will arise.

[8] It has been shown elsewhere that intertemporal knowledge spillovers in settings with perfect competition can lead to an emission tax above the Pigouvian level. This result is for instance captured in the "standing on shoulders of others" scenario in Greaker and Pade (2009) with endogenous technological change driven by R&D. Moreover, Gerlagh et al. (2007) show that when R&D subsidies are not feasible both R&D and learning-by-doing driven technological change are spurred by a tax rate set above the Pigouvian level.When emission stocks are rising this outcome also holds if both emission-saving and production investments are undersupplied (Hart, 2008). For similar results under a tradable emissions quota system see Golombek and Hoel (2006, 2008).

ities emanating from the emissions and simultaneously reduce the marginal costs of abatement which allows for a greater market share of the firm investing in R&D. This effect is bolstered if the firms' capabilities in accumulating knowledge are heterogeneous, that is, one firm possesses a comparative advantage in building up knowledge capital. Heterogeneity in resources, in this case in the factor knowledge, is the foundation of Ricardian rents which only accrue if the particular resource is inimitable and if its supply is limited and exceeds demand (Peteraf, 1993). Without heterogeneous resources symmetry prevails and a sustained comparative advantage is precluded. We will utilise this notion and apply it to the following analysis by furnishing the domestic firm with a comparatively higher capability in accumulating knowledge. It is then shown that due to the heterogeneity assumption the domestic government chooses a higher tax rate in period 1 compared to the foreign firm. Furthermore, under certain conditions a domestic tax rate in period 1 that is set above the Pigouvian level becomes optimal.

2. The model

We consider a two-period Cournot game in which two firms that are located in two different countries produce a homogenous consumption good.[9] Producing the good entails the creation of environmentally harmful emissions. Each country also harbours a welfare-maximising governmental agency that aims at internalising the negative externality of pollution. To do so it sets a tax rate per unit of emission.

The game comprises two periods, each containing three stages. Due to the specific sequence of the game it can be solved via backward induction beginning with stage 6 (that is the third stage in period 2). In the respective third stages the firms choose their equilibrium quantities and take the choice variables of the other stages as given. The output is then sold on a third country's market which allows for the omission of consumer surplus in the welfare functions. In the second stages firms choose their optimal level of emission-reducing expenditures. As will be shortly explicated the basic model differentiates between the domestic and the foreign extent of knowledge capitalisation. Finally, in the first stages the governments choose a welfare-maximising tax rate. This structure has two important implications. First, the strategy space in period 2 resembles the strategy space of a one-period model since no further periods are considered. Therefore, in period 2 the actors do not account for a further accumulation of the firms' knowledge capital. Hence, the latter's cumulativeness only applies for the transition between period 1 and 2. Second, in period 1 all actors have to factor in that the knowledge capital created intratemporally serves as the fundament for its counterpart in period 2. Depending on assumptions about depreciation (and therefore discounting) the players know that they make an intertemporal decision in period 1. That is, they need to account for the effects that will emerge intertemporally while in period 2 they only consider intratemporal effects. By solving the game backwards only decisions that are intratemporally effective will be obtained in period 2. These, in turn, constitute information necessary to make an intertemporally optimal decision in period 1. Fig. 1 summarises the sequence of the game.

Generally, the model is symmetrical except for the asymmetric treatment of knowledge parameters which captures the idea of heterogeneous resources. Throughout the game superscripts i,j refer to domestic (d) and foreign (f) while subscripts t = 1,2 refer to period 1 and two, respectively.[10] Furthermore, the following notations and functional relationships apply:

Firms face a downward-sloping inverse demand function $P(q_t^i + q_t^j)$ for the consumption good on the third country market with q_t^i denoting the output of firm i in period t.

The emissions of firm i in period t are denoted e_t^i and given by the function $e_t^i(q_t^i, \kappa_t^i)$. Hence, they depend on q_t^i and κ_t^i, firm i's knowledge capital in period t. Emissions are assumed to be solely local. The following properties apply:

$$\frac{\partial e_t^i}{\partial q_t^i} > 0 \quad \frac{\partial^2 e_t^i}{\partial (q_t^i)^2} = 0 \tag{A1}$$

$$\frac{\partial e_t^i}{\partial \kappa_t^i} < 0 \quad \frac{\partial^2 e_t^i}{\partial (\kappa_t^i)^2} > 0 \tag{A2}$$

Assumptions (A1) and (A2) define that emissions are linear in quantities and strictly convex in knowledge capital. The linear property arises to avoid ambiguities in the comparative static analyses of the following stages. Due to the convexity property returns from knowledge capital in reducing emissions are diminishing.

Moreover, each firm has the cost function $C^i(q_t^i, t_t^i, \kappa_t^i)$ with t_t^i denoting country i's tax rate in period t. The following properties apply:

$$\frac{\partial C^i}{\partial q_t^i} > 0 \quad \frac{\partial^2 C^i}{\partial (q_t^i)^2} = 0 \tag{A3}$$

$$\frac{\partial C^i}{\partial t_t^i} > 0 \quad \frac{\partial^2 C^i}{\partial (t_t^i)^2} \leq 0 \tag{A4}$$

$$\frac{\partial C^i}{\partial \kappa_t^i} < 0 \quad \frac{\partial^2 C^i}{\partial (\kappa_t^i)^2} > 0 \tag{A5}$$

By the previous assumptions costs are linear in output, concave in taxes and strictly convex in knowledge capital. Assumption (A3) implies that the production process is subject to constant returns to scale. The concavity property in assumption (A4) captures a linear as well as a concave relation between costs and the respective tax rate. The latter may arise if (A4) also includes the indirect effects of an increasing tax rate (that is, the marginal effect of a growing tax rate on costs is decreasing since, as will be proved later,

[9] Analysing a Cournot-setup guaranteesa high degree of comparability to previous strategic environmental policy games and thereby enables us to investigate the different strategic effects. Furthermore, many, if not all, pollution intensive industries are characterised by oligopolistic structures.

[10] Whenever feasible, time indices are suppressed. Moreover, all functions are assumed to be time-invariant.

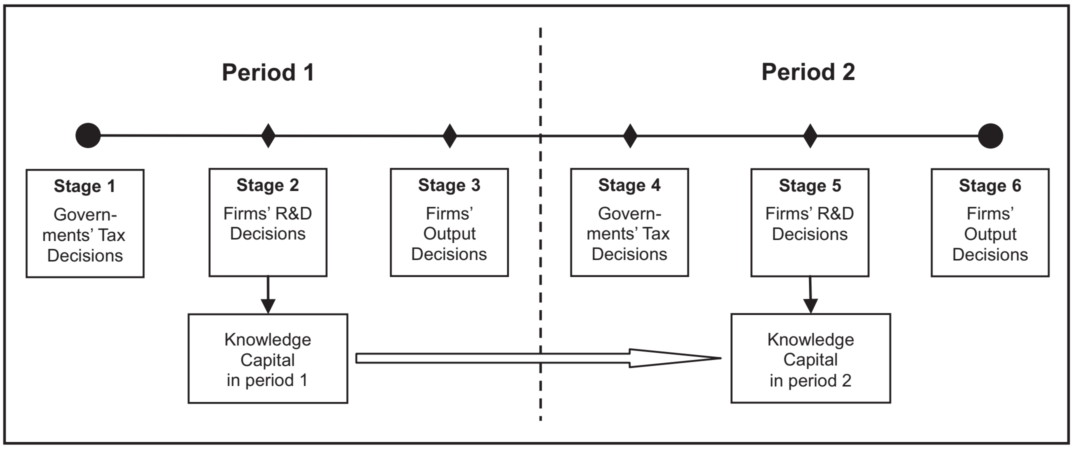

Fig. 1. The sequence of the game.

an intensified tax policy results in less quantities which reduces production costs). The convexity in (A5) follows from (A2).

In period 1 knowledge capital $\kappa_1^i = \kappa_1^i(I_1^i)$ solely accrues from R&D expenditures I_1^i:

$$\kappa_1^i = \alpha^i \cdot I_1^i \tag{A6}$$

Furthermore, the parameter $\alpha^i > 0$ measures the effect of R&D expenditures on knowledge capital in period 1 (that is, the success of R&D expenditures).[11] In combination with (A5) this implies $\partial C^i/\partial I_t^i < 0$.

In period 2 the increments in κ_2^i resulting from intratemporal R&D expenditures build upon the stock of knowledge from period 1 and generate the intertemporal knowledge capital $\kappa_2^i = \kappa_2^i(\kappa_1^i(\cdot), I_2^i)$:

$$\kappa_2^i = \kappa_1^i(\cdot) + \beta^i \cdot I_2^i \tag{A7}$$

The parameter $\beta^i > 0$ measures the effect of R&D expenditures on knowledge capital in period 2. We assume that $\alpha^i > \beta^i$ (early units of R&D are more effective in creating knowledge capital than later units which is tantamount to decreasing returns of knowledge capital). Heterogeneity is introduced by differentiated knowledge parameters: $\alpha^d > \alpha^f > \beta^d > \beta^f$. Hence, the domestic firm has a comparative advantage in terms of creating novel knowledge.

Finally, environmental harm is captured in the damage function $D(e_t^i)$:

$$\frac{\partial D}{\partial e_t^i} > 0 \quad \frac{\partial^2 D}{\partial (e_t^i)^2} \geq 0 \tag{A8}$$

By assumption (9) environmental damage is convex in emissions.[12]

In the third stages of the game the firms choose their optimal quantities which maximise the according profit function:

$$\max_{q_t^i} \Pi_t^i = P(q_t^i + q_t^j) \cdot q_t^i - C^i(q_t^i, t_t^i, \kappa_t^i) \tag{OF1}$$

Maximising (OF1) will yield optimal quantities as functions of both the domestic and foreign strategic variables from stages 2 and 1. Reinserting the optimal quantities from stage 3 into (OF1) and including R&D expenditures yields the objective function in the second stage:

$$\max_{I_t^i} \Pi_t^i = P(q_t^i + q_t^j) \cdot q_t^i - C^i(q_t^i, t_t^i, \kappa_t^i) - I_t^i \tag{OF2}$$

Maximising (OF2) yields the equilibrium R&D expenditures that, in turn, depend on domestic and foreign tax rates.

In the first stages the governments set the optimal tax rates by maximising their welfare functions:

$$\max_{t_t^i} \Phi_t^i = P(q_t^i + q_t^j) \cdot q_t^i - C^i(q_t^i, t_t^i, \kappa_t^i) - I_t^i - D(e_t^i(\cdot)) + t_t^i \cdot e_t^i(\cdot) \tag{OF3}$$

Finally, the following condition guarantees a globally stable and unique equilibrium:

$$|\Omega_s| = \frac{\partial^2 \Pi_t^i}{\partial (s_t^i)^2} \cdot \frac{\partial^2 \Pi_t^j}{\partial (s_t^j)^2} - \frac{\partial^2 \Pi_t^i}{\partial s_t^i s_t^j} \cdot \frac{\partial^2 \Pi_t^j}{\partial s_t^j s_t^i} > 0 \quad \text{with}$$

$$s_t^i = q_t^i, I_t^i, t_t^i \tag{A9}$$

Additionally, condition (A9) – where s^i denotes the respective strategic variable in country i – implies that own effects dominate cross-effects:

Furthermore, due to the previous assumptions $\partial \Pi_t^i/\partial q_t^i \partial q_t^j < 0$ holds which restates the conventional Cournot result that domestic and foreign quantities are strategic substitutes.

Additionally it is assumed that all respective second-order conditions are satisfied. Thus, all objective functions are strictly concave. Finally, a stringent tax policy or tax rate henceforth refers to a tax rate that is set above the according intratemporal Pigouvian level.

[11] To be sure, a positive knowledge parameter ignores the possibility that R&D activities may fail to create knowledge capital. That is, R&D is always successful.

[12] It is assumed that emissions are a flow pollutant.

3. Decisions in period 2

In stage 6 both firms choose their output quantities. They do so by differentiating (OF1) with respect to quantities. This yields the following first-order conditions which implicitly define the Nash-Equilibrium in quantities (assuming that an interior solution exists):

$$\frac{\partial \Pi_2^i}{\partial q_2^i} = P'(\cdot)\cdot q_2^i + P(\cdot) - \frac{\partial C^i}{\partial q_2^i} = 0 \quad (1)$$

First-order condition (1) implies the reaction functions $\tilde{q}_2^i = q_2^i(q_2^j)$. Equilibrium quantities can therefore be written as $q_2^i = q_2^i(\kappa_2^i, \kappa_2^j, t_2^i, t_2^j)$.

The direct effects of the strategic variables on quantities can be analysed by totally differentiating the first-order conditions with respect to the according variable. In the following we will focus on the impact of the domestic variables beginning with the tax rate (see Appendix A for details).[13] The results replicate the common findings $dq_t^d/dt_t^d < 0$ and $dq_t^f/dt_t^d > 0$. By an increase in the domestic tax rate domestic costs increase which entails an output cutback. And whenever domestic quantities decrease foreign quantities partly fill the gap and increase. However, these differentials ignore the impact of R&D. That is, ultimately an increase in the tax rate may increase quantities indirectly via the impact of R&D.

To assess the effects of increases in domestic R&D expenditures on quantities the first-order conditions need to be totally differentiated with respect to domestic R&D expenditures (see Appendix B for details). Via the cost-reducing effect of domestic R&D expenditures domestic quantities increase ($dq_t^d/dI_t^d > 0$). And since everything that decreases domestic costs also increases domestic quantities and consequently decreases foreign quantities dq_t^f/dI_t^d is negative.

Moreover, (by virtue of the assumed demand structure) the conventional Cournot results are obtained, namely that even when the respective rival's reaction is optimal total industry output declines. This is a direct consequence of the well-established stability condition for reaction functions: the absolute value of the slope of $\tilde{q}_t^f$ has to be lower than the absolute value of the slope of $\tilde{q}_t^d$ (Tirole, 1988, p. 220).[14]

In stage 5 the firms decide on their R&D expenditures. Differentiating (OF2) with respect to R&D expenditures yields the following first-order conditions which implicitly define the Nash-Equilibrium in R&D expenditures (again, assuming an interior solution):

$$\frac{\partial \Pi_2^i}{\partial I_2^i} = \left(P'(\cdot)\cdot q_2^i + P(\cdot) - \frac{\partial C^i}{\partial q_2^i}\right)\cdot\frac{\partial q_2^i}{\partial \kappa_2^i}\cdot\frac{\partial \kappa_2^i}{\partial I_2^i} + P'(\cdot)\cdot\frac{\partial q_2^j}{\partial \kappa_2^i}\cdot\frac{\partial \kappa_2^i}{\partial I_2^i}\cdot q_2^i - \frac{\partial C^i}{\partial \kappa_2^i}\cdot\frac{\partial \kappa_2^i}{\partial I_2^i} - 1 = 0 \quad (2)$$

[13] The according results for the foreign strategic variables can be easily obtained.

[14] A sufficient condition for stability in reaction functions is $\left|\tilde{q}_t^i\right| < 1$ (Tirole, 1988, p. 220 (footnote 15), Dixit, 1986, pp. 109-111).

By (1), (2) reduces to:

$$\frac{\partial \Pi_2^i}{\partial I_2^i} = P'(\cdot)\cdot\frac{\partial q_2^j}{\partial \kappa_2^i}\cdot q_2^i\cdot\beta^i - \frac{\partial C^i}{\partial \kappa_2^i}\cdot\beta^i = 1 \quad (3)$$

First-order condition (3) shows that in equilibrium the cross effect of own R&D expenditures (via own knowledge capital) on rival quantities minus own cost reductions due to lower emissions equal the last Euro spent on R&D expenditures. Hence, a firm invests in R&D until the ensuing cost reductions are compensated by the decline in relative revenues which result from falling market prices. The market price falls because the negative cross effect ($\partial q_2^j/\partial\kappa_2^i < 0$) and own cost reductions imply an increase in domestic quantities.

Although both firms face the same optimisation schedule the domestic firm has an incentive to reduce its R&D expenditures in period 2 for two reasons. First, the game ends with period 2 which precludes further knowledge accumulation. Hence, if the domestic firm sufficiently invested in R&D in period 1 it will benefit from an according knowledge accumulation (this interdependency will be proved later). Second, due to $\beta^d > \beta^f$ the domestic firm has an advantage over its foreign competitor. That is, if both firms would want to avoid the same amount of emissions the domestic firm benefits from comparatively lower costs since it possesses higher capabilities in creating knowledge capital. If, in a homogenous world, the parameters were identical this comparative advantage would vanish resulting in symmetric incentives for both firms to reduce R&D expenditures in period 2.

What remains unsolved is the question whether an increase in the tax rate actually induces R&D expenditures. This issue can be analysed by totally differentiating the second stage first-order conditions with respect to the domestic tax rate (see Appendix C for details). Solving the ensuing equation system with Cramer's Rule yields

$$\frac{dI_t^d}{dt_t^d} = \frac{\left(\frac{\partial^2 C^d}{\partial I_t^d \partial t_t^d}\cdot\frac{\partial^2 \Pi_t^f}{\partial (I_t^f)^2} - \frac{\partial^2 C^f}{\partial I_t^f \partial t_t^d}\cdot\frac{\partial^2 \Pi_t^d}{\partial I_t^d \partial I_t^f}\right)}{\left|\Omega_I\right|} \quad (4a)$$

$$\frac{dI_t^f}{dt_t^d} = \frac{\left(\frac{\partial^2 \Pi_t^d}{\partial (I_t^d)^2}\cdot\frac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} - \frac{\partial^2 \Pi_t^f}{\partial I_t^f \partial I_t^d}\cdot\frac{\partial^2 C^d}{\partial I_t^d \partial t_t^d}\right)}{\left|\Omega_I\right|} \quad (4b)$$

At first glance the signs of the differentials are ambiguous and depend on two factors:

An increase in the domestic tax rate impacts the marginal cost reductions to be had from an increase in R&D expenditures in both firms. Obviously, in (4a) the existence of induced innovations in the domestic firm necessitates $\partial^2 C^d/\partial I_t^d \partial t_t^d < 0$ which implies that the marginal effect of R&D expenditures on costs declines with an increasing tax rate. This reflects the diminishing returns of R&D expenditures in creating knowledge capital and moreover emphasises the fact that taxes are not only an incentive to invest in R&D but also costs whose direct effect is a reduction in quantities (see stage 6).[15]

The sign of $\partial^2 C^f/\partial I_t^f \partial t_t^d$ is negative due to the heterogeneity in knowledge accumulation. An increase in the domestic tax rate benefits the creation of cost-reducing domestic knowledge capital which results in lower foreign quantities. This gap cannot be compensated by an equal foreign investment which shows that the marginal effect that foreign R&D expenditures exact on foreign costs is comparatively lower. To be sure, this rationale only applies if the cost-reductions from domestic induced innovation, captured by an outward shift of the domestic firm's reaction function, preponderate domestic tax payments which cause an outward shift of the foreign firm's reaction function (Ulph, 1994).

The signs of $\partial^2 \Pi_t^i/\partial I_t^i \partial I_t^j$ are negative since an increase in firm j's R&D expenditures increases its quantities at the expense of firm i's output which lowers the marginal effect that firm i's R&D expenditures have on its profits.

It follows from the above that $dI_t^d/dt_t^d > 0$ and $dI_t^f/dt_t^d > 0$: an increase in the domestic tax rate induces domestic innovations but also prompts foreign R&D expenditures.

Finally, in stage 4 the governments fix their period 2 tax rates based on their policy decision in period 1. Using the fact that by Shepard's Lemma $\partial C^i/\partial t_t^i = e_t^i$ and, after reinserting the results from previous stages, differentiating (OF3) with respect to the tax rates yields, after accounting for (1) and (3), the following first-order condition:[16]

$$\frac{\partial \Phi_2^i}{\partial t_2^i} = P'(\cdot) \cdot \frac{\partial q_2^j}{\partial t_2^i} \cdot q_2^i + P'(\cdot) \cdot \frac{\partial q_2^j}{\partial \kappa_2^j} \cdot \frac{\partial I_2^j}{\partial t_2^i} \cdot q_2^i \cdot \beta^j - \frac{\partial D}{\partial e_2^i} \cdot \gamma^i + t_2^i \cdot \gamma^i = 0 \qquad (5)$$

Solving first-order condition (5) for the domestic tax rate yields the optimal domestic regulation schedule[17] inperiod 2[18]:

$$t_2^d = \frac{\partial D}{\partial e_2^d} + \frac{1}{\gamma^d} \cdot (\theta_5^d + \theta_6^d) \qquad (6)$$

Optimality condition (6) shows that several strategic effects distort the Pigouvian level $t_2^d = \partial D/\partial e_2^d$ at which the tax rate equals marginal damage. The multiplier $1/\gamma^d$ captures the effects of altered quantities and knowledge capital on emissions. In detail the multiplier contains four strategic effects which determine its sign and therefore the basic distortion from the Pigouvian level which is then multiplied with each of the remaining strategic effects in the parenthesis. Hence, if the multiplier is negative an effect in the parenthesis has to be negative (positive) to entail an upward (downward) shift of the optimal tax rate. To begin with, the four effects included in the multiplier will be explained.

Direct output cutback effect: the negative term θ_1^d captures the direct impact of an increase in the tax rate ($dq_2^d/dt_2^d < 0$), namely an output cutback which entails fewer emissions.

Aggregate emissions effect: the positive term θ_2^d describes how an increase in domestic quantities due to a growing domestic knowledge capital also increases total domestic emissions.

Indirect output cutback effect: the negative term θ_3^d shows how an increasing domestic tax rate also induces foreign R&D expenditures which entail a growing foreign knowledge capital. The latter, in turn, reduces foreign costs which increases foreign quantities and thereby decreases domestic quantities.

Innovation effect: the negative term θ_4^d captures the direct impact of induced innovations which increase domestic knowledge capital and thus decrease domestic relative emissions.

To avoid undue ambiguities it will be assumed that the three negative effects outweigh the single positive effect which implies that the sum of the reductions in relative emissions are not again overcompensated by an increase in aggregate emissions that may ensue from increased quantities. Hence, a negative multiplier is guaranteed if the *emission-overcompensation condition* (7) holds:

$$\left| \frac{\partial e_2^d}{\partial q_2^d} \cdot \left(\frac{\partial q_2^d}{\partial t_2^d} + \frac{\partial q_2^d}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot \beta^f \right) + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot \beta^d \right| > \left| \frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot \beta^d \right| \qquad (7)$$

The optimal tax rate then follows from the remaining strategic effects in the parenthesis of (6).

Direct rent-shifting effect: The positive term θ_5^d shows that an increase in domestic costs due to a higher tax rate entails increased foreign quantities which in turn results in decreasing domestic quantities. However, since total industry output falls the equilibrium price for the commodity increases which benefits the foreign firm (that is to say, domestic revenues decline). Thus, the rent-shifting effect exercises a downward pressure on the tax rate.

Indirect rent-shifting effect: The positive term θ_6^d augments the rent-shifting effect through the ramifications of $\partial I_2^f/\partial t_2^d > 0$ (see stage 5). Hence, a rise in the domestic tax rate increases foreign knowledge capital and accordingly foreign quantities. The latter, of course, happens at the expense of domestic quantities. Consequently, the downward pressure on the tax rate is intensified.

The intratemporal perspective of period 2 allows investigating the stringency of the according period 2 domestic

[15] Moreover, emissions need to be sufficiently convex to allow for $\partial^2 C^d/\partial I_t^d \partial t_t^d < 0$ because the effect of reduced tax payments due to diminishing emissions must not be overcompensated by rising regulation costs from increased aggregate domestic output. See condition (7).

[16] With $\gamma^i = \theta_1^i + \theta_2^i + \theta_3^i + \theta_4^i = \frac{\partial e_2^i}{\partial q_2^i} \cdot \left(\frac{\partial q_2^i}{\partial t_2^i} + \frac{\partial q_2^i}{\partial \kappa_2^i} \cdot \frac{\partial I_2^i}{\partial t_2^i} \cdot \beta^i + \frac{\partial q_2^i}{\partial \kappa_2^j} \cdot \frac{\partial I_2^j}{\partial t_2^i} \cdot \beta^j \right) + \frac{\partial e_2^i}{\partial \kappa_2^i} \cdot \frac{\partial I_2^i}{\partial t_2^i} \cdot \beta^i$ and $\theta_1^i = \frac{\partial e_2^i}{\partial q_2^i} \cdot \frac{\partial q_2^i}{\partial t_2^i}$; $\theta_2^i = \frac{\partial e_2^i}{\partial q_2^i} \cdot \frac{\partial q_2^i}{\partial \kappa_2^i} \cdot \frac{\partial I_2^i}{\partial t_2^i} \cdot \beta^i$; $\theta_3^i = \frac{\partial e_2^i}{\partial q_2^i} \cdot \frac{\partial q_2^i}{\partial \kappa_2^j} \cdot \frac{\partial I_2^j}{\partial t_2^i} \cdot \beta^j$; $\theta_4^i = \frac{\partial e_2^i}{\partial \kappa_2^i} \cdot \frac{\partial I_2^i}{\partial t_2^i} \cdot \beta^i$.

[17] The foreign regulation schedule only differs in terms of the knowledge parameter.

[18] With $\theta_5^d = -P'(\cdot) \cdot \frac{\partial q_2^f}{\partial t_2^d} \cdot q_2^d$; $\theta_6^d = -P'(\cdot) \cdot \frac{\partial q_2^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot q_2^d \cdot \beta^f$.

tax rate. A tax rate set above the Pigouvian benchmark requires that in total the product of the multiplier and the remaining strategic effects has a positive sign. Since the only remaining effects are positive *rent shifting effects* the overall effect has to be negative. Hence, testing the intratemporal case for the stringency hypothesis proves that a stringent tax policy is suboptimal. This replicates the result from standard one-period models.

Proposition 1 (.). *The domestic government will not set a tax rate above the Pigouvian level in period 2 since the overall effect distorting the Pigouvian level is negative* (Proof: see Appendix D).

Next, the decisions in period 1 will be analysed.

4. Decisions in period 1

In stage 3 firms set their optimal output quantities. The first order conditions in stage 3 are the period 1 equivalents from the results in stage 6.

$$\frac{\partial \Pi_1^i}{\partial q_1^i} = P'(\cdot)\cdot q_1^i + P(\cdot) - \frac{\partial C^i}{\partial q_1^i} = 0 \tag{8}$$

The previous results apply accordingly.

In stage 2 both firms set their period 1 R&D expenditures which affects both periods. This gives rise to the intertemporal objective function (OF2i):

$$\begin{aligned} \Pi^i = \Pi_1^i + \Pi_2^i = P(q_1^i + q_1^j)\cdot q_1^i - C^i(q_1^i, t_1^i, \kappa_1^i) - I_1^i \\ + P(q_2^i + q_2^j)\cdot q_2^i - C^i(q_2^i, t_2^i, \kappa_2^i) - I_2^i \end{aligned} \tag{OF2i}$$

Reinserting the previous results into (OF2i) and maximising intertemporal profits with respect to period 1 R&D expenditures yields the following first-order condition:

$$\begin{aligned} \frac{\partial \Pi^i}{\partial I_1^i} &= P'(\cdot)\cdot\frac{\partial q_1^j}{\partial \kappa_1^i}\cdot q_1^i\cdot\alpha^i - \frac{\partial C^i}{\partial \kappa_1^i}\cdot\alpha^i + P'(\cdot)\cdot\frac{\partial q_2^j}{\partial \kappa_2^i}\cdot q_2^i\cdot\alpha^i \\ &\quad - \frac{\partial C^i}{\partial \kappa_2^i}\cdot\alpha^i = 1 \end{aligned} \tag{9}$$

In contrast to the first-order condition in period 2 (9) includes the intertemporal equivalents to (3) from period 1(these are the third and the fourth term in (9)). Therefore, satisfaction of condition (9) necessitates that both intratemporal and intertemporal effects equal the last Euro spent on R&D expenditures in period 1. Furthermore, the knowledge effects are now measured by α^i. Since period 1 R&D expenditures lead to cost reductions in both periods each firm faces an incentive to invest relatively more in period 1 R&D to benefit from an early commencement with the accumulation of knowledge capital.

In stage 1 the governments set their initial equilibrium tax rates. To account for the intertemporal effects of the policy choice in period 1 the intertemporal objective function (OF3i) has to be formed:

$$\begin{aligned} \Phi^i = \Phi_1^i + \Phi_2^i = P(q_1^i + q_1^j)\cdot q_1^i - C^i(q_1^i, t_1^i, \kappa_1^i) - I_1^i - D(e_1^i(\cdot)) + t_1^i\cdot e_1^i(\cdot) \\ + P(q_2^i + q_2^j)\cdot q_2^i - C^i(q_2^i, t_2^i, \kappa_2^i) - I_2^i - D(e_2^i(\cdot)) + t_2^i\cdot e_2^i(\cdot) \end{aligned} \tag{OF3i}$$

After incorporating the previous results the maximisation of intertemporal welfare yields the according first-order condition (after factoring in (8) and (9)):[19]

$$\begin{aligned} \frac{\partial \Phi^i}{\partial t_1^i} &= P'(\cdot)\cdot\frac{\partial q_1^j}{\partial t_1^i}\cdot q_1^i + P'(\cdot)\cdot\frac{\partial q_1^j}{\partial \kappa_1^j}\cdot\frac{\partial I_1^j}{\partial t_1^i}\cdot q_1^i\cdot\alpha^j - \frac{\partial D}{\partial e_1^i}\cdot\eta^i + t_1^i\cdot\eta^i + P'(\cdot)\cdot\frac{\partial q_2^j}{\partial \kappa_2^j}\cdot\frac{\partial I_1^j}{\partial t_1^i}\cdot q_2^i\cdot\alpha^j \\ &\quad - \left(\frac{\partial D}{\partial e_2^i} - t_2^i\right)\cdot\left[\frac{\partial e_2^i}{\partial q_2^i}\cdot\left(\frac{\partial q_2^i}{\partial \kappa_2^i}\cdot\frac{\partial I_1^i}{\partial t_1^i}\cdot\alpha^i + \frac{\partial q_2^i}{\partial \kappa_2^j}\cdot\frac{\partial I_1^j}{\partial t_1^i}\cdot\alpha^j\right) + \frac{\partial e_2^i}{\partial \kappa_2^i}\cdot\frac{\partial I_1^i}{\partial t_1^i}\cdot\alpha^i\right] = 0 \end{aligned} \tag{10}$$

The optimal domestic tax rate[20] consequently is[21]:

$$t_1^d = \frac{\partial D}{\partial e_1^d} + \frac{1}{\eta^d}\cdot(\omega_5^d + \omega_6^d + \omega_7^d + \omega_8^d) \tag{11}$$

Note that when fixing its tax rate in period 1 the domestic government has to consider two additional intertemporal effects (see below). The period 1 equivalents of the *direct rent-shifting effect* and the *indirect rent-shifting effect* are maintained. Furthermore, the multiplier $1/\eta^d$ now contains the according period 1 counterparts to the *direct output cutback effect*, the *aggregate emissions effect*, the *indirect output cutback effect*, and the *innovation effect* from period 2. Again, to guarantee a negative multiplier the following *emission-overcompensation condition* has to hold (cf. condition (7)):

$$\begin{aligned} &\left|\frac{\partial e_1^d}{\partial q_1^d}\cdot\left(\frac{\partial q_1^d}{\partial t_1^d} + \frac{\partial q_1^d}{\partial \kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot\alpha^f\right) + \frac{\partial e_1^d}{\partial \kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right| \\ &\quad > \left|\frac{\partial e_1^d}{\partial q_1^d}\cdot\frac{\partial q_1^d}{\partial \kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right| \end{aligned} \tag{12}$$

Finally, the two novel strategic effects are:

Intertemporal indirect rent-shifting effect: The positive term ω_7^d captures the intertemporal cross effect of induced innovations. An increase in domestic period 1 taxes affects

[19] With $\eta^i = \omega_1^i + \omega_2^i + \omega_3^i + \omega_4^i = \frac{\partial e_1^i}{\partial q_1^i}\cdot\left(\frac{\partial q_1^i}{\partial t_1^i} + \frac{\partial q_1^i}{\partial \kappa_1^i}\cdot\frac{\partial I_1^i}{\partial t_1^i}\cdot\alpha^i + \frac{\partial q_1^i}{\partial \kappa_1^j}\cdot\frac{\partial I_1^j}{\partial t_1^i}\cdot\alpha^j\right) + \frac{\partial e_1^i}{\partial \kappa_1^i}\cdot\frac{\partial I_1^i}{\partial t_1^i}\cdot\alpha^i$ and $\omega_1^i = \frac{\partial e_1^i}{\partial q_1^i}\cdot\frac{\partial q_1^i}{\partial t_1^i}$; $\omega_2^i = \frac{\partial e_1^i}{\partial q_1^i}\cdot\frac{\partial q_1^i}{\partial \kappa_1^i}\cdot\frac{\partial I_1^i}{\partial t_1^i}\cdot\alpha^i$; $\omega_3^i = \frac{\partial e_1^i}{\partial q_1^i}\cdot\frac{\partial q_1^i}{\partial \kappa_1^j}\cdot\frac{\partial I_1^j}{\partial t_1^i}\cdot\alpha^j$; $\omega_4^i = \frac{\partial e_1^i}{\partial \kappa_1^i}\cdot\frac{\partial I_1^i}{\partial t_1^i}\cdot\alpha^i$.

[20] In the foreign regulation schedule own effects differ in terms of the lower knowledge parameter and α^d replaces α^f in the according rent-shifting effects.

[21] $\omega_5^d$and ω_6^d are the intratemporal equivalents to period 2 effects θ_5^d and θ_6^d. Moreover, $\omega_7^d = -P'(\cdot)\cdot\frac{\partial q_2^f}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_2^d\cdot\alpha^f$ and $\omega_8^d = \left(\frac{\partial D}{\partial e_2^d} - t_2^d\right)\cdot\left[\frac{\partial e_2^d}{\partial q_2^d}\cdot\left(\frac{\partial q_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d + \frac{\partial q_2^d}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot\alpha^f\right) + \frac{\partial e_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right]$.

foreign R&D expenditures in period 1 and therefore also enhances the foreign period 2 knowledge capital. The ensuing increase in foreign period 2 quantities takes place at the expense of their domestic counterpart. Hence, this effect lowers the domestic tax rate.

Policy adjustment effect: The policy adjustment effect ω_8^d captures the intertemporal adjustment of the tax rate. It would vanish in case the government chooses the Pigouvian level in period 2 (at the Pigouvian benchmark $\partial D/\partial e_2^d - t_2^d$ becomes zero). However, as the investigation of the intratemporal case has shown $\partial D/\partial e_2^d > t_2^d$ is the optimal policy choice in period 2 which yields a positive expression in the first parenthesis. Provided that their balance is nonzero, the terms in the brackets represent a fundamental trade-off: the last term shows how intertemporal knowledge accumulation lowers domestic emissions in period 2. This term reflects the *intertemporal innovation effect*. But this reduction may be (over)compensated by an increase in total domestic emissions due to increased domestic output as described in the first term which captures the *intertemporal aggregate emissions effect*. Although the second term, the *intertemporal indirect output cutback effect*, in the brackets is negative the expression in the according parenthesis is positive since direct effects dominate indirect effects.[22] It follows that if the emission-decreasing effect captured in the last term outweighs according increases in aggregate output the policy adjustment effect will be negative. This *intertemporal emission-overcompensation condition* is captured in (13):

$$\left|\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot\alpha^f+\frac{\partial e_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right| > \left|\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right| \tag{13}$$

Thus, by (13) a lax tax policy in period 2 produces an upward pressure on the tax rate in period 1.[23]

Fig. 2 presents the according optimal regulation schedule:

By virtue of the negative policy adjustment effect the governments face an incentive to tighten their environmental regulation in period 1: due to the *intertemporal innovation effect* inducing innovations early puts each firm intertemporally in a better position. If this effect outweighs the *intertemporal aggregate emissions effect* it will entail a downward adjustment of the tax rate in period 2. Whether a government chooses to do so depends on the tax rate in period 1: if the tax rate exceeds the Pigouvian benchmark the reductions in emissions will exceed the intratemporally optimal amount of abatement in period 1. This, in turn, gives rise to a stronger policy adjustment effect. If, however, a lax taxation policy emerges due to strong *rent-shifting effects* abatement in period 1 will be suboptimal. Hence, a stringent tax policy in period 1 entails an accordingly adjusted tax rate in period 2 which reduces the respective costs of regulation. The intertemporal perspective therefore offers a strong argument for prompting early R&D.

It follows that, by virtue of the assumed knowledge parameter configuration, the domestic government in period 1 has a higher incentive to induce R&D expenditures.

Proposition 2 (.). *The domestic government will set a higher tax rate in period 1 than the foreign government.*

The comparative static analysis in stage 5 has proven that an increase in the tax rate induces R&D expenditures. Due to the heterogeneity in knowledge parameters the ensuing knowledge capital will be higher in the domestic firm (for a given amount of R&D expenditures). An increase in knowledge capital, in turn, entails an increasing *innovation effect* θ_4^i. Since the latter's respective strength is measured by the knowledge parameter it follows that $\theta_4^d > \theta_4^f$. Moreover, by (7) the *innovation effect* will outweigh the *aggregate emissions effect*.

The advance in accumulating knowledge capital is furthered by the intertemporal accumulation of knowledge capital. As the first-order conditions in stage 2 have shown the domestic firm needs less R&D expenditures to obtain the same level of knowledge capital. This intertemporal property is captured in the *policy adjustment effect* which furthers the upward pressure on the period 1 tax rate the stronger the *intertemporal innovation effect* becomes. The latter's strength is again measured by α^d which entails $\omega_8^d > \omega_8^f$. Consequently, the domestic government has a comparatively stronger incentive to set a higher tax rate in period 1. Again, in a world with homogenous knowledge parameters the domestic firm would not have such a comparative advantage which would entail symmetric intra- and intertemporal innovation effects in both firms. This, in turn, would dissolve the domestic government's incentive to play first-mover.

With this issue settled the question of stringency remains. It turns out that a tax rate set above the Pigouvian benchmark requires two conditions which can be inferred from first-order condition (10): first, the negative *policy adjustment effect* presupposes that the according expression in the second row of first-order condition (10), which has a negative sign, is positive. To have a stringent tax policy in period 1 the remaining negative effects (see below) need to be overcompensated. This is captured in the *policy adjustment condition* which therefore has to be positive. Hence, this condition is necessary for a stringent tax policy in period 1. Since the tax policy in period 2 is lax and (13) applies the policy adjustment condition will be positive. Second, the policy adjustment effect has to predominate the sum of the rent-shifting effects. If this does not happen $t_1^d - \partial D/\partial e_1^d$ would have to be negative to satisfy first-order condition (10) which would result in a suboptimal internalisation of the negative externality. However, if

[22] Moreover, the heterogeneity in knowledge parameters corroborates the positive sign.

[23] To be sure, the adjustment effect emanates because the whole game is about finding the optimal environmental policy. Contrary to such an optimisation approach the agency may want to gradually strengthen its policy to maintain the incentive to reduce emissions (or substitute input factors). This would entail the setting of an environmental goal. In the present setting therefore less emissions in period 1 imply less environmental damage which, from an equilibrium perspective, entails a lower tax rate in period 2 compared to period 1.

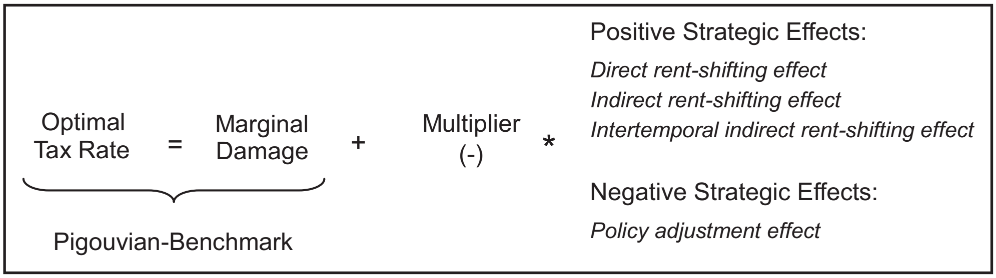

Fig. 2. The optimal regulation schedule in the two-period model.

this *predominance condition* is fulfilled a stringent domestic tax policy in period 1 will emerge. The *predominance condition* is therefore necessary and sufficient for a stringent tax policy in period 1.

Proposition 3 (.). *The domestic government will set a tax rate above the Pigouvian level in period 1 if the policy adjustment condition and the predominance condition hold* (Proof: see Appendix E).

As expected the preceding intertemporal analysis gave rise to some ambiguities. Although these preclude clear-cut results it is shown that a tax policy above the Pigouvian level in the first period can be the optimal choice. The latter necessitates that the intertemporal benefits of accumulating knowledge capital captured in the policy adjustment effect outweigh the rent-shifting effects. Hence, a stringent tax policy is more likely when knowledge accumulation is considered. Whether the domestic tax rate will actually be set above the Pigouvian level ultimately depends on the extent of the parameters, especially the value of the knowledge parameter. If the knowledge parameter is sufficiently high the conditions for a stringent tax policy in period 1 will be fulfilled. Nevertheless, even if the parameter constellation does not allow for a stringent tax policy the magnitude of the suboptimal amount of pollution abatement regularly predicted in one-period models will decrease if the long-term effects of knowledge accumulation are considered.

Moreover, when heterogeneity in the ability to build knowledge capital is introduced unilaterally setting a higher tax rate may be optimal: the government under whose jurisdiction a firm with a comparative advantage in knowledge accumulation resides has an incentive to harness the ensuing intertemporal benefits by inducing early R&D expenditures.[24] Finally, the latter bears an interesting implication. Given that the difference between α^d and α^f needs to be significant to guarantee the *predominance condition* to hold it follows that an increase in α^d increases marginal domestic welfare. Hence, a stringent tax policy will remain ineffective if firm-level knowledge-based capabilities are insufficiently developed.

[24] To be sure, this result is somewhat tautological since the difference in the magnitude of regulatory policies with all the ensuing effects results from the initial heterogeneity in knowledge parameters. However, heterogeneity in resources is a real-world phenomenon which renders this assumption not too far-fetched. Although one might argue that perfect factor-markets preclude any heterogeneity especially the concept of internal knowledge accumulation captures firm-specific assets that are hard to imitate and sometimes not even alienable.

5. Conclusion

The previous results give rise to a revaluation of the conventional result that strategic environmental policy games produce, namely that tax policies most likely will be subject to the forces of ecological dumping. We assert that this outcome is the inevitable consequence of using a one-period game to investigate an inherently dynamic topic. Introducing a two-period game, however, allows for taking the dynamic properties of knowledge creation into account. To be sure, we concede that an approach which analyses only initial R&D expenditures leads to the prediction that governments will install a lax tax policy which involves the notorious suboptimal amount of abatement. Our results, however, suggest that incorporating the benefits from building upon previous knowledge capital results in a decreasing magnitude of the suboptimal internalisation of environmental harm and moreover may in some cases even give rise to a stringent first-mover policy. The latter prediction is of course contingent upon the respective model setting. It has been shown that a scenario with bilateral knowledge accumulation and heterogeneous knowledge parameters supports the idea that an early ambitious approach to policy making allows the affected firm to benefit from the intertemporal externalities of accumulating knowledge capital. Moreover, our main finding corresponds to the results of the models that investigated intertemporal knowledge externalities in a setting with perfect competition (see footnote 9) and shows that an ambitious approach to taxing emissions early also can be optimal when imperfect competition prevails.

Although we believe that the previous results shed new light on the strategic environmental policy debate we acknowledge that our model lacks some important features. First, we did not include knowledge spillovers to avoid further ambiguities. It is, however, reasonable to predict that the domestic policymaker has an incentive to curb the stringency of his regulation if domestic knowledge can be imitated without or with only insignificant costs by foreign competitors. A domestic firm facing a stringent regulation may therefore be worse off if it is not able to sufficiently appropriate the benefits from its R&D activities. See Ziesemer (2010) for a more comprehensive account on the impact of knowledge spillovers in a strategic environmental policy game. Second, problems may arise if policymakers have imperfect information. In this case the governments may not know about the difference in the knowledge parameters and therefore they have to base their policy choice on possibly crude estimations of the underlying dependencies. Consequently, they may either under- or overestimate the benefits from learning and set a too lax or too stringent tax rate. Third, as usual in strategic environmental policy models we entirely omitted considerations of different attitudes towards risk and uncertainty. Undertaking R&D is a chancy endeavour and it is by no means guaranteed that it results in a marketable innovation. Nevertheless, an educated guess is that a venturesome firm will react quite differently to a stringent emission tax compared to a risk-averse rival. Fourth, as mentioned in footnote 3, we limited the analysis to local pollution which neglects the importance of greenhouse gases. Incorporating global or transboundary emissions would create more strategic effects with a positive sign which would weaken the domestic government's incentive to set an early stringent tax rate. Finally, despite their empirical relevance we did not model emissions in form of a stock pollutant. The latter would in itself carry an incentive for each government to increase the tax rate in period 1 compared to our game with flow pollutants, since aggregated environmental damage will increase if emissions from period 1 remain effective in period 2.

These shortcomings notwithstanding, our results show that a unilateral stringent tax policy can be optimal whenever the transnational differences between the capabilities in accumulating knowledge are significant.

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We are grateful for the comments of two anonymous referees.

Appendix A.

Totally differentiating the domestic and the foreign variant of first-order condition (1) in stage 3 with respect to the domestic tax rate leads to the following equation system:[25]

$$\begin{bmatrix} \frac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} & \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \frac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} \end{bmatrix} \cdot \begin{bmatrix} \frac{dq_t^d}{dt_t^d} \\ \frac{dq_t^f}{dt_t^d} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \\ \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} \end{bmatrix} \tag{A.1}$$

Using (A9) and solving (A.1) with Cramer's Rule yields:

$$\frac{dq_t^d}{dt_t^d} = \frac{\begin{vmatrix} \frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} & \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} & \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} \end{vmatrix}}{|\Omega_q|}$$

$$= \frac{\left(\frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \cdot \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} - \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} \cdot \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \right)}{|\Omega_q|} < 0 \tag{A.2}$$

$$\frac{dq_t^f}{dt_t^d} = \frac{\begin{vmatrix} \frac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} & \frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \\ \frac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} \end{vmatrix}}{|\Omega_q|}$$

$$= \frac{\left(\frac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} \cdot \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} - \frac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} \cdot \frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \right)}{|\Omega_q|} > 0 \tag{A.3}$$

The signs of dq_t^d/dt_t^d and dq_t^f/dt_t^d necessitate $\partial^2 C^d/\partial q_t^d \partial t_t^d > 0$ and $\partial^2 C^f/\partial q_t^f \partial t_t^d < 0$. The first cross derivative implies that an increasing tax rate increases the marginal cost-increasing effect of producing the consumption good. Since units of emissions are taxed the cost-increasing effect of an increase in quantities is furthered. The second cross derivative follows from this because everything that increases the domestic marginal effect of increasing domestic quantities on according costs decreases the according foreign effect.

Appendix B.

Totally differentiating the domestic and the foreign variant of first-order condition (1) in stage 3 with respect to domestic R&D expenditures yields the following equation system:

$$\begin{bmatrix} \frac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} & \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \frac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \frac{\partial^2 \Pi_t^f}{\partial \left(q_t^f\right)^2} \end{bmatrix} \cdot \begin{bmatrix} \frac{dq_t^d}{dI_t^d} \\ \frac{dq_t^f}{dI_t^d} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \\ \frac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} \end{bmatrix} \tag{B.1}$$

Using (A9) and solving (B.1) by Cramer's Rule yields:

$$\frac{dq_t^d}{dI_t^d} = \frac{\begin{vmatrix} \frac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} & \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \frac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} & \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} \end{vmatrix}}{|\Omega_q|}$$

$$= \frac{\left(\frac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \cdot \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} - \frac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} \cdot \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \right)}{|\Omega_q|} > 0 \tag{B.2}$$

[25] Since these effects are equivalent in both periods the following holds throughout the game (hence subscripts t).

$$\frac{dq_t^f}{dI_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} & \dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \\ \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} \end{vmatrix}}{|\Omega_q|} = \frac{\left(\dfrac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} \cdot \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} - \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} \cdot \dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \right)}{|\Omega_q|} < 0 \qquad \text{(B.3)}$$

(B.2) requires $\partial^2 C^d / \partial q_t^d \partial I_t^d < 0$ which captures the marginal effect of an increase in domestic quantities on domestic costs that decreases with increasing R&D expenditures. This is due to the emission-reducing and cost-decreasing effect of increasing knowledge capital. (B.3) necessitates $\partial^2 C^f / \partial q_t^f \partial I_t^d > 0$ which captures the opposing cross effect that an increase in domestic R&D expenditures imposes on the foreign firm.

Appendix C.

Totally differentiating the domestic and the foreign variant of first-order condition (3) in stage 5 with respect to the domestic tax rate yields the following equation system:

$$\begin{bmatrix} \dfrac{\partial^2 \Pi_t^d}{\partial (I_t^d)^2} & \dfrac{\partial^2 \Pi_t^d}{\partial I_t^d \partial I_t^f} \\ \dfrac{\partial^2 \Pi_t^f}{\partial I_t^f \partial I_t^d} & \dfrac{\partial^2 \Pi_t^f}{\partial (I_t^f)^2} \end{bmatrix} \cdot \begin{bmatrix} \dfrac{dI_t^d}{dt_t^d} \\ \dfrac{dI_t^f}{dt_t^d} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \\ \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} \end{bmatrix} \qquad \text{(C.1)}$$

Using (A9) and solving (C.1) with Cramer's Rule yields:

$$\frac{dI_t^d}{dt_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} & \dfrac{\partial^2 \Pi_t^d}{\partial I_t^d \partial I_t^f} \\ \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} & \dfrac{\partial^2 \Pi_t^f}{\partial (I_t^f)^2} \end{vmatrix}}{|\Omega_I|} = \frac{\left(\dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \cdot \dfrac{\partial^2 \Pi_t^f}{\partial (I_t^f)^2} - \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} \cdot \dfrac{\partial^2 \Pi_t^d}{\partial I_t^d \partial I_t^f} \right)}{|\Omega_I|} > 0 \qquad \text{(C.2)}$$

$$\frac{dI_t^f}{dt_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 \Pi_t^d}{\partial (I_t^d)^2} & \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \\ \dfrac{\partial^2 \Pi_t^f}{\partial I_t^f \partial I_t^d} & \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} \end{vmatrix}}{|\Omega_I|} = \frac{\left(\dfrac{\partial^2 \Pi_t^d}{\partial (I_t^d)^2} \cdot \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} - \dfrac{\partial^2 \Pi_t^f}{\partial I_t^f \partial I_t^d} \cdot \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \right)}{|\Omega_I|} > 0 \qquad \text{(C.3)}$$

Results (C.2) and (C.3) necessitate $\partial^2 C^d / \partial I_t^d \partial t_t^d < 0$, $\partial^2 C^f / \partial I_t^f \partial t_t^d < 0$ and $\partial^2 \Pi_t^i / \partial I_t^i \partial I_t^j < 0$ (see Section 3 for a detailed discussion).

Appendix D.

Rearranging the domestic firm's first-order condition (5) in period 2 reveals the strategic effects:

$$\underset{(?)}{\left(t_2^d - \frac{\partial D}{\partial e_2^d} \right)} \cdot \underset{(-)}{\gamma^d} + P'(\cdot) \cdot \underset{(-)}{\frac{\partial q_2^f}{\partial t_2^d}} \cdot q_2^d + P'(\cdot) \cdot \underset{(-)}{\frac{\partial q_2^f}{\partial \kappa_2^f}} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot q_2^d \cdot \beta^f = 0 \qquad \text{(D.1)}$$

At the Pigouvian level the term in the first parenthesis becomes zero. Therefore, for $t^d > \partial D / \partial e^d$ the product of the expression in the first parenthesis and μ^i is negative. Consequently, to satisfy the according first-order condition a stringent tax rate necessitates the subsequent effects to be positive. However, since both strategic effects on the LHS are negative only $t^d - \partial D / \partial e^d < 0$ satisfies (5).

Appendix E.

To evaluate the intertemporal effect the results of stage 1 need to be considered. Rearranging the domestic variant of first-order condition (10) from stage 1 yields:

$$\begin{aligned} &\underset{(?)}{\left(t_1^d - \frac{\partial D}{\partial e_1^d} \right)} \cdot \underset{(-)}{\eta^d} + P'(\cdot) \cdot \underset{(-)}{\frac{\partial q_1^f}{\partial t_1^d}} \cdot q_1^d + P'(\cdot) \cdot \underset{(-)}{\frac{\partial q_1^f}{\partial \kappa_1^f}} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_1^d \cdot \alpha^f + P'(\cdot) \cdot \underset{(-)}{\frac{\partial q_2^f}{\partial \kappa_2^f}} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_2^d \cdot \alpha^f \\ &- \underset{(+)}{\left(\frac{\partial D}{\partial e_2^d} - t_2^d \right)} \cdot \left[\frac{\partial e_2^d}{\partial q_2^d} \cdot \left(\underset{(+)}{\frac{\partial q_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha^d} + \underset{(-)}{\frac{\partial q_2^d}{\partial \kappa_2^f} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot \alpha^f} \right) + \underset{(-)}{\frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha^d} \right] \end{aligned} \qquad \text{(E.1)}$$

Since in period 2 the domestic government will set a lax tax policy (see the proof in Appendix D) the *policy adjustment condition* will be positive if the expression in the brackets is negative which is granted by condition (13):

$$-\left(\frac{\partial D}{\partial e_2^d}-t_2^d\right)\cdot\left[\frac{\partial e_2^d}{\partial q_2^d}\cdot\left(\frac{\partial q_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d+\frac{\partial q_2^d}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot\alpha^f\right)+\frac{\partial e_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right]>0 \tag{E.2}$$

The *policy adjustment condition* (E.2) implies that the emission-reducing effect of induced domestic innovations is not overcompensated by an emission-increasing effect. This is guaranteed if (13) holds.The *predominance condition* is:

$$\left|P'(\cdot)\cdot\frac{\partial q_1^f}{\partial t_1^d}\cdot q_1^d+P'(\cdot)\cdot\frac{\partial q_1^f}{\partial \kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_1^d\cdot\alpha^f+P'(\cdot)\cdot\frac{\partial q_2^f}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_2^d\cdot\alpha^f\right|$$
$$<\left|-\left(\frac{\partial D}{\partial e_2^d}-t_2^d\right)\cdot\left[\frac{\partial e_2^d}{\partial q_2^d}\cdot\left(\frac{\partial q_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d+\frac{\partial q_2^d}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot\alpha^f\right)+\frac{\partial e_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right]\right| \tag{E.3}$$

The absolute value of the tax-decreasing *rent-shifting effects* needs to be less in magnitude than the absolute value of the *policy adjustment effect*. To allow for a larger RHS α^d needs to be sufficiently large to exploit the effect of accumulated knowledge. And since by definition $\alpha^d > \alpha^f$ a stringent tax policy in period 1 becomes more likely when one allows for intertemporal knowledge accumulation.

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