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Abstract

Recent political discussions about the possible advantages of first-mover behaviour in terms of environmental policy again called attention to the well-established controversy about the effects of environmental regulation on international competitiveness. Conventional theory claims that the trade-off between regulation and competitiveness will be negative while the revisionist view, also known as the Porter Hypothesis, argues for the opposite. Several previous attempts that analysed this quarrel by means of strategic trade game settings indeed support the former claim and conclude that, to increase a firm's competitiveness, ecological dumping is the most likely outcome in a Cournot duopoly configuration. However, these results were derived from one period games in which so-called innovation offsets are unlikely to occur. The present paper considers a two-period model that includes an intertemporally growing firm-level knowledge capital. In doing so the accumulation of knowledge is modelled in a unilateral and a bilateral variant. It is shown that for both scenarios in period 1 the domestic government will set a higher emission tax rate compared to its foreign counterpart. Furthermore, we identify conditions for which the domestic tax rate will be set above the Pigouvian level in period 1 in both model variants.

Keywords: first-mover behaviour, Porter Hypothesis, strategic environmental policy, environmental regulation, international competitiveness.

JEL Classification: F18, Q55, Q58

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1. Introduction

Usually, the establishment of environmental policies is subject to a considerable debate concerning their impact on the competitiveness of thus affected firms, industries or even whole nations. The elusiveness of the notion competitiveness notwithstanding, the academic dispute on this quarrel has spawned two diametrical opposed views. The classic view argues that environmental regulation inevitably creates costs of compliance which accordingly lower any previously held comparative advantage in using the environment as a factor of production (Palmer et al. 1995). By contrast the revisionist perception, also known as the Porter Hypothesis, posits that stringent incentive-based regulation indeed may produce a welfare-maximising win-win situation in which both the environment and the economy benefit (Porter 1991, Porter & van der Linde 1995a, 1995b). Although the latter view has its argumentative merits it lacks a thorough theoretical fundament. However, it is widely held that the revisionist view is founded on the belief that market-based environmental regulation provokes a thorough search for innovative solutions to the problem of increasing compliance costs. In this sense an increase of competitiveness is an increase in productivity: successfully induced innovations trigger a decrease of a firm's marginal costs (Simpson & Bradford 1996). Hence, a decline in marginal costs is the sufficient condition for a higher competitiveness while a cost-reducing innovation serves as the necessary condition. The notion of stringency, in turn, commonly refers to an environmental policy set above the according Pigouvian level. Consequently, the questions if and how innovations under a scenario of stringent regulation emerge prove to be essential for a sound analysis of the Porter Hypothesis.

Empirical evidence for Porter's assertions is mixed: while older studies mostly find either no or only a small negative correlation between stringent regulation and some proxy for competitiveness (see the surveys by Jaffe et al. 1995, Jeppesen et al. 1999 and Mulatu et al. 2001)[2] more recent evidence suggests that a positive link between regulation and patenting (Lanjouw & Mody 1996), private R&D expenditures (Jaffe & Palmer 1997), productivity (Berman & Bui 2001) and technical efficiency (Murty & Kumar 2003) exists.

Analytical evidence is also ambiguous. The basic argument against the assertions of the Porter Hypothesis is that the possibility of a systematic free or even paid lunch is highly unlikely (Palmer et al. 1995). Indeed, the widely used strategic environmental policy models, which are based upon the seminal strategic trade models (Spencer & Brander 1983, Brander & Spencer 1985), usually find that ecological dumping is the most likely

[2] It has to be noted that most of the older studies rely on evidence from times when mainly command and control regulation was issued. However, such data cannot be readily used to analyse the Porter Hypothesis as Porter calls for market-based policies (Wagner 2003).

outcome (cf. Barrett 1994, Rauscher 1994). In doing so they draw some important conclusions: usually a range of ambiguous effects (e.g. rent-shifting vs. innovation effects) shape the ultimate outcome of such a game (Ulph & Ulph 1996). Depending on the properties of the utilised functions results differ largely: while for some constellations so-called innovation offsets are conceivable they do not take place in other cases (Simpson & Bradford 1996). This hints at the sensibility of such models for analysing the regulation-competitiveness interdependency.

The Porter Hypothesis is derived from the basic insight that competitiveness, and its sibling the national competitive advantage, is created and not inherited like a classic endowment with production factors (Porter 1990). Sure enough this view is not completely new. Based on the "Kaldor paradox"[3] Fagerberg (1988, 1996) identifies technological advance as the main driver for a nation's competitiveness. Applying this finding to a dual dimension approach (cf. Dollar 1993, Ezeala-Harrison 2005) then leads to a framework in which firm-level competitiveness is based upon technological or knowledge advantages and national competitiveness is bolstered by an institutional framework that encourages and supports the generation of new profitable knowledge.

The Porter Hypothesis follows this rationale and asserts that market-based environmental regulation establishes an exogenous pressure which induces the affected firms to conduct R&D to offset the compliance costs (Porter & van der Linde 1995a, 1995b). The basic idea that environmental regulation induces innovation has been widely acknowledged (Zerbe 1970, Magat 1978, Downing & White 1986, Milliman & Prince 1989, Jung et al. 1996, Fischer et al. 2003) while the notion of innovation offsets so far seems only possible when one attenuates the restrictive assumptions of neo-classical theory (Ayres 1994, Gabel & Sinclair-Desgagné 1999). In the revisionist view such innovation offsets constitute the first cornerstone of the hypothesis. The second and so far widely neglected cornerstone is the first-mover effect. It states that a domestic firm which is affected by a novel and stringent environmental regulation needs to adjust immediately to this exogenous pressure while its foreign rival at this point still operates under a comparatively lax regulation. Intuition suggests that such an early adjustment indeed increases costs in the short-run but these may as well decrease in the long-run. We hypothesise that such an outcome can only be brought about when the notion of knowledge accumulation is considered[4]: By leaving the boundary of a one-period game early R&D expenditures may also influence later knowledge capital if one assumes that

3 Since the occurrence of the "Kaldor paradox" measures like unit labour costs have been viewed as an inappropriate indicator for competitiveness (Kaldor 1978).

4 Another way to achieve a fulfilment of the Porter Hypothesis is to view the black box of firm decision making as defective. The latter e.g. requires agency problems, bounded rationality or path dependencies.

intratemporal knowledge capital does not get entirely lost intertemporally. Moreover, the accumulation of knowledge capital appears to be especially suited for capturing the properties of process-integrated innovations which are especially advocated in the Porter Hypothesis. However, it is obvious that the benefits of long-term knowledge accumulation and possibly ensuing innovation offsets cannot be properly analysed in a one-period setting because the accumulation of knowledge involves a technological trajectory which cannot be fully captured in one period. Since each period yields instantaneous conditions for optimality at a certain point in time the time path is neglected. Hence, future cost reductions that stem from early investments will be underestimated.

Thus, to evaluate whether a first-mover effect is a decisive constituent one needs to extend the popular one-period model by at least a second period (Taistra 2000, Feess & Taistra 2000, Feess & Muehlheusser 2002)[5]. For instance, in their two-period model Feess and Muehlheusser (2002) show that an environmental service sector that is subject to an intertemporal learning curve effect benefits from early and even stringent regulation. Given that this model misses the basic consideration of the Porter Hypothesis – the polluting firms shall be induced to invest in process-integrated R&D – it nevertheless hints at the importance of incorporating growing knowledge.

Our model follows the previous arguments: we construe a two-period model in the line of strategic environmental policy games. Thereby we allow for an analysis of the first-mover effect by introducing a growing firm-level knowledge capital. Our investigation commences with a basic model with unilateral knowledge accumulation and subsequently allows for bilateral knowledge accumulation. In doing so our aim is twofold: First, we analyse whether the domestic government will set a higher tax rate than its foreign counterpart in period 1. Second, we identify the conditions under which the domestic tax rate is set above the Pigouvian level in period 1.

Section 2 explicates the configuration of our model and introduces its basic version with unilateral knowledge accumulation. Section 3 then extends the analysis by allowing for bilateral knowledge accumulation. Section 4 presents our conclusions.

2. The Basic Model with Unilateral Knowledge Accumulation

We consider a two-period Cournot game in which an duopoly produces a homogenous consumption good. The two firms are located in two different countries. Production of the good entails the creation of environmentally harmful emissions. Each country also

[5] The model by Taistra (2000) and the ensuing model by Feess and Taistra (2000) – both are discrete models – have a major shortcoming: The decision of the foreign government to adopt the domestic environmental policy is not strategic as it depends on an exogenous probability.

harbours an governmental agency that aims at maximising welfare by internalising the external effect of pollution. To do so it sets a tax rate per units of emission.

The game comprises two periods, each containing three stages. Due to the specific sequence of the game it can be solved via backwards induction beginning with stage 6 (that is the third stage in period two). In the respective third stages the firms choose their equilibrium quantities. They 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.[6] In the second stages firms choose their level of emission-reducing expenditures. As will be shortly explicated the basic model differentiates between the domestic and the foreign extent of knowledge capitalisation. That is, by deciding on the optimal amount of according R&D expenditures the domestic firm also set its intratemporal and partly determines its intertemporal knowledge capital while the foreign firm may only invest intratemporally. In the first stages the governments choose a welfare maximising tax rate. Figure 1 summarises the sequence of the game.

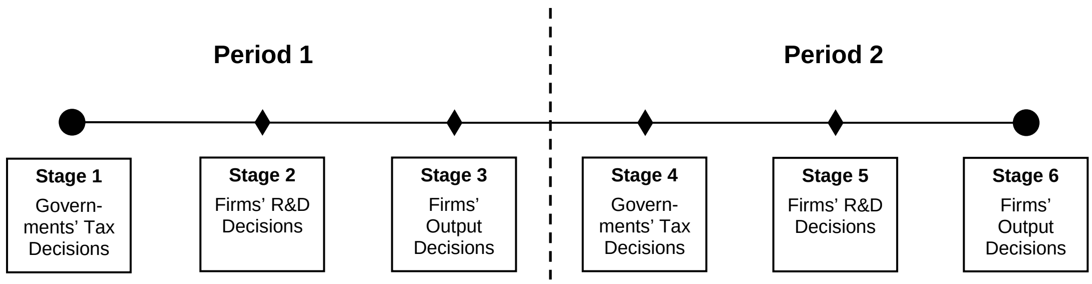

Figure 1: The sequence of the game

2.1. Notations and functional relationships

Unless otherwise noted in section 3 the following assumptions hold for both versions of the model. Generally, the model is symmetrical except for the asymmetric treatment of knowledge parameters. These asymmetries are needed to motivate a domestic first-mover behaviour. An entirely symmetrical constellation would not allow to analyse the Porter Hypothesis whose realisation necessitates a difference in at least one decisive parameter. Put in other words, an optimising policymaker needs a lever to initiate a respective action, in the present model the choice of an emission tax rate. Except for the necessary inclusion of a particular asymmetric modification the assumption of symmetry prevails which shall allow to single out the decisive effects.

[6] Omitting consumer surplus is a common assumption in strategic environmental policy games (cf. Simpson & Bradford 1996, Ulph & Ulph 1996).

In the following superscripts i,j refer to domestic (d) and foreign (f) while subscripts t=1,2 refer to period one and two, respectively.

Inverse demand: Firms face the downward-sloping inverse demand function $P\left(q_t^i, q_t^j\right)$ for the consumption good on the third country market.

$$P'(\cdot) < 0;\ P''(\cdot) \leq 0 \tag{1}$$

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

$$\partial e_t^i / \partial q_t^i > 0 \qquad \partial^2 e_t^i / \partial\left(q_t^i\right)^2 = 0 \tag{2}$$

$$\partial e_t^i / \partial \kappa_t^i < 0 \qquad \partial^2 e_t^i / \partial\left(\kappa_t^i\right)^2 > 0 \tag{3}$$

Assumptions (2) and (3) 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 form growing knowledge capital in reducing emissions are diminishing.

Costs: Each firm has the cost function $C^i\left(q_t^i, t_t^i, \kappa_t^i\right)$ with q_t^i denoting firm i's quantity of the output of the consumption good in period t, t_t^i denoting country i's tax rate in period t and κ_t^i denoting firm i's knowledge capital in period t. The following properties apply:

$$\partial C^i / \partial q_t^i > 0 \qquad \partial^2 C^i / \partial\left(q_t^i\right)^2 = 0 \tag{4}$$

$$\partial C^i / \partial t_t^i > 0 \qquad \partial^2 C^i / \partial\left(t_t^i\right)^2 \leq 0 \tag{5}$$

$$\partial C^i / \partial \kappa_t^i < 0 \qquad \partial^2 C^i / \partial\left(\kappa_t^i\right)^2 > 0 \tag{6}$$

By the previous assumptions costs are linear in output, concave in taxes and strictly convex in knowledge capital. Assumption (4) implies that the production process is subject to constant returns to scale. The concavity property in assumption (5) captures a linear as well as a concave relation between costs and the respective tax rate. The latter may arise if (5) 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 proofed later, an intensified tax policy results in less quantities which reduces production costs). The convexity in (6) follows from (3).

Knowledge Capital: The knowledge capital κ_t^i accrues from R&D expenditures I_t^i. In this basic version of the model knowledge accumulation only occurs in the domestic country. This rather restrictive assumption may be explained by different approaches to emission reduction. The foreign firm is only capable to invest in an end-of-pipe technology. In each period costs of installation, maintenance and disposal of the device (e.g. a filter) occur. The domestic firm, however, invests in a process-integrated technology. In so doing it is able to accumulate knowledge about the novel technology over time, that is, the domestic firm improves its technology continuously. Note that, strictly speaking, the foreign firm does not invest in something like knowledge capital since an externally procured end-of-pipe device does not qualify as an outcome of any knowledge-based activities on behalf of the foreign firm.[7] Thus, in this basic version I_t^i can also be interpreted as emission-reducing expenditures because ultimately the process-integrated technology as well as the end-of-pipe approach aim at curtailing environmental harm.

For period 1 $\kappa_1^i = \kappa_1^i\left(I_1^i\right)$ applies for both firms:

$$\kappa_1^i = \alpha \cdot I_1^i \tag{7}$$

The parameter $\alpha > 0$ measures the effect of R&D expenditures on knowledge capital in period 1 (that is, the success of R&D expenditures).
For period 2 $\kappa_2^d = \kappa_2^d\left(\kappa_1^d(\cdot), I_2^d\right)$ applies for the domestic firm while the foreign firm faces $\kappa_2^f = \kappa_2^f\left(I_2^f\right)$:

$$\kappa_2^d = \kappa_1^d(\cdot) + \beta \cdot I_2^d \;;\; \kappa_2^f = \alpha \cdot I_2^f \tag{8}$$

The parameter $\beta > 0$ measures the domestic effect of R&D expenditures on knowledge capital in period 2. (8) therefore implies $\partial\kappa_2^d / \partial I_2^d = \beta$ and $\partial\kappa_2^d / \partial I_1^d = \alpha$. Furthermore, we assume $\alpha > \beta$ (early units of R&D are more effective in creating knowledge capital than later units which is tantamount to decreasing returns of knowledge capital). Hence, the foreign firm in period 2 still benefits from a knowledge effect with the strength α, but it is not able to utilize period 1 knowledge capital since it invests in an end-of-pipe technology. The domestic firm, however, can access accumulated knowledge, whose strength is then measured by $\alpha + \beta$.

Environmental Harm: Environmental harm is captured in the damage function $D\left(e_t^i\right)$:

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[7] To avoid undue verbiage this differentiation will be suppressed throughout the text. Therefore, for the foreign firm the notion of knowledge capital is restricted to manners of end-of-pipe abatement.

$$\partial D / \partial e_t^i > 0 \qquad \partial^2 D / \partial \left(e_t^i\right)^2 \geq 0 \tag{9}$$

Assumption (9) says that environmental damage is convex in emissions which, of course, includes the possibility that marginal environmental damage is linear.

Objective functions:

Third stages (Firms maximise their profits Π_t^i and thusly obtain optimal quantities.):

$$\max \ \Pi_t^i = P\left(q_t^i, q_t^j\right) \cdot q_t^i - C^i\left(q_t^i, t_t^i, \kappa_t^i\right) \tag{10}$$

Second stages (Firms maximise their profits Π_t^i and determine their equilibrium R&D expenditures.):

$$\max \ \Pi_t^i = P\left(q_t^i, q_t^j\right) \cdot q_t^i - C^i\left(q_t^i, t_t^i, \kappa_t^i\right) - I_t^i \tag{11}$$

First stages (Governments maximise national welfare Φ_t^i and choose the optimal tax policy.):

$$\max \ \Phi_t^i = P\left(q_t^i, q_t^j\right) \cdot q_t^i - C^i\left(q_t^i, t_t^i, \kappa_t^i\right) - I_t^i - D\left(e_t^i(\cdot)\right) + t_t^i \cdot e_t^i(\cdot) \tag{12}$$

Stability: Stability requires the determinant of the Hessian (where s_t^i denotes the respective strategic variable in country i in period t) to be positive which is tantamount to own effects dominating cross-effects:

$$\left|H_s\right| = \frac{\partial^2 \Pi_t^d}{\partial \left(s_t^d\right)^2} \cdot \frac{\partial^2 \Pi_t^f}{\partial \left(s_t^f\right)^2} - \frac{\partial^2 \Pi_t^d}{\partial s_t^d s_t^f} \cdot \frac{\partial^2 \Pi_t^f}{\partial s_t^f s_t^d} > 0 \qquad \text{with } s_t^i = q_t^i, I_t^i, t_t^i \tag{13}$$

Strategic Substitutes:

$$\partial \Pi_t^i / \partial q_t^i \partial q_t^j < 0 \tag{14}$$

Due to the previous assumptions (14) restates the conventional Cournot result that domestic and foreign quantities are strategic substitutes.

Furthermore, we assume that all respective second-order conditions are satisfied. This implies that emissions are sufficiently convex in knowledge capital.8 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.

[8] See the discussion of the comparative static analysis in section 2.2.

2.2. Decisions in period 2

In stage 6 both firms choose their output quantities. They do so by differentiating (10) 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):

$$\frac{\partial \Pi_2^i}{\partial q_2^i} = \frac{\partial P(\cdot)}{\partial q_2^i} \cdot q_2^i + P(\cdot) - \frac{\partial C^i}{\partial q_2^i} = 0 \tag{15}$$

(15) implies the reaction functions $\tilde{q}_2^i = q_2^i\left(q_2^j\right)$. Equilibrium quantities can therefore be written as $q_2^i = q_2^i\left(\kappa_2^i, \kappa_2^j, t_2^i, t_2^j\right)$.

The effects of the other strategic variables on quantities can be analysed by totally differentiating the first-order conditions with respect to the domestic tax rate (see Appendix A 1 for details). The results replicate the common findings $\mathrm{d}q_t^d / \mathrm{d}t_t^d < 0$ and $\mathrm{d}q_t^f / \mathrm{d}t_t^d > 0$. 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.

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 A 2 for details). Via the cost-reducing effect of domestic R&D expenditures domestic quantities increase ($\mathrm{d}q_t^d / \mathrm{d}I_t^d > 0$). And since everything that decreases domestic costs also increases domestic quantities and consequently decreases foreign quantities $\mathrm{d}q_t^f / \mathrm{d}I_t^d$ is negative.

Thus, (by virtue of the assumed demand structure) the conventional Cournot results are obtained, namely that $\partial q_2^i / \partial C_2^i < 0$, $\partial q_2^i / \partial C_2^j > 0$ and $\partial q_2^i / \partial C_2^i + \partial q_2^i / \partial C_2^j < 0$. Hence, 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).[9]

In stage 5 the firms decide on their R&D expenditures. Differentiating (11) 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):

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

$$\frac{\partial \Pi_2^d}{\partial I_2^d} = \left(\frac{\partial P(\cdot)}{\partial q_2^d} \cdot q_2^d + P(\cdot) - \frac{\partial C^d}{\partial q_2^d} \right) \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial I_2^d} + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial I_2^d} \cdot q_2^d - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial I_2^d} - 1 = 0 \quad (16)$$

$$\Rightarrow P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot q_2^d \cdot \beta - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \beta = 1$$

(16) shows that in equilibrium the cross effect of domestic R&D expenditures (via domestic knowledge capital) on foreign quantities minus domestic cost reductions due to lower emissions equal the last Euro spent on R&D expenditures. From the domestic firm's point of view this means that it invests in R&D until the ensuing cost reductions are compensated by the decline in relative revenues which result from falling market prices ($P' < 0$). The market price falls because the negative cross effect ($\partial q_2^j / \partial \kappa_2^i < 0$) implies an increase in domestic quantities.

The foreign firm's foc is equivalent to (16) except for a different knowledge parameter:

$$\frac{\partial \Pi_2^f}{\partial I_2^f} = P' \cdot \frac{\partial q_2^d}{\partial \kappa_2^f} \cdot q_2^f \cdot \alpha - \frac{\partial C^f}{\partial \kappa_2^f} \cdot \alpha = 1 \quad (17)$$

Due to $\alpha > \beta$ the domestic firm has an incentive to reduce its R&D expenditures in period 2. The foreign firm, however, has to keep up its level of according expenditures (if it aims at reducing the same amount of emissions as in the first period). Therefore, if both firms would want to avoid the same amount of emissions the domestic firm benefits from comparatively lower costs since it can access its knowledge capital from period 1.

Moreover, domestic and foreign R&D expenditures are strategic substitutes because an increase in domestic (foreign) R&D increases domestic (foreign) quantities via the cost-reducing effect and accordingly decreases foreign (domestic) quantities. Therefore, everything that decreases costs in one firm decreases the other firm's quantities which also lowers the latter's incentive to further reduce its costs (Ulph 1994, p. 214). Consequently, strategic substitutes imply downward-sloping reaction functions which, in turn, determine the sign of the cross derivatives $\partial^2 \Pi_2^d / \partial I_2^d \partial I_2^f$ and $\partial^2 \Pi_2^d / \partial I_2^f \partial I_2^d$.

Lemma 1. Downward-sloping reaction functions imply negative cross derivatives $\partial^2 \Pi_2^d / \partial I_2^d \partial I_2^f$ and $\partial^2 \Pi_2^d / \partial I_2^f \partial I_2^d$.

Proof. (see Appendix A 3)

Thus, reaction functions can only be downward-sloping if $\partial^2\Pi_2^d / \partial I_2^d \partial I_2^f < 0$ and $\partial^2\Pi_2^d / \partial I_2^f \partial I_2^d < 0$ holds. This result has important implications for the following comparative static analysis.

Whether an increase in the tax rate actually induces R&D expenditures can be analysed by totally differentiating the second stage first-order conditions with respect to the domestic tax rate. This gives rise to the following equation system:

$$\begin{bmatrix} \dfrac{\partial^2\Pi_t^d}{\partial\left(I_t^d\right)^2} & \dfrac{\partial^2\Pi_t^d}{\partial I_t^d \partial I_t^f} \\ \dfrac{\partial^2\Pi_t^f}{\partial I_t^f \partial I_t^d} & \dfrac{\partial^2\Pi_t^f}{\partial\left(I_t^f\right)^2} \end{bmatrix} \cdot \begin{bmatrix} \dfrac{\mathrm{d}I_t^d}{\mathrm{d}t_t^d} \\ \dfrac{\mathrm{d}I_t^f}{\mathrm{d}t_t^d} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \\ \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} \end{bmatrix} \qquad (18)$$

Using (13) and solving (18) with Cramer's Rule yields:

$$\frac{\mathrm{d}I_t^d}{\mathrm{d}t_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} & \dfrac{\partial^2\Pi_t^d}{\partial I_t^d \partial I_t^f} \\ \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} & \dfrac{\partial^2\Pi_t^f}{\partial\left(I_t^f\right)^2} \end{vmatrix}}{\left|H_I\right|} = \frac{\left(\dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \cdot \dfrac{\partial^2\Pi_t^f}{\partial\left(I_t^f\right)^2} - \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} \cdot \dfrac{\partial^2\Pi_t^d}{\partial I_t^d \partial I_t^f}\right)}{\left|H_I\right|} > 0 \qquad (19a)$$

$$\frac{\mathrm{d}I_t^f}{\mathrm{d}t_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2\Pi_t^d}{\partial\left(I_t^d\right)^2} & \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d} \\ \dfrac{\partial^2\Pi_t^f}{\partial I_t^f \partial I_t^d} & \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} \end{vmatrix}}{\left|H_I\right|} = \frac{\left(\dfrac{\partial^2\Pi_t^d}{\partial\left(I_t^d\right)^2} \cdot \dfrac{\partial^2 C^f}{\partial I_t^f \partial t_t^d} - \dfrac{\partial^2\Pi_t^f}{\partial I_t^f \partial I_t^d} \cdot \dfrac{\partial^2 C^d}{\partial I_t^d \partial t_t^d}\right)}{\left|H_I\right|} > 0 \qquad (19b)$$

Given that domestic and foreign R&D expenditures are strategic substitutes, which entails $\partial^2\Pi_t^d / \partial I_t^d \partial I_t^f < 0$, ambiguities arise due the sign of $\partial^2 C^d / \partial I_t^d \partial t_t^d$. If emissions are sufficiently convex in knowledge capital it will be negative, if not it will be positive.[10] In the latter case $\mathrm{d}I_t^d / \mathrm{d}t_t^d < 0$. However, for the following we will assume the opposite and therefore allow for tax induced innovation which is a necessary assumption to further pursue the assertions of the Porter Hypothesis. The sign of $\mathrm{d}I_t^f / \mathrm{d}t_t^d$ is unambiguously positive since $\partial^2 C^f / \partial I_t^f \partial t_t^d$ is negative because everything that increases costs for the domestic firm increases the foreign firm's incentive to further reduce its costs. The ambiguity in $\partial^2 C^d / \partial I_t^d \partial t_t^d$ does not matter due to the stability requirement (i.e. own effects dominate cross effects).

[10] Sufficiently convex emissions imply that the effect of reduced tax payments due to diminishing emissions is not again overcompensated by rising costs due to increased output.

Finally, in stage 4 the governments fix their period 2 tax rates. Using the fact that by Shepard's Lemma $\partial C^i / \partial t_t^i = e_t^i$ [11] and differentiating (12) with respect to the tax rates yields the following first-order conditions:

$$\begin{aligned}\frac{\partial \Phi_2^d}{\partial t_2^d} = {} & P' \cdot \frac{\partial q_2^f}{\partial t_2^d} \cdot q_2^d + P(\cdot) \cdot \frac{\partial q_2^d}{\partial t_2^d} + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot q_2^d \cdot \beta + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot q_2^d \cdot \beta \\ & - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot \beta - \frac{\partial I_2^d}{\partial t_2^d} - \frac{\partial D}{\partial e_2^d} \cdot \left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial t_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial t_2^d} \right) \\ & + t_2^d \cdot \left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial t_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial t_2^d} \right) = 0 \end{aligned} \tag{20}$$

$$\begin{aligned}\frac{\partial \Phi_2^f}{\partial t_2^f} = {} & P' \cdot \frac{\partial q_2^d}{\partial t_2^f} \cdot q_2^f + P(\cdot) \cdot \frac{\partial q_2^f}{\partial t_2^f} + P' \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^f} \cdot q_2^f \cdot \alpha + P' \cdot \frac{\partial q_2^d}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^f} \cdot q_2^f \cdot \alpha \\ & - \frac{\partial C^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^f} \cdot \alpha - \frac{\partial I_2^f}{\partial t_2^f} - \frac{\partial D}{\partial e_2^f} \cdot \left(\frac{\partial e_2^f}{\partial q_2^f} \cdot \frac{\partial q_2^f}{\partial t_2^f} + \frac{\partial e_2^f}{\partial \kappa_2^f} \cdot \frac{\partial \kappa_2^f}{\partial t_2^f} \right) \\ & + t_2^f \cdot \left(\frac{\partial e_2^f}{\partial q_2^f} \cdot \frac{\partial q_2^f}{\partial t_2^f} + \frac{\partial e_2^f}{\partial \kappa_2^f} \cdot \frac{\partial \kappa_2^f}{\partial t_2^f} \right) = 0 \end{aligned} \tag{21}$$

Solving foc (20) for the tax rate yields the optimal domestic regulation schedule in period 2:

$$t_2^d = \frac{\partial D}{\partial e_2^d} + \frac{1}{\left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial t_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial t_2^d} \right)} \cdot \begin{pmatrix} -P' \cdot \frac{\partial q_2^f}{\partial t_2^d} \cdot q_2^d - P(\cdot) \cdot \frac{\partial q_2^d}{\partial t_2^d} \\ -P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot q_2^d \cdot \beta \\ -P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot q_2^d \cdot \beta \\ + \frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot \beta + \frac{\partial I_2^d}{\partial t_2^d} \end{pmatrix} \tag{22}$$

Solving foc (21) for the tax rate yields the optimal foreign regulation schedule in period 2:

[11] Using Shepard's Lemma implies that the production function is strictly quasiconcave.

$$t_2^f = \frac{\partial D}{\partial e_2^f} + \frac{1}{\left(\frac{\partial e_2^f}{\partial q_2^f}\cdot\frac{\partial q_2^f}{\partial t_2^f} + \frac{\partial e_2^f}{\partial \kappa_2^f}\cdot\frac{\partial \kappa_2^f}{\partial t_2^f}\right)}\cdot\begin{pmatrix} -P'\cdot\frac{\partial q_2^d}{\partial t_2^f}\cdot q_2^f - P(\cdot)\cdot\frac{\partial q_2^f}{\partial t_2^f} \\ -P'\cdot\frac{\partial q_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_2^d}{\partial t_2^f}\cdot q_2^f\cdot\alpha \\ -P'\cdot\frac{\partial q_2^d}{\partial \kappa_2^f}\cdot\frac{\partial I_2^f}{\partial t_2^f}\cdot q_2^f\cdot\alpha \\ +\frac{\partial C^f}{\partial \kappa_2^f}\cdot\frac{\partial I_2^f}{\partial t_2^f}\cdot\alpha + \frac{\partial I_2^f}{\partial t_2^f} \end{pmatrix} \quad (23)$$

Several strategic effects distort the Pigouvian level at which the tax rate equals marginal damage. These effects will be explained on the basis of the domestic regulation schedule. In combination with the unambiguously negative multiplier $1\Big/\left(\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial t_2^d}+\frac{\partial e_2^d}{\partial \kappa_2^d}\cdot\frac{\partial \kappa_2^d}{\partial t_2^d}\right)$ (an increase in the tax rate decreases domestic quantities as well as emissions, hence both terms are negative) each effect shifts the optimal tax rate either upward or downward.

Rent-shifting effect

The positive term $-P'\cdot\frac{\partial q_2^f}{\partial t_2^d}\cdot q_2^d - P(\cdot)\cdot\frac{\partial q_2^d}{\partial t_2^d}$ 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 $-P'\cdot\frac{\partial q_2^f}{\partial \kappa_2^f}\cdot\frac{\partial I_2^f}{\partial t_2^d}\cdot q_2^d\cdot\beta$ augments the rent-shifting effect through the ramifications of $\partial I_2^f \big/ \partial t_2^d > 0$. A rise in the domestic tax rate increases foreign R&D expenditures because an increase in domestic costs (that is the direct effect of an increasing tax rate) decreases domestic quantities and therefore increases the foreign firm’s incentive to further invest in cost-reducing measures. Consequently, the downward pressure on the tax rate is intensified.

Indirect innovation effect

The negative term $-P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot q_2^d \cdot \beta$ describes how the quantity-increasing effect of domestic cost-reducing innovations decreases foreign quantities. Since domestic quantities increase the domestic firm benefits from an increasing market price. Consequently, this effect countervails the rent-shifting effects and exacts an upward pressure on the tax rate.

Innovation effect

The negative term $\frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot \beta$ signifies the reductions in costs due to increased domestic knowledge capital. This effect shifts the tax rate upwards.

Innovation cost effect

The positive term $\frac{\partial I_2^d}{\partial t_2^d}$ describes the direct cost-increasing effect of R&D expenditures (that is, the impact of R&D on emissions is neglected) and consequently produces a downward pressure on the tax rate.

2.3. Decisions in period 1

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

$$\frac{\partial \Pi_1^i}{\partial q_1^i} = \frac{\partial P(\cdot)}{\partial q_1^i} \cdot q_1^i + P(\cdot) - \frac{\partial C^i}{\partial q_1^i} = 0 \tag{24}$$

The previous results apply accordingly.

In stage 2 firms again choose their equilibrium R&D expenditures. The foreign firm, being unable to benefit from knowledge accumulation, maximises its second stage objective function with respect to period 1 R&D expenditures yielding the straightforward replication of foc (17) from stage 5.

$$\frac{\partial \Pi_1^f}{\partial I_1^f} = P' \cdot \frac{\partial q_1^d}{\partial I_1^f} \cdot q_1^f \cdot \alpha - \frac{\partial C^f}{\partial \kappa_1^f} \cdot \alpha - 1 = 0 \tag{25}$$

The domestic firm, however, sets its R&D expenditures by maximising intertemporal profits (11.1):

$$\Pi^{i} = \Pi_1^{i} + \Pi_2^{i} = P\left(q_1^{i}, q_1^{j}\right)\cdot q_1^{i} - C^{i}\left(q_1^{i}, t_1^{i}, \kappa_1^{i}\right) - I_1^{i} + P\left(q_2^{i}, q_2^{j}\right)\cdot q_2^{i} - C^{i}\left(q_2^{i}, t_2^{i}, \kappa_2^{i}\right) - I_2^{i} \quad (11.1)$$

$$\begin{aligned}\frac{\partial \Pi^{d}}{\partial I_1^{d}} &= P'\cdot\frac{\partial q_1^{f}}{\partial \kappa_1^{d}}\cdot q_1^{d}\cdot\alpha + P(\cdot)\cdot\frac{\partial q_1^{d}}{\partial \kappa_1^{d}}\cdot\alpha - \frac{\partial C^{d}}{\partial \kappa_1^{d}}\cdot\alpha \\ &+ P'\cdot\frac{\partial q_2^{f}}{\partial \kappa_2^{d}}\cdot q_2^{d}\cdot\alpha + P(\cdot)\cdot\frac{\partial q_2^{d}}{\partial \kappa_2^{d}}\cdot\alpha - \frac{\partial C^{d}}{\partial \kappa_2^{d}}\cdot\alpha - 1 = 0\end{aligned} \quad (26)$$

In contrast to the foreign firm's foc (26) includes the intertemporal equivalent to (16) in the second row. Therefore, the satisfaction of condition (26) necessitates that both intratemporal and intertemporal effects equal the last Euro spent on R&D expenditures in period 1. Furthermore, the knowledge effects benefiting the domestic firm are now measured by α. Since period 1 R&D expenditures lead to cost reductions in both periods the domestic firm faces an incentive to invest relatively more in period 1 R&D to benefit from the first-mover effect of early commencing with the accumulation of knowledge capital.

In stage 1 the governments set their initial equilibrium tax rates. Again, due to the lack of intertemporal effects the foreign government maximises intratemporal welfare in period 1 while the domestic government maximises intertemporal welfare.

$$\begin{aligned}\frac{\partial \Phi_1^{f}}{\partial t_1^{f}} &= P'\cdot\frac{\partial q_1^{d}}{\partial t_1^{f}}\cdot q_1^{f} + P(\cdot)\cdot\frac{\partial q_1^{f}}{\partial t_1^{f}} + P'\cdot\frac{\partial q_1^{d}}{\partial \kappa_1^{d}}\cdot\frac{\partial I_1^{d}}{\partial t_1^{f}}\cdot q_1^{f}\cdot\alpha + P'\cdot\frac{\partial q_1^{d}}{\partial \kappa_1^{f}}\cdot\frac{\partial I_1^{f}}{\partial t_1^{f}}\cdot q_1^{f}\cdot\alpha \\ &+ P'\cdot\frac{\partial q_2^{d}}{\partial \kappa_2^{d}}\cdot\frac{\partial I_1^{d}}{\partial t_1^{f}}\cdot q_1^{f}\cdot\alpha - \frac{\partial C^{f}}{\partial \kappa_1^{f}}\cdot\frac{\partial I_1^{f}}{\partial t_1^{f}}\cdot\alpha - \frac{\partial I_1^{f}}{\partial t_1^{f}} \\ &- \frac{\partial D}{\partial e_1^{f}}\cdot\left(\frac{\partial e_1^{f}}{\partial q_1^{f}}\cdot\frac{\partial q_1^{f}}{\partial t_1^{f}} + \frac{\partial e_1^{f}}{\partial \kappa_1^{f}}\cdot\frac{\partial \kappa_1^{f}}{\partial t_1^{f}}\right) + t_1^{f}\cdot\left(\frac{\partial e_1^{f}}{\partial q_1^{f}}\cdot\frac{\partial q_1^{f}}{\partial t_1^{f}} + \frac{\partial e_1^{f}}{\partial \kappa_1^{f}}\cdot\frac{\partial \kappa_1^{f}}{\partial t_1^{f}}\right) = 0\end{aligned} \quad (27)$$

(27) then leads to the optimal foreign regulation schedule in period 1 which is, except for one modification, the equivalent to the result in period 2:

$$t_1^{f} = \frac{\partial D}{\partial e_1^{f}} + \frac{1}{\left(\frac{\partial e_1^{f}}{\partial q_1^{f}}\cdot\frac{\partial q_1^{f}}{\partial t_1^{f}} + \frac{\partial e_1^{f}}{\partial \kappa_1^{f}}\cdot\frac{\partial \kappa_1^{f}}{\partial t_1^{f}}\right)}\cdot\left(\begin{aligned} &- P'\cdot\frac{\partial q_1^{d}}{\partial t_1^{f}}\cdot q_1^{f} - P(\cdot)\cdot\frac{\partial q_1^{f}}{\partial t_1^{f}} \\ &- P'\cdot\frac{\partial q_1^{d}}{\partial \kappa_1^{d}}\cdot\frac{\partial I_1^{d}}{\partial t_1^{f}}\cdot q_1^{f}\cdot\alpha \\ &- P'\cdot\frac{\partial q_2^{d}}{\partial \kappa_2^{d}}\cdot\frac{\partial I_1^{d}}{\partial t_1^{f}}\cdot q_2^{f}\cdot\alpha \\ &- P'\cdot\frac{\partial q_1^{d}}{\partial \kappa_1^{f}}\cdot\frac{\partial I_1^{f}}{\partial t_1^{f}}\cdot q_1^{f}\cdot\alpha \\ &+ \frac{\partial C^{f}}{\partial \kappa_1^{f}}\cdot\frac{\partial I_1^{f}}{\partial t_1^{f}}\cdot\alpha + \frac{\partial I_1^{f}}{\partial t_1^{f}}\end{aligned}\right) \quad (28)$$

Note that when fixing its tax rate the foreign government has to consider an intertemporal indirect rent-shifting effect which favours the domestic firm due to its capability to accumulate knowledge.

Intertemporal indirect rent-shifting effect

The positive term $-P'\cdot\frac{\partial q_2^d}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^f}\cdot q_2^f\cdot\alpha$ captures the intertemporal cross effect of induced innovations. An increase in foreign period 1 taxes affects domestic R&D expenditures in period 1 and therefore also the domestic period 2 knowledge capital. Hence, this effects lowers the foreign tax rate.

The domestic firm faces the intertemporal welfare function (12.1):

$$\begin{aligned}\Phi^i=\Phi_1^i+\Phi_2^i=&P\left(q_1^i,q_1^j\right)\cdot q_1^i-C^i\left(q_1^i,t_1^i,\kappa_1^i\right)-I_1^i-D\left(e_1^i(\cdot)\right)+t_1^i\cdot e_1^i(\cdot)\\&+P\left(q_2^i,q_2^f\right)\cdot q_2^i-C^i\left(q_2^i,t_2^i,\kappa_2^i\right)-I_2^i-D\left(e_2^i(\cdot)\right)+t_2^i\cdot e_2^i(\cdot)\end{aligned}\tag{12.1}$$

Optimisation of (12.1) leads to the following foc:

$$\begin{aligned}\frac{\partial\Phi^d}{\partial t_1^d}=&P'\cdot\frac{\partial q_1^f}{\partial t_1^d}\cdot q_1^d+P(\cdot)\cdot\frac{\partial q_1^d}{\partial t_1^d}+P'\cdot\frac{\partial q_1^f}{\partial\kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_1^d\cdot\alpha+P'\cdot\frac{\partial q_1^f}{\partial\kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot q_1^d\cdot\alpha\\&-\frac{\partial C^d}{\partial\kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha-\frac{\partial I_1^d}{\partial t_1^d}-\frac{\partial D}{\partial e_1^d}\cdot\left(\frac{\partial e_1^d}{\partial q_1^d}\cdot\frac{\partial q_1^d}{\partial t_1^d}+\frac{\partial e_1^d}{\partial\kappa_1^d}\cdot\frac{\partial\kappa_1^d}{\partial t_1^d}\right)\\&+t_1^d\cdot\left(\frac{\partial e_1^d}{\partial q_1^d}\cdot\frac{\partial q_1^d}{\partial t_1^d}+\frac{\partial e_1^d}{\partial\kappa_1^d}\cdot\frac{\partial\kappa_1^d}{\partial t_1^d}\right)+P'\cdot\frac{\partial q_2^f}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot q_2^d\cdot\alpha-\frac{\partial C^d}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha\\&-\left(\frac{\partial D}{\partial e_2^d}-t_2^d\right)\cdot\left(\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha+\frac{\partial e_2^d}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha\right)=0\end{aligned}\tag{29}$$

Rearranging (29) yields the domestic government’s equilibrium regulation schedule:

$$t_1^d = \frac{\partial D}{\partial e_1^d} + \frac{1}{\left(\frac{\partial e_1^d}{\partial q_1^d} \cdot \frac{\partial q_1^d}{\partial t_1^d} + \frac{\partial e_1^d}{\partial \kappa_1^d} \cdot \frac{\partial \kappa_1^d}{\partial t_1^d} \right)} \cdot \left(\begin{array}{c} -P' \cdot \frac{\partial q_1^f}{\partial t_1^d} \cdot q_1^d - P(\cdot) \cdot \frac{\partial q_1^d}{\partial t_1^d} \\ -P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^f} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_1^d \cdot \alpha \\ -P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot q_1^d \cdot \alpha \\ -P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot q_2^d \cdot \alpha \\ +\frac{\partial C^d}{\partial \kappa_1^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha + \frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha \\ +\frac{\partial I_1^d}{\partial t_1^d} \\ +\left(\frac{\partial D}{\partial e_2^d} - t_2^d \right) \cdot \left[\left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \right) \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha \right] \end{array} \right) \quad (30)$$

The optimal domestic tax rate in (30) has three additional effects compared to its foreign pendant. Both aforementioned innovation effects are augmented by intertemporal counterparts. The intertemporal indirect innovation effect $-P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot q_2^d \cdot \alpha$ emphasises the intertemporal quantity-shifting in favour of the domestic firm. Furthermore, and more importantly, the intertemporal innovation effect $\frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha$ demonstrates that an increase in period 1 taxes facilitates the cost-decreasing accumulation of knowledge. Thus, the impact of early induced innovations persists.

The policy adjustment effect $\left(\frac{\partial D}{\partial e_2^d} - t_2^d \right) \cdot \left[\left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \right) \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha \right]$ only becomes effective whenever the optimal tax rate in period 2 differs from the according Pigouvian level (at the Pigouvian benchmark $\left(\partial D / \partial e_2^d - t_2^d \right)$ becomes zero) or when an in total nonzero effect appears in the brackets. Although the second term in the second parenthesis shows how intertemporal knowledge accumulation lowers domestic emissions in period 2 the very same dependency may ultimately increase total domestic emissions due to increased domestic output as described in the first term.[12] Both effects then have different impacts on the optimal regulation schedule since the maximisation of welfare includes (1) the reduction of environmental harm – i.e. a downward (upward) pressure on the optimal tax rate in period 1 in case of a stringent (lax) tax policy in period 2 – and (2) the collection of tax revenue – i.e. an upward (downward) pressure on the opti-

[12] A dominance of the first term requires demand to be sufficiently flat so that an increase in quantities entails a relatively small decline in marginal revenue.

mal tax rate in period 1 in case of a stringent (lax) tax policy in period 2. This effect can therefore be interpreted as the policy adjustment process that follows from the firms' measures to reduce their emissions in period 1: Less emissions means less environmental damage which, from an equilibrium perspective, entails a lower tax rate in period 2 compared to period 1.[13]

Consequently, the domestic government faces a further incentive to tighten its environmental regulation in period 1: Given that intertemporal innovations effects exist inducing innovations early puts the domestic firm intertemporally in a better position. This effect may then be intensified by a downward adjustment of the tax rate in period 2. The domestic government can choose this option if environmental harm has already been reduced in period 1. Furthermore, an adjusted tax rate reduces regulation costs of the domestic firm in period 2 which increases its competitiveness.

The previous discussion culminates in the questions (1) whether the domestic tax rate in period 1 will be higher than its foreign counterpart and (2) whether the domestic tax rate in period 1 will be set above the Pigouvian level. These questions will be addressed in the following propositions.

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

Proof. (see Appendix A 4 for details)

Since the domestic tax rate in period 1 will be higher compared to its foreign counterpart the question of stringency remains. To highlight the difference of the two periods we investigate the second question in two steps. First, we analyse the domestic government's behaviour in period 2. Second, we turn to the stringency of its tax policy in period 1.

It turns out that the domestic first-order condition (20) contains two necessary conditions which have to hold to allow for a stringent domestic tax policy in period 2. Furthermore, these conditions constitute a hierarchy which follows the rationale of the innovation effect in the Porter Hypothesis. First, the benefits from cost-reducing innovation must outweigh according R&D expenditures which is tantamount to the existence

[13] 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).

of an innovation effect. Second, innovation offsets have to occur which is tantamount to the predominance of the innovation effect over any rent-shifting.[14]

Proposition 2. The domestic government will set a tax rate above the Pigouvian level in period 2 if the existence condition for an innovation effect and the predominance condition for an innovation offset hold.

Proof. (see Appendix A 5)

It is evident that the domestic government will only set a stringent tax policy in period 2 for a sufficiently high value of the knowledge parameter. This result may then be interpreted as the replication of the common finding that a stringent tax policy remains unlikely in a one-period game.

The intertemporal analysis, however, emphasises the ramifications of unilateral knowledge accumulation. The two additional intertemporal innovation effects imply that the conditions for $t_1^d > \partial D / \partial e_1^d$ are weaker than in the former case since early R&D reduces domestic costs in both periods. However, an additional condition has to be introduced to capture the impact of the policy adjustment effect. This condition does not directly interfere with the aforementioned hierarchy of necessary conditions.

Proposition 3. The domestic government will set a tax rate above the Pigouvian level in period 1 if the policy adjustment condition, the existence condition for an innovation effect, and the predominance condition for an innovation offset hold.

Proof. (see Appendix A 6)

The intertemporal analysis shows that the unilateral ability of the domestic firm to accumulate knowledge results in weaker conditions for the existence of an innovation effect and for the predominance of the innovation effects over the rent-shifting effects. This means that innovation offsets in the spirit of the revisionist view are more likely when knowledge accumulation is considered. Moreover, the policy adjustment condition provides a further comparative cost advantage for the domestic firm in period 2 since its regulation costs decrease due the downward adjustment of the optimal domestic tax rate.

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[14] An innovation offset is defined as an overcompensation of the benefits of innovation over all according costs. The latter also contain indirect costs such as losses from a decreasing market share that is caused by tax-induced rent-shifting.

Of special importance is the value of α. If the knowledge parameter is sufficiently high the necessary conditions for a stringent tax policy in period 1 appear to be not overly restrictive.

In the following section this conclusion will be challenged by introducing bilateral knowledge accumulation with asymmetric knowledge parameters.

3. Bilateral Knowledge Accumulation

In this section both firms are able to accumulate knowledge that accrues from R&D expenditures. Hence, both firms now dismiss end-of-pipe abatement and invest in process integrated technologies to reduce their emissions. However, to motivate a domestic first-mover behaviour an asymmetric factor has to be introduced. By differentiating the knowledge parameters on the basis of their strength into foreign and domestic types this fundamental requirement is met. To keep the different versions of the model coherent, the domestic knowledge parameters are assumed to be higher than their foreign pendants (see below for details).

3.1. Basic Modifications

Since both firms are able to benefit from knowledge accumulation (8) becomes:

$$\kappa_2^i = \kappa_1^i(\cdot) + \beta^i \cdot I_2^i \tag{8´}$$

Another novelty is the differentiation of the knowledge parameters which is needed to allow for an asymmetry in the otherwise symmetric game. For the following we shall assume $\alpha^d > \alpha^f > \beta^d > \beta^f$ with $\alpha^d, \alpha^f, \beta^d, \beta^f > 0$. It follows that $\alpha^d + \beta^d > \alpha^f + \beta^f$. Therefore, (7) changes to:

$$\kappa_1^i = \alpha^i \cdot I_1^i \tag{7´}$$

3.2. Decisions in period 2

In stage 6 firms choose their optimal period 2 quantities. Differentiating (10) with respect to quantities yields:

$$\frac{\partial \Pi_2^i}{\partial q_2^i} = \frac{\partial P(\cdot)}{\partial q_2^i} \cdot q_2^i + P(\cdot) - \frac{\partial C^i}{\partial q_2^i} = 0 \tag{31}$$

For the comparative static analysis the results from section 2.2. apply.

In stage 5 R&D expenditures are set by differentiating (11) with respect to R&D expenditures. This yields the following first-order conditions which now comprise the modified knowledge parameters:

$$\frac{\partial \Pi_2^d}{\partial I_2^d} = P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot q_2^d \cdot \beta^d - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \beta^d = 1 \tag{32}$$

$$\frac{\partial \Pi_2^f}{\partial I_2^f} = P' \cdot \frac{\partial q_2^d}{\partial \kappa_2^f} \cdot q_2^f \cdot \beta^f - \frac{\partial C^f}{\partial \kappa_2^f} \cdot \beta^f = 1 \tag{33}$$

Following the argument in section 2.2. domestic and foreign R&D expenditures continue to be strategic substitutes. Now, however, four reaction functions emerge because both firms are able to accumulate knowledge intertemporally. Consequently, whenever intratemporal and intertemporal reaction functions are downward-sloping the signs of the cross derivatives $\partial^2 \Pi_2^d \big/ \partial I_2^d \partial I_2^f$ and $\partial^2 \Pi_2^d \big/ \partial I_2^f \partial I_2^d$ as well as the signs of the intertemporal derivatives $\partial^2 \Pi^d \big/ \partial I_2^d \partial I_1^d$ and $\partial^2 \Pi^d \big/ \partial I_1^d \partial I_2^d$ can be determined.

Lemma 2. Downward-sloping reaction functions imply negative cross derivatives $\partial^2 \Pi_2^d \big/ \partial I_2^d \partial I_2^f$ and $\partial^2 \Pi_2^d \big/ \partial I_2^f \partial I_2^d$ and positive intertemporal derivatives $\partial^2 \Pi^d \big/ \partial I_2^d \partial I_1^d$ and $\partial^2 \Pi^d \big/ \partial I_1^d \partial I_2^d$.

Proof. (see Appendix A 7)

Again, differentiating (12) with respect to tax rates yields stage 4 first-order conditions which can be rearranged to obtain the equilibrium tax policies in period 2:

$$t_2^d = \frac{\partial D}{\partial e_2^d} + \frac{1}{\left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial t_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial t_2^d} \right)} \cdot \begin{pmatrix} - P' \cdot \frac{\partial q_2^f}{\partial t_2^d} \cdot q_2^d - P(\cdot) \cdot \frac{\partial q_2^d}{\partial t_2^d} \\ - P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot q_2^d \cdot \beta^d \\ - P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot q_2^d \cdot \beta^d \\ + \frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^d} \cdot \beta^d + \frac{\partial I_2^d}{\partial t_2^d} \end{pmatrix} \tag{34}$$

$$t_2^f = \frac{\partial D}{\partial e_2^f} + \frac{1}{\left(\frac{\partial e_2^f}{\partial q_2^f} \cdot \frac{\partial q_2^f}{\partial t_2^f} + \frac{\partial e_2^f}{\partial \kappa_2^f} \cdot \frac{\partial \kappa_2^f}{\partial t_2^f} \right)} \cdot \begin{pmatrix} - P' \cdot \frac{\partial q_2^d}{\partial t_2^f} \cdot q_2^f - P(\cdot) \cdot \frac{\partial q_2^f}{\partial t_2^f} \\ - P' \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_2^d}{\partial t_2^f} \cdot q_2^f \cdot \alpha^f \\ - P' \cdot \frac{\partial q_2^d}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^f} \cdot q_2^f \cdot \alpha^f \\ + \frac{\partial C^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^f} \cdot \alpha^f + \frac{\partial I_2^f}{\partial t_2^f} \end{pmatrix} \tag{35}$$

These optimal regulation schedules give rise to the well-established strategic effects that were discussed in section 2.2.

3.3. Decisions in period 1

Optimisation of (10) in stage 3 leads to the following first-order conditions:

$$\frac{\partial \Pi_2^i}{\partial q_2^i} = \frac{\partial P(\cdot)}{\partial q_2^i} \cdot q_2^i + P(\cdot) - \frac{\partial C^i}{\partial q_2^i} = 0 \tag{36}$$

In stage 2 both firms now maximise intertemporal profits (11.1) which yields:

$$\begin{aligned} \frac{\partial \Pi^i}{\partial I_1^i} = P' \cdot \frac{\partial q_1^j}{\partial \kappa_1^i} \cdot q_1^i \cdot \alpha^i + P(\cdot) \cdot \frac{\partial q_1^i}{\partial \kappa_1^i} \cdot \alpha^i - \frac{\partial C^i}{\partial \kappa_1^i} \cdot \alpha^i \\ + P' \cdot \frac{\partial q_2^j}{\partial \kappa_2^i} \cdot q_2^i \cdot \alpha^i + P(\cdot) \cdot \frac{\partial q_2^i}{\partial \kappa_2^i} \cdot \alpha^i - \frac{\partial C^i}{\partial \kappa_2^i} \cdot \alpha^i - 1 = 0 \end{aligned} \tag{37}$$

This result can be interpreted as its counterpart in the original model.

Finally, due to the introduction of bilateral knowledge accumulation both governments maximise intertemporal welfare (12.1) in stage 1:

$$\begin{aligned} \frac{\partial \Phi^d}{\partial t_1^d} = P' \cdot \frac{\partial q_1^f}{\partial t_1^d} \cdot q_1^d + P(\cdot) \cdot \frac{\partial q_1^d}{\partial t_1^d} + P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^f} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_1^d \cdot \alpha^f + P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot q_1^d \cdot \alpha^d - \frac{\partial I_1^d}{\partial t_1^d} \\ - \frac{\partial C^d}{\partial \kappa_1^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha^d - \frac{\partial D}{\partial e_1^d} \cdot \left(\frac{\partial e_1^d}{\partial q_1^d} \cdot \frac{\partial q_1^d}{\partial t_1^d} + \frac{\partial e_1^d}{\partial \kappa_1^d} \cdot \frac{\partial \kappa_1^d}{\partial t_1^d} \right) + t_1^d \cdot \left(\frac{\partial e_1^d}{\partial q_1^d} \cdot \frac{\partial q_1^d}{\partial t_1^d} + \frac{\partial e_1^d}{\partial \kappa_1^d} \cdot \frac{\partial \kappa_1^d}{\partial t_1^d} \right) \\ + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^f} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_2^d \cdot \alpha^f + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot q_2^d \cdot \alpha^d - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha^d \\ - \left(\frac{\partial D}{\partial e_2^d} - t_2^d \right) \cdot \left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha^d + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha^d \right) = 0 \end{aligned} \tag{38}$$

$$\begin{aligned}\frac{\partial\Phi^f}{\partial t_1^f} &= P'\cdot\frac{\partial q_1^d}{\partial t_1^f}\cdot q_1^f + P(\cdot)\cdot\frac{\partial q_1^f}{\partial t_1^f} + P'\cdot\frac{\partial q_1^d}{\partial\kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^f}\cdot q_1^f\cdot\alpha^d + P'\cdot\frac{\partial q_1^d}{\partial\kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot q_1^f\cdot\alpha^f - \frac{\partial I_1^f}{\partial t_1^f}\\ &-\frac{\partial C^f}{\partial\kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f - \frac{\partial D}{\partial e_1^f}\cdot\left(\frac{\partial e_1^f}{\partial q_1^f}\cdot\frac{\partial q_1^f}{\partial t_1^f}+\frac{\partial e_1^f}{\partial\kappa_1^f}\cdot\frac{\partial\kappa_1^f}{\partial t_1^f}\right)+t_1^f\cdot\left(\frac{\partial e_1^f}{\partial q_1^f}\cdot\frac{\partial q_1^f}{\partial t_1^f}+\frac{\partial e_1^f}{\partial\kappa_1^f}\cdot\frac{\partial\kappa_1^f}{\partial t_1^f}\right)\\ &+P'\cdot\frac{\partial q_2^d}{\partial\kappa_2^d}\cdot\frac{\partial I_2^d}{\partial t_1^f}\cdot q_2^f\cdot\alpha^d + P'\cdot\frac{\partial q_2^d}{\partial\kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot q_2^f\cdot\alpha^f - \frac{\partial C^f}{\partial\kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f\\ &-\left(\frac{\partial D}{\partial e_2^f}-t_2^f\right)\cdot\left(\frac{\partial e_2^f}{\partial q_2^f}\cdot\frac{\partial q_2^f}{\partial\kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f + \frac{\partial e_2^f}{\partial\kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f\right)=0\end{aligned}\tag{39}$$

The optimal tax rates consequently are:

$$t_1^d = \frac{\partial D}{\partial e_1^d} + \frac{1}{\left(\frac{\partial e_1^d}{\partial q_1^d}\cdot\frac{\partial q_1^d}{\partial t_1^d}+\frac{\partial e_1^d}{\partial\kappa_1^d}\cdot\frac{\partial\kappa_1^d}{\partial t_1^d}\right)}\cdot\left(\begin{array}{c} -P'\cdot\frac{\partial q_1^f}{\partial t_1^d}\cdot q_1^d - P(\cdot)\cdot\frac{\partial q_1^d}{\partial t_1^d}\\ -P'\cdot\frac{\partial q_1^f}{\partial\kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_1^d\cdot\alpha^f\\ -P'\cdot\frac{\partial q_2^f}{\partial\kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_2^d\cdot\alpha^f\\ -P'\cdot\frac{\partial q_1^f}{\partial\kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot q_1^d\cdot\alpha^d\\ -P'\cdot\frac{\partial q_2^f}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot q_2^d\cdot\alpha^d\\ +\frac{\partial C^d}{\partial\kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d+\frac{\partial C^d}{\partial\kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\\ +\frac{\partial I_1^d}{\partial t_1^d}\\ +\left(\frac{\partial D}{\partial e_2^d}-t_2^d\right)\cdot\left[\left(\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial\kappa_2^d}+\frac{\partial e_2^d}{\partial\kappa_2^d}\right)\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right]\end{array}\right)\tag{40}$$

$$t_1^f = \frac{\partial D}{\partial e_1^f} + \frac{1}{\left(\frac{\partial e_1^f}{\partial q_1^f}\cdot\frac{\partial q_1^f}{\partial t_1^f} + \frac{\partial e_1^f}{\partial \kappa_1^f}\cdot\frac{\partial \kappa_1^f}{\partial t_1^f}\right)} \cdot \left(\begin{array}{c} -P'\cdot\frac{\partial q_1^d}{\partial t_1^f}\cdot q_1^f - P(\cdot)\cdot\frac{\partial q_1^f}{\partial t_1^f} \\ -P'\cdot\frac{\partial q_1^d}{\partial \kappa_1^d}\cdot\frac{\partial I_1^d}{\partial t_1^f}\cdot q_1^f\cdot\alpha^d \\ -P'\cdot\frac{\partial q_2^d}{\partial \kappa_2^d}\cdot\frac{\partial I_1^d}{\partial t_1^f}\cdot q_2^f\cdot\alpha^d \\ -P'\cdot\frac{\partial q_1^d}{\partial \kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot q_1^f\cdot\alpha^f \\ -P'\cdot\frac{\partial q_2^d}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot q_2^f\cdot\alpha^f \\ +\frac{\partial C^f}{\partial \kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f + \frac{\partial C^f}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f \\ +\frac{\partial I_1^f}{\partial t_1^f} \\ +\left(\frac{\partial D}{\partial e_2^f} - t_2^f\right)\cdot\left[\left(\frac{\partial e_2^f}{\partial q_2^f}\cdot\frac{\partial q_2^f}{\partial \kappa_2^f} + \frac{\partial e_2^f}{\partial \kappa_2^f}\right)\cdot\frac{\partial I_1^f}{\partial t_1^f}\cdot\alpha^f\right] \end{array} \right) \tag{41}$$

It is evident that both optimal regulation schedules in the first modification of the model have the same qualitative properties. Both firms now are able to accumulate knowledge intertemporally and therefore benefit from the intertemporal innovation effects. Furthermore, this modification leads to the incorporation of the intertemporal indirect rent-shifting effect known from (28) in both equilibrium regulation schedules. Again, the same questions as in the basic version come to the fore: Will the domestic government set a unilaterally higher tax rate in period 1 and will it be set above the Pigouvian level?

Proposition 4. The domestic government will set a higher tax rate in period 1 than the foreign government.

Proof. (see Appendix A 8)

Proposition 5. The domestic government will set a tax rate above the Pigouvian level in period 1 if the policy adjustment condition, the existence condition, and the predominance condition hold.

Proof. (see Appendix A 9)

The introduction of bilateral knowledge accumulation – while the asymmetry is maintained through different knowledge parameters – demonstrates that the original results are weakened. Qualitatively, the effects are equivalent except for the additional rent-shifting effect. Quantitative differences arise from the specific magnitudes of the knowledge parameters. Still, the domestic government will set a higher tax rate than its foreign counterpart. Whether this tax rate exceeds the Pigouvian level is not easy to clarify since the governing effects are ambiguous. But if α^d is sufficiently high a domestic tax rate above the Pigouvian level becomes optimal.

4. Conclusion

The previous results give rise to a revaluation of the conventional prediction of strategic environmental policy games, 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 very likely will lead to the prediction that governments should install a lax tax policy. But our results suggest that the incorporation of the benefits from building upon and improving previous knowledge may result in a stringent first-mover policy.

This prediction is of course contingent upon the respective environment. It has been shown that a scenario with unilateral domestic knowledge accumulation facilitates the policy recommendations: If for whatever reason the foreign firm is incapable of applying a knowledge-based approach to its efforts in reducing emissions the domestic firm may very likely benefit from intertemporal innovation effects which renders a stringent first-mover tax policy the optimal choice for the domestic government. Even in a world with bilateral knowledge accumulation this recommendation can be maintained if the domestic firm has higher knowledge parameters. The transnational difference between the latter may for instance describe that the domestic firm is savvier regarding its knowledge-based activities.

Although we believe that the previous results shed new light on the regulation-competitiveness 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 its 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 efforts. 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 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 risks. 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.

These shortcomings notwithstanding, our results show that a stringent tax policy is the optimal choice whenever (1) only the firms located under the policymaker's jurisdiction are able to accumulate knowledge over time or whenever (2) the differences between the transnational knowledge parameters are significant. Moreover, 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 insufficient.

Appendix

A 1

Totally differentiating the first-order conditions with respect to the domestic tax rate leads to the following equation system:[15]

$$\begin{bmatrix} \frac{\partial^2 \Pi_t^d}{\partial (q_t^d)^2} & \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \frac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} \end{bmatrix} \cdot \begin{bmatrix} \frac{dq_t^d}{dt_t^d} \\ \frac{dq_t^f}{dt_t^d} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \\ \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} \end{bmatrix} \tag{42}$$

Using (13) and solving (42) with Cramer's Rule yields:

$$\frac{\mathrm{d}q_t^d}{\mathrm{d}t_t^d} = \frac{\begin{vmatrix} \frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} & \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} & \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} \end{vmatrix}}{|H_q|} = \frac{\left(\frac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \cdot \frac{\partial^2 \Pi_t^f}{\partial (q_t^f)^2} - \frac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} \cdot \frac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \right)}{|H_q|} < 0 \tag{43a}$$

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

$$\frac{\mathrm{d}q_t^f}{\mathrm{d}t_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 \Pi_t^d}{\partial \left(q_t^d\right)^2} & \dfrac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \\ \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \dfrac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} \end{vmatrix}}{\left|H_q\right|} = \frac{\left(\dfrac{\partial^2 \Pi_t^d}{\partial \left(q_t^d\right)^2} \cdot \dfrac{\partial^2 C^f}{\partial q_t^f \partial t_t^d} - \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} \cdot \dfrac{\partial^2 C^d}{\partial q_t^d \partial t_t^d} \right)}{\left|H_q\right|} > 0 \tag{43b}$$

Due to the assumptions about the cost and emission functions $\partial^2 C^d / \partial q_t^d \partial t_t^d > 0$ and $\partial^2 C^f / \partial q_t^f \partial t_t^d = 0$.

A 2

Totally differentiating the first-order conditions with respect to domestic R&D expenditures yields the following equation system:

$$\begin{bmatrix} \dfrac{\partial^2 \Pi_t^d}{\partial \left(q_t^d\right)^2} & \dfrac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \dfrac{\partial^2 \Pi_t^f}{\partial \left(q_t^f\right)^2} \end{bmatrix} \cdot \begin{bmatrix} \dfrac{dq_t^d}{dI_t^d} \\ \dfrac{dq_t^f}{dI_t^d} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \\ \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} \end{bmatrix} \tag{44}$$

Using (13) and solving (44) by Cramer's Rule yields:

$$\frac{dq_t^d}{dI_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} & \dfrac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \\ \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} & \dfrac{\partial^2 \Pi_t^f}{\partial \left(q_t^f\right)^2} \end{vmatrix}}{\left|H_q\right|} = \frac{\left(\dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \cdot \dfrac{\partial^2 \Pi_t^f}{\partial \left(q_t^f\right)^2} - \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} \cdot \dfrac{\partial^2 \Pi_t^d}{\partial q_t^d \partial q_t^f} \right)}{\left|H_q\right|} > 0 \tag{45a}$$

$$\frac{dq_t^f}{dI_t^d} = \frac{\begin{vmatrix} \dfrac{\partial^2 \Pi_t^d}{\partial \left(q_t^d\right)^2} & \dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \\ \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} & \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} \end{vmatrix}}{\left|H_q\right|} = \frac{\left(\dfrac{\partial^2 \Pi_t^d}{\partial \left(q_t^d\right)^2} \cdot \dfrac{\partial^2 C^f}{\partial q_t^f \partial I_t^d} - \dfrac{\partial^2 \Pi_t^f}{\partial q_t^f \partial q_t^d} \cdot \dfrac{\partial^2 C^d}{\partial q_t^d \partial I_t^d} \right)}{\left|H_q\right|} < 0 \tag{45b}$$

Due to $\partial \kappa_t^d / \partial I_t^d > 0$ and the assumptions about the cost functions $\partial^2 C^d / \partial q_t^d \partial I_t^d < 0$ and $\partial^2 C^f / \partial q_t^f \partial I_t^d = 0$.

A 3

Totally differentiating first-order conditions (16) and (17) yields

$$\partial^2 \Pi_2^d / \partial \left(I_2^d\right)^2 \, \mathrm{d}I_2^d + \partial^2 \Pi_2^d / \partial I_2^d \partial I_2^f \, \mathrm{d}I_2^f = 0 \tag{46a}$$

$$\partial^2 \Pi_2^f / \partial \left(I_2^f\right)^2 \, \mathrm{d}I_2^f + \partial^2 \Pi_2^f / \partial I_2^f \partial I_2^d \, \mathrm{d}I_2^d = 0, \tag{46b}$$

which can be solved to

$$\frac{\mathrm{d}I_2^d}{\mathrm{d}I_2^f} = -\frac{\partial^2 \Pi_2^d / \partial I_2^d \partial I_2^f}{\partial^2 \Pi_2^d / \partial \left(I_2^d\right)^2} < 0 \quad \text{for } \partial^2 \Pi_2^d / \partial I_2^d \partial I_2^f < 0 \tag{46c}$$

$$\frac{\mathrm{d}I_2^f}{\mathrm{d}I_2^d} = -\frac{\partial^2 \Pi_2^f / \partial I_2^f \partial I_2^d}{\partial^2 \Pi_2^f / \partial \left(I_2^f\right)^2} < 0 \quad \text{for } \partial^2 \Pi_2^d / \partial I_2^f \partial I_2^d < 0 \tag{46d}$$

A 4

Were the game completely symmetric the symmetry of Π_1^d and Π_1^f would imply that in equilibrium $t_1^d = t_1^f$. This requires that the foreign government's foc (27) is satisfied:

$$\frac{\partial \Pi_1^f}{\partial t_1^f} - \frac{\partial D}{\partial t_1^f} + t' \cdot \frac{\partial e_1^f}{\partial t_1^f} = 0 \tag{47}$$

However, the domestic government's foc (29) is only satisfied when the additional intertemporal innovation effects (IIE)[16] are taken into consideration.

$$\frac{\partial \Pi_1^d}{\partial t_1^d} - \frac{\partial D}{\partial t_1^d} + t' \cdot \frac{\partial e_1^d}{\partial t_1^d} + \text{IIE} = 0 \tag{48}$$

Since the IIE are positive this means that domestic marginal welfare is still increasing at the symmetric equilibrium in (47). Therefore, $t_1^d > t_1^f$.

A 5

Due to the setting of the model, deriving clear-cut results is not possible. However, the differences between intra- and intertemporal results allow for a qualitative prediction. To highlight these differences we begin with the domestic firm's foc in period 2. Rearranging 20) yields:

$$\begin{aligned}&\left(t_2^d - \frac{\partial D}{\partial e_2^d}\right) \cdot \underset{(-)}{\left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial t_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \cdot \frac{\partial \kappa_2^d}{\partial t_2^d}\right)} + \underset{(-)}{P' \cdot \frac{\partial q_2^f}{\partial t_2^d}} \cdot q_2^d + P(\cdot) \cdot \frac{\partial q_2^d}{\partial t_2^d} \\ &+ \underset{(-)}{P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \frac{\partial I_2^f}{\partial t_2^d}} \cdot \beta \cdot q_2^d + \left(\underset{(+)}{P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \beta \cdot q_2^d} - \underset{(+)}{\frac{\partial C^d}{\partial \kappa_2^d} \cdot \beta} - 1\right) \underset{(-)}{\frac{\partial I_2^d}{\partial t_2^d}} = 0\end{aligned} \tag{49}$$

At the Pigouvian level the term in the first parenthesis becomes zero. Therefore, in its stringent variant $t_2^d > \partial D / \partial e_2^d$ multiplication of the first and the second parenthesis, which contains the numerator of the familiar negative multiplier, yields a negative term. Consequently, to satisfy the according foc the subsequent positive terms (these are the innovation effects) need to be sufficiently strong.

The existence of an innovation effect requires a positive balance of the effects that the domestic tax policy exercises on domestic R&D expenditures. Hence, the sign of the sum of the effects in the last parenthesis has to be positive which implies the following necessary condition:

$$P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \beta \cdot q_2^d - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \beta > 1 \tag{50}$$

Satisfaction of (50) demands that the cost-reducing (part of the innovation effect) and the cross-quantity-shifting effect (part of the indirect innovation effect) exceed the last unit of induced R&D expenditures. It is revealing that (50) emphasises the impact of β: The larger the knowledge parameter the stronger the innovation effects of own R&D expenditures.

[16] These are the tax-increasing intertemporal indirect innovation effect and the intertemporal innovation effect.

The predominance condition for an innovation offset is captured in the second necessary condition:

$$\left| P' \cdot \frac{\partial q_2^f}{\partial t_2^d} \cdot q_2^d + P(\cdot) \cdot \frac{\partial q_2^d}{\partial t_2^d} + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^f} \cdot \frac{\partial I_2^f}{\partial t_2^d} \cdot \beta \cdot q_2^d \right| < \left| \left(P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot \beta \cdot q_2^d - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \beta - 1 \right) \frac{\partial I_2^d}{\partial t_2^d} \right| \qquad (51)$$

(51) demands that the absolute value of the tax-decreasing effects needs to be less than the absolute value of the induced innovation effects (given that (50) holds]. Hence, by (50) and (51) an intratemporally stringent regulation may only be issued for a sufficiently large β.

To eventually obtain $t_2^d > \partial D / \partial e_2^d$, which means that the first parenthesis in (49) has a negative sign, the sufficient condition is $\partial \Phi_2^d / \partial t_2^d = 0$ which is the domestic foc in stage 4. If the necessary conditions hold $\left(t_2^d - \partial D / \partial e_2^d \right)$ becomes positive if $\partial \Phi_2^d / \partial t_2^d = 0$.

<u>A 6</u>

To evaluate the intertemporal effect the results of stage 1 need to be considered. Rearranging (29) yields:

$$\begin{aligned}
&\left(t_1^d - \frac{\partial D}{\partial e_1^d} \right) \cdot \left(\frac{\partial e_1^d}{\partial q_1^d} \cdot \frac{\partial q_1^d}{\partial t_1^d} + \frac{\partial e_1^d}{\partial \kappa_1^d} \cdot \frac{\partial \kappa_1^d}{\partial t_1^d} \right) + \underset{(-)}{P' \cdot \frac{\partial q_1^f}{\partial t_1^d} \cdot q_1^d} + \underset{(-)}{P(\cdot) \cdot \frac{\partial q_1^d}{\partial t_1^d}} + \underset{(-)}{P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^f} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_1^d \cdot \alpha} \\
&+ \left(\underset{(+)}{P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^d} \cdot q_1^d \cdot \alpha} - \underset{(+)}{\frac{\partial C^d}{\partial \kappa_1^d} \cdot \alpha} + \underset{(+)}{P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot q_2^d \cdot \alpha} - \underset{(+)}{\frac{\partial C^d}{\partial \kappa_2^d} \cdot \alpha} \underset{(-)}{- 1} \right) \cdot \frac{\partial I_1^d}{\partial t_1^d} \qquad (52) \\
&- \left(\frac{\partial D}{\partial e_2^d} - t_2^d \right) \cdot \left[\left(\underset{(+)}{\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial \kappa_2^d}} + \underset{(-)}{\frac{\partial e_2^d}{\partial \kappa_2^d}} \right) \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha \right] = 0
\end{aligned}$$

(52) reveals the policy adjustment condition:

$$-\left(\frac{\partial D}{\partial e_2^d} - t_2^d \right) \cdot \left[\left(\frac{\partial e_2^d}{\partial q_2^d} \cdot \frac{\partial q_2^d}{\partial \kappa_2^d} + \frac{\partial e_2^d}{\partial \kappa_2^d} \right) \cdot \frac{\partial I_1^d}{\partial t_1^d} \cdot \alpha \right] \geq 0 \qquad (53)$$

Condition (53) implies that the emission-reducing effect of induced domestic innovations must not be overcompensated by an emission-increasing effect. The latter may occur when relative emission reductions are dwarfed by a rise in total domestic emissions due to increased domestic quantities (see footnote 13). Assuming a predominance of the emission-reducing effect gives rise to a laxer domestic tax policy in period 2.

However, (53) might not be important at all because either part of the remaining effects may be strong enough to shape the regulation schedule. But since the use of general functions does not allow for such a simplification (53) is binding.

The counterpart to the existence condition (50) is:

$$P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^d} \cdot q_1^d \cdot \alpha - \frac{\partial C^d}{\partial \kappa_1^d} \cdot \alpha + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot q_2^d \cdot \alpha - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \alpha > 1 \qquad (54)$$

Condition (54) demands that the sum of all domestic innovation effects exceeds the last unit of tax-induced R&D. By virtue of knowledge accumulation now both intra- and intertemporal innovation effects become effective. Hence, (54) is weaker and therefore more likely to hold than (50).

Consequently, and according to the previous approach the necessary predominance condition is:

$$\left| P' \cdot \frac{\partial q_1^f}{\partial t_1^d} \cdot q_1^d + P(\cdot) \cdot \frac{\partial q_1^d}{\partial t_1^d} + P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^f} \cdot \frac{\partial I_1^f}{\partial t_1^d} \cdot q_1^d \cdot \alpha \right| < \left| \left(P' \cdot \frac{\partial q_1^f}{\partial \kappa_1^d} \cdot q_1^d \cdot \alpha - \frac{\partial C^d}{\partial \kappa_1^d} \cdot \alpha + P' \cdot \frac{\partial q_2^f}{\partial \kappa_2^d} \cdot q_2^d \cdot \alpha - \frac{\partial C^d}{\partial \kappa_2^d} \cdot \alpha - 1 \right) \cdot \frac{\partial I_1^d}{\partial t_1^d} \right| \tag{55}$$

Again, by (55) the absolute value of the tax-decreasing effects needs to be less in magnitude than the absolute value of the induced innovation effects (given that (53) and (54) hold). To allow for a larger RHS α needs to be sufficiently large to exploit the effect of accumulated knowledge.[17] And since by definition $\alpha > \beta$ a stringent tax policy in period 1 becomes more likely when one allows for knowledge accumulation. Thus, condition (55) is weaker in comparison to the predominance condition in the intratemporal case.

In the intertemporal case the sufficient condition is the intertemporal foc: If the necessary conditions hold a stringent domestic tax policy in period 1, that is a positive expression $\left(t_1^d - \partial D / \partial e_1^d\right)$, can be obtained if the foc $\partial \Phi^d / \partial t_1^d = 0$ holds.

A 7

Totally differentiating the domestic intertemporal first-order condition yields:

$$\partial^2 \Pi^d / \partial \left(I_1^d\right)^2 \, dI_1^d + \partial^2 \Pi^d / \partial I_1^d \partial I_2^d \, dI_2^d + \partial^2 \Pi^d / \partial I_1^d \partial I_1^f \, dI_1^f = 0 \tag{56a}$$

$$\partial^2 \Pi^d / \partial I_2^d \partial I_1^d \, dI_1^d + \partial^2 \Pi^d / \partial \left(I_2^d\right)^2 \, dI_2^d + \partial^2 \Pi^d / \partial I_2^d \partial I_2^f \, dI_2^f = 0 \tag{56b}$$

First, solving equation (56b) for dI_1^d yields:

$$dI_1^d = -\frac{\partial^2 \Pi^d / \partial \left(I_2^d\right)^2}{\partial^2 \Pi^d / \partial I_2^d \partial I_1^d} dI_2^d - \frac{\partial^2 \Pi^d / \partial I_2^d \partial I_2^f}{\partial^2 \Pi^d / \partial I_2^d \partial I_1^d} dI_2^f \tag{56c}$$

Reinserting equation (56c) into equation (56a) yields:

$$\Delta_1 dI_2^d = -\partial^2 \Pi^d / \partial I_1^d \partial I_1^f \cdot \partial^2 \Pi^d / \partial I_2^d \partial I_1^d \, dI_1^f + \partial^2 \Pi^d / \partial \left(I_1^d\right)^2 \cdot \partial^2 \Pi^d / \partial I_2^d \partial I_2^f \, dI_2^f \tag{56d}$$

$$\text{with } \Delta_1 = \partial^2 \Pi^d / \partial \left(I_1^d\right)^2 \cdot \left(-\partial^2 \Pi^d / \partial \left(I_2^d\right)^2\right) + \partial^2 \Pi^d / \partial I_1^d \partial I_2^d \cdot \partial^2 \Pi^d / \partial I_2^d \partial I_1^d < 0$$

$\Delta_1 < 0$ is a stability condition which ensures that intratemporal effects dominate intertemporal effects.

Second, solving equation (56b) for dI_2^d yields:

$$dI_2^d = -\frac{\partial^2 \Pi^d / \partial I_2^d \partial I_1^d}{\partial^2 \Pi^d / \partial \left(I_2^d\right)^2} dI_1^d - \frac{\partial^2 \Pi^d / \partial I_2^d \partial I_2^f}{\partial^2 \Pi^d / \partial \left(I_2^d\right)^2} dI_2^f \tag{56e}$$

Reinserting equation (56e) into equation (56a) yields:

$$\Delta_2 dI_1^d = -\partial^2 \Pi^d / \partial \left(I_2^d\right)^2 \cdot \partial^2 \Pi^d / \partial I_1^d \partial I_1^f \, dI_1^f + \partial^2 \Pi^d / \partial I_1^d \partial I_2^d \cdot \partial^2 \Pi^d / \partial I_2^d \partial I_2^f \, dI_2^f \tag{56f}$$

$$\text{with } \Delta_2 = \partial^2 \Pi^d / \partial \left(I_2^d\right)^2 \cdot \partial^2 \Pi^d / \partial \left(I_1^d\right)^2 - \partial^2 \Pi^d / \partial I_1^d \partial I_2^d \cdot \partial^2 \Pi^d / \partial I_2^d \partial I_1^d > 0$$

$\Delta_2 > 0$ is a stability condition which ensures that intratemporal effects dominate intertemporal effects.

[17] Note that the domestic firm need not consider an intertemporal indirect rent-shifting effect.

From (42d) the reactions of $\mathrm{d}I_2^d$ with respect to foreign R&D expenditures from both periods can be calculated:

$$\frac{\mathrm{d}I_2^d}{\mathrm{d}I_2^f} = \frac{\partial^2\Pi^d / \partial\left(I_1^d\right)^2 \cdot \partial^2\Pi^d / \partial I_2^d \partial I_2^f}{\Delta_1} < 0 \quad \text{for } \partial^2\Pi^d / \partial I_2^d \partial I_2^f < 0 \tag{57a}$$

$$\frac{\mathrm{d}I_2^d}{\mathrm{d}I_1^f} = \frac{-\partial^2\Pi^d / \partial I_1^d \partial I_1^f \cdot \partial^2\Pi^d / \partial I_2^d \partial I_1^d}{\Delta_1} < 0 \quad \text{for } \partial^2\Pi^d / \partial I_1^d \partial I_1^f < 0 \text{ and } \partial^2\Pi^d / \partial I_2^d \partial I_1^d > 0 \tag{57b}$$

(57a) merely replicates the result known from (46c). (57b), however, additionally requires $\partial^2\Pi^d / \partial I_2^d \partial I_1^d > 0$ to allow for a downward-sloping intertemporal reaction function. That is to say, R&D expenditures in period 1 increase the marginal effect of period 2 R&D expenditures on intertemporal domestic profits. The intuition behind this is straightforward: Due to the endurance of early knowledge capital the effect of subsequent R&D activities is increased because the latter can build upon existent knowledge.

The reactions of $\mathrm{d}I_1^d$ with respect to foreign R&D expenditures from both periods can be interpreted accordingly. The reactions can be inferred from (56f):

$$\frac{\mathrm{d}I_1^d}{\mathrm{d}I_1^f} = \frac{-\partial^2\Pi^d / \partial\left(I_2^d\right)^2 \cdot \partial^2\Pi^d / \partial I_1^d \partial I_1^f}{\Delta_2} < 0 \quad \text{for } \partial^2\Pi^d / \partial I_1^d \partial I_1^f < 0 \tag{57c}$$

$$\frac{\mathrm{d}I_1^d}{\mathrm{d}I_2^f} = \frac{\partial^2\Pi^d / \partial I_1^d \partial I_2^d \cdot \partial^2\Pi^d / \partial I_2^d \partial I_2^f}{\Delta_2} < 0 \quad \text{for } \partial^2\Pi^d / \partial I_2^d \partial I_2^f < 0 \text{ and } \partial^2\Pi^d / \partial I_1^d \partial I_2^d > 0 \tag{57d}$$

A 8

As before, an entirely symmetric game would entail $t_1^d = t_1^f$. In equilibrium the foreign government's foc (39) has to be satisfied. Contrary to the setting with unilateral knowledge accumulation the foreign firm now also benefits from intertemporal innovation effects:

$$\frac{\partial\Pi_1^f}{\partial t_1^f} - \frac{\partial D}{\partial t_1^f} + t' \cdot \frac{\partial e_1^f}{\partial t_1^f} + \mathrm{IIE}\left(\alpha^f\right) = 0 \tag{58}$$

Simultaneously, the domestic government's foc (38) has to be satisfied:

$$\frac{\partial\Pi_1^d}{\partial t_1^d} - \frac{\partial D}{\partial t_1^d} + t' \cdot \frac{\partial e_1^d}{\partial t_1^d} + \mathrm{IIE}\left(\alpha^d\right) = 0 \tag{59}$$

Both $\mathrm{IIE}\left(\alpha^f\right)$ and $\mathrm{IIE}\left(\alpha^d\right)$ are positive. However, since $\alpha^d > \alpha^f$ it follows that $\mathrm{IIE}\left(\alpha^d\right) > \mathrm{IIE}\left(\alpha^f\right)$. Thus, at (58) t_1^d is still increasing (that is, (59) is not satisfied), which proofs that $t_1^d > t_1^f$.

A 9

Similar to the proof of proposition 3 the domestic government's period 1 foc (38) can be rearranged to obtain:

$$\begin{aligned}&\left(t_1^d-\frac{\partial D}{\partial e_1^d}\right)\cdot\left(\frac{\partial e_1^d}{\partial q_1^d}\cdot\frac{\partial q_1^d}{\partial t_1^d}+\frac{\partial e_1^d}{\partial \kappa_1^d}\cdot\frac{\partial \kappa_1^d}{\partial t_1^d}\right)+P'\cdot\frac{\partial q_1^f}{\partial t_1^d}\cdot q_1^d+P(\cdot)\cdot\frac{\partial q_1^d}{\partial t_1^d}\\&+P'\cdot\frac{\partial q_1^f}{\partial \kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_1^d\cdot\alpha^f+P'\cdot\frac{\partial q_2^f}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_2^d\cdot\alpha^f\\&+\left(P'\cdot\frac{\partial q_1^f}{\partial \kappa_1^d}\cdot q_1^d\cdot\alpha^d-\frac{\partial C^d}{\partial \kappa_1^d}\cdot\alpha^d+P'\cdot\frac{\partial q_2^f}{\partial \kappa_2^d}\cdot q_2^d\cdot\alpha^d-\frac{\partial C^d}{\partial \kappa_2^d}\cdot\alpha^d-1\right)\cdot\frac{\partial I_1^d}{\partial t_1^d}\\&-\left(\frac{\partial D}{\partial e_2^d}-t_2^d\right)\cdot\left[\left(\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial \kappa_2^d}+\frac{\partial e_2^d}{\partial \kappa_2^d}\right)\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right]=0\end{aligned}\tag{60}$$

It follows that three necessary conditions have to hold to allow for a stringent domestic tax policy:

$$-\left(\frac{\partial D}{\partial e_2^d}-t_2^d\right)\cdot\left[\left(\frac{\partial e_2^d}{\partial q_2^d}\cdot\frac{\partial q_2^d}{\partial \kappa_2^d}+\frac{\partial e_2^d}{\partial \kappa_2^d}\right)\cdot\frac{\partial I_1^d}{\partial t_1^d}\cdot\alpha^d\right]\geq 0\tag{61}$$

Condition (61) again captures the policy adjustment effect and demands that the emission-reducing effect of induced domestic innovations is stronger or at least equal to the emission-increasing effect of a rise in total domestic quantities.

The existence condition is:

$$P'\cdot\frac{\partial q_1^f}{\partial \kappa_1^d}\cdot q_1^d\cdot\alpha^d-\frac{\partial C^d}{\partial \kappa_1^d}\cdot\alpha^d+P'\cdot\frac{\partial q_2^f}{\partial \kappa_2^d}\cdot q_2^d\cdot\alpha^d-\frac{\partial C^d}{\partial \kappa_2^d}\cdot\alpha^d>1\tag{62}$$

Condition (62) demands that the sum of all domestic innovation effects exceeds the last unit of induced R&D expenditures. If this existence condition holds an innovation effect occurs.

The predominance condition is:

$$\begin{aligned}&\left|P'\cdot\frac{\partial q_1^f}{\partial t_1^d}\cdot q_1^d+P(\cdot)\cdot\frac{\partial q_1^d}{\partial t_1^d}+P'\cdot\frac{\partial q_1^f}{\partial \kappa_1^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_1^d\cdot\alpha^f+P'\cdot\frac{\partial q_2^f}{\partial \kappa_2^f}\cdot\frac{\partial I_1^f}{\partial t_1^d}\cdot q_2^d\cdot\alpha^f\right|\\&<\left|\left(P'\cdot\frac{\partial q_1^f}{\partial \kappa_1^d}\cdot q_1^d\cdot\alpha^d-\frac{\partial C^d}{\partial \kappa_1^d}\cdot\alpha^d+P'\cdot\frac{\partial q_2^f}{\partial \kappa_2^d}\cdot q_2^d\cdot\alpha^d-\frac{\partial C^d}{\partial \kappa_2^d}\cdot\alpha^d-1\right)\cdot\frac{\partial I_1^d}{\partial t_1^d}\right|\end{aligned}\tag{63}$$

Qualitatively the predominance condition (63) corresponds to (55) insofar as it also demands the tax-decreasing effects to be less in magnitude than the induced innovation effects. However, due to (1) the introduction of the intertemporal indirect rent-shifting effect and (2) $\alpha^d>\alpha^f$ there is a quantitative difference. If the difference between α^d and α^f becomes marginal the additional rent-shifting effect may produce an impact on a scale that violates the predominance condition which would obviate innovation offsets. Consequently, (63) is stronger than (55).

The sufficient condition, in turn, is the according foc. That is to say for $\left(t_1^d-\partial D/\partial e_1^d\right)>0$ to hold $\partial\Phi^d/\partial t_1^d=0$ has to hold, too.

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