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Linking Emissions Trading Schemes in the Presence of Research and Development Spillovers

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Linking Emissions Trading Schemes in the Presence of Research and Development Spillovers

Abstract

I analyze the role of research and development (R&D) spillovers on the incentives to link emissions trading schemes (ETSs) under different timings with respect to the determination of the emissions reduction target (ERT) and to the linking decision. When countries decide upon linking their ETSs prior to setting their ERTs, the permit importing country may not consent to link in the absence of R&D spillovers. The reason is that the other country strategically decreases its ERT to increase its revenues from permit trading, thereby increasing the costs for the permit importing country. However, in the presence of R&D spillovers, the permit importing country benefits from higher R&D spillovers and from lower environmental damage under linking relative to autarky and is therefore willing to link.

When countries determine their ERTs prior to the linking decision, the role of R&D spillovers on the linking decision reverses. In the absence of R&D spillovers, both countries unambiguously are willing to link their ETSs due to the efficiency gains from trade. However, if R&D spillovers are relevant, the permit exporting country may be worse off under linking because its R&D spillovers deteriorate due to lower abatement effort by the other country. Hence, there is a trade-off between the efficiency gains from trade and the reduced R&D spillovers, causing the permit exporting country to reject linking if the spillover effect is sufficiently large.

Keywords: climate change, emissions trading, technology spillovers, linking

JEL Classification Numbers: H41, O30, Q54, Q56

1 Introduction

In the last years, several emissions trading schemes (ETS), such as the European Union ETS, have been established worldwide in order to act against global warming. More recently, China launched ETSs in seven pilot regions and has announced to establish a national ETS by 2016. Economic theory suggests that linking existing trading schemes equalizes marginal abatement costs across regions, thereby minimizing the abatement costs and leading to benefits for all countries involved. However, this argument neglects two crucial factors. First, the number of issued emissions allowances, or equivalently the emissions reduction target (ERT), is a political decision and may vary depending on whether or not trading schemes are linked. Second, the price signal of the permit market is decisive for (private) investments in research and development (R&D) of climate friendly technologies. Moreover, a part of the knowledge created in one country may spill over to other countries. The question arises whether or not countries benefit from linking their ETSs in the presence of induced technological change and R&D spillovers when the ERT is not fixed, but is determined endogenously.

Helm (2003) analyzes the case when countries set their ERTs (in his paper the number of emission allowances) endogenously, but does not consider R&D spillovers. He finds that the permit importing country may not consent to link because of a negative strategic price effect that is imposed by the other country. Relative to autarky, the permit exporting country has an incentive to relax its ERT in order to increase its revenue from permit trading. To counteract this increase, the permit importing country expands its ERT which leads to higher permit payments, making this country potentially worse off under linkage relative to autarky.

Golombek and Hoel (2008) study the welfare consequences of linking ETSs in the presence of R&D spillovers. In their model, countries cooperatively choose their ERTs in the first stage and decide upon their R&D levels (via local subsidies) non-cooperatively in the second stage. They find that allowing for trade in permits after the ERTs have been

determined reduces the joint welfare of the countries. The reason is that permit trading equalizes marginal abatement costs whereas the welfare optimum generally requires marginal abatement costs to be distinct. Since the ERT triggers investment in R&D and therefore internalizes partially the positive technology spillovers across countries, any deviation from the optimal ERTs distorts the R&D investments of each country, leading to a decrease of the joint welfare.

The crucial assumption of Golombek and Hoel (2008) is that countries choose their emissions allowances cooperatively in the first stage. While maintaining the assumption that the ERTs are determined prior to the R&D investments, I assume countries to set their ERTs non-cooperatively. Non-cooperative behavior seems to reflect the political reality in climate negotiations more accurately than cooperative behavior.¹ Furthermore, I analyze the incentives of countries to link their ETSs for different timings with respect to the linking decision. In particular, I distinguish between whether countries decide upon linking their ETS before or after ERTs have been determined.

If countries take the linking decision prior to setting the ERTs, then the permit importing country may not consent to link in the absence of spillovers due to the negative strategic effect identified by Helm (2003). However, if spillovers are substantial, this country may be willing to link. The reason is that relative to autarky the permit exporting country increases its abatement effort and therefore also its R&D investments, which is beneficial for the permit importing country due to higher spillovers. Hence, while the permit importing country may not consent to link its ETSs in the absence of spillovers, it may do so if R&D spillovers are sufficiently large.

This result is reversed when countries determine their ERTs prior to the linking decision. If spillovers do not exist, then both countries will consent to link their ETSs given

¹Even though the Paris agreement is celebrated as a breakthrough in international climate negotiations by many scholars, the determination of the intended nationally determined contributions (INDC) of each country rather reflects a non-cooperative solution than a solution that have been agreed upon in a cooperative way. Thus, assuming non-cooperative behavior of countries when setting their ERTs seems to be appropriate despite the Paris agreement.

the ERTs have been already set because they benefit from the efficiency gains from trade. This is the standard argument in favor of linking ETSs. However, if spillovers are substantial, then the permit exporting country may not be willing to link. The reason is that in the case of linkage, the permit importing country will reduce its abatement effort and, therefore, also its R&D investments, leading to lower spillovers for the permit exporting country. Hence, there is a trade-off between the efficiency gains from trade and the reduced R&D spillovers which is why the permit exporting country may not benefit from linking. Thus, while countries unambiguously opt for linking in the absence of spillovers, they may not link their ETSs if spillovers are sufficiently high.

Related literature

There are some papers asking whether linking ETSs is in the best interest of each individual country. Babiker et al. (2004) show in a partial equilibrium model that linking leads to higher social costs if the permit price interacts with domestic taxes. In Marschinski et al. (2012), the authors analyze linkage in a general equilibrium model and identify a terms of trade effect that may lead to a deterioration of welfare. Anger (2008) shows in a two-sector general equilibrium model that linkage may not be beneficial if only one sector is linked and the national allocation of allowances towards the two sectors is endogenous. More recently, Doda and Taschini (2015) argue that fixed set up costs associated with linking may outweigh the efficiency gains from trade.

The results of Helm (2003) also suggest that linking may not be in the best interest of some countries. The reason in his paper is that countries determine the number of emissions allowances endogenously which gives rise to a negative strategic price effect. Permit exporting countries will issue more emissions allowances under linking relative to not linking, thereby decreasing the welfare of permit importing countries. In total, permit importing countries may be better off under autarky. This conclusion is partly confirmed by Carbone et al. (2009) who use a computable general equilibrium model to calculate the welfare consequences of permit trading. Holtmark and Sommervoll (2012)

show in a two country setting that the negative price effect can be so large that the joint welfare of both countries is inferior when countries allow for permit trading. The reason is that under certain conditions with respect to the slope of the marginal abatement costs and to the size of the countries, the overall ERT under linking is smaller than under autarky. This leads to higher environmental damage for both countries which outweighs the efficiency gains from trade associated with linking permit markets.²

The papers above do not include R&D investments and technology spillovers. This is included in Golombek and Hoel (2004) who study the impact of technology spillovers on carbon leakage. They show in a two-country setting that if one country increases its abatement effort, then this does not necessarily lead to an increase of emissions in the other country as would have been predicted by a model without technology spillovers. The reason is that a higher abatement level triggers additional investments in R&D, causing a reduction of abatement costs in the other country due to the spillovers and leading to an increase of this country's abatement level. Technically, I follow the approach of Golombek and Hoel (2004) in many aspects. In their model, both countries simultaneously and non-cooperatively choose their abatement effort and their R&D investments as to minimize their social costs which consist of abatement, investment and environmental damage costs. In an extension, they analyze the case where R&D investments are strategic in the sense that they are set prior to the abatement level.³ However, Golombek and Hoel (2004) do not study the role of permit trading which is the focus of this paper. The interaction between permit trading and technology spillovers is analyzed by Golombek and Hoel (2008).⁴ As explained above, the authors of this study find that

²A different timing is analyzed by Mackenzie (2011) who compares initial allocation choices of permits when two countries sequentially determine their number of allowances. Relative to simultaneous decisions, sequential choices may lead to higher total emissions. However, Mackenzie (2011) does not analyze whether or not both countries are better off under linking relative to no linking.

³Strategic investments in R&D in the context of global environmental problems have been first analyzed by Buchholz and Konrad (1994). Closer to my research question is Grecker and Hagem (2014) who analyze the role of permit trading on the strategic incentives of a developed country to invest in R&D at home and, via technology transfers, in a developing country. They find that in the case of permit trading, the industrialized country has an incentive to invest more in R&D at home.

⁴Golombek and Hoel (2006) also analyzes climate agreements in the presence of technology spillovers.

linking permit markets leads to a deviation of optimally determined ERTs, causing joint welfare to deteriorate.

This paper is organized as follows: Section 2 describes the model and derives the optimality conditions for both countries under linking and under autarky. Section 3 analyzes the social costs and the linking decision under different timings. Finally, Section 4 concludes.

2 The model

In the model, there are two countries i and $-i$ and I disregard from any uncertainties.

Following Goulder and Mathai (2000), the costs of abating greenhouse gases (GHG) are decreasing in the technology level K_i of each country. The technology level in each country i increases in investments in R&D, labeled as R_i . Investments in R&D are defined narrowly in the sense that they are not assumed to encompass very long term R&D projects such as research in breakthrough technologies or any kind of basic research, but focus on rather short term measures. This includes enhancing existing technologies such as photovoltaic solar panels or wind turbines, deploying new technologies or even the education of professionals. The technology level does not only increase by R&D investments at home, but also by R&D investments of the other country due to technological spillovers. This reflects the fact that the experiences and improvements made by one country can also be used partly by the other country. Additionally, in the case of the education of professionals spillovers stem from the mobility of workers and from international networking. In particular, I assume that a fraction $\alpha < 1$ of the R&D investments abroad can be used in the home country. Thus, technology diffusion is not perfect. As

However, in their paper linking permit markets would have no effect since countries are assumed to be symmetric.

in Golombek and Hoel (2004), the technology level of country i can be written as

$$K_i = R_i + \alpha R_{-i} \quad (1)$$

where R_{-i} represents the R&D investments of country $-i$. Assuming a linear relationship of R&D investments is standard in the literature. This way of modeling goes back to Spence (1984) and has been employed by several authors.⁵ Moreover, I assume the spillover parameter α to be the same for both countries.

Investments in R&D are costly. Countries are assumed to differ in their unit costs of each unit R&D which are given by k_i and k_{-i} respectively. To enhance tractability, I assume the national governments to choose directly the level of R&D in their jurisdiction. An alternative modeling approach that follows Golombek and Hoel (2008) would have been that firms privately invest in R&D and governments can indirectly determine the level of R&D by subsidies. Formally, both approaches are equivalent as long as the subsidy exclusively aims at the R&D level and does not influence the abatement level directly and as long as the spillover parameter between domestic firms is higher than that between firms located in distinct countries.

The abatement cost function depends on both the level of abatement a and the technology level K . The cost function of the two countries are assumed to be symmetric and is given by $C(a, K)$. The function is assumed to be twice differentiable and has the following properties:

$$\begin{aligned} \frac{\partial C(a, K)}{\partial a} &> 0, \frac{\partial^2 C(a, K)}{\partial a^2} > 0, \frac{\partial C(a, K)}{\partial K} < 0, \frac{\partial^2 C(a, K)}{\partial K^2} > 0 \\ \frac{\partial^2 C(a, K)}{\partial a \partial K} = \frac{\partial^2 C(a, K)}{\partial K \partial a} &< 0, \frac{\partial^2 C(a, K)}{\partial a^2} \frac{\partial^2 C(a, K)}{\partial K^2} - \left(\frac{\partial^2 C(a, K)}{\partial a \partial K} \right)^2 > 0 \end{aligned}$$

Marginal abatement costs are increasing in the level of abatement. A higher technology level reduces the abatement costs at a decreasing rate and also reduces the marginal

⁵See for example Rosendahl (2004) and Golombek and Hoel (2006, 2008).

abatement costs. Moreover, the standard regulatory condition are assumed to be satisfied. Finally, I assume $C(0, K) = 0$, $\lim_{a \rightarrow 0} \partial C(a, K)/\partial a = 0$, $\lim_{a \rightarrow \infty} \partial C(a, K)/\partial a = \infty$ and $\lim_{K \rightarrow 0} \partial C(a, K)/\partial K = -\infty$ in order to avoid corner solutions.

Both countries suffer from environmental damage caused by transboundary GHG emissions. Let \bar{e} be the global emissions under business as usual, then the environmental damage of country i is given by

$$ED_i = d_i(\bar{e} - e_i - e_{-i}) \quad (2)$$

where e_i and e_{-i} are the ERTs of country i and $-i$. Countries may differ in their marginal environmental damage $d_i > 0$. This reflects the fact that climate change affects the regions of the world asymmetrically.

Taking everything together, the social costs of country i under autarky are given by

$$SC_i^A = d_i(\bar{e} - e_i - e_{-i}) + C(e_i, K_i) + k_i R_i \quad (3)$$

whereas the social costs when carbon markets are linked read

$$SC_i^L = d_i(\bar{e} - e_i - e_{-i}) + C(a_i, K_i) + k_i R_i + p \cdot (e_i - a_i). \quad (4)$$

In the case of linkage, the last term of equation (4) represents the carbon revenue from trading permits with the other country. This term is positive and therefore increases the social costs whenever $e_i > a_i$, i.e. when the country's ERT is higher than the actual abatement effort. This is the case when the country is a permit importer.

Timing

In the following, I analyze three different timings. In all timings, the R&D investments take place in the last stage. This reflects the fact that R&D investments in this paper are thought of as rather short-term measures. Thus, countries are assumed to determine

first the political parameters before making any decision regarding R&D.

In the first timing, countries simultaneously decide in the first stage upon linking their ETSs. Linking will only occur, if both countries consent to link. In the second stage, countries simultaneously and non-cooperatively determine their ERTs. In the last stage, countries choose their R&D investments and, in the case of linkage, also their abatement effort while the permit market clears.

Relative to the first timing, countries are assumed to decide simultaneously upon both their ERTs and their linking decision in the second timing. In the third timing, countries first determine their ERTs before deciding upon linking their ETSs. The last stage of timings 2 and 3 is equivalent to timing one.

3 Analysis of different timings

3.1 Timing 1

The problem is solved by backwards induction starting with the last stage of the game and differentiating between whether or not countries have linked their ETSs in the previous stage.

3.1.1 Stage 3

Autarky

Under autarky, both countries abate the emissions that have been determined by their ERTs in the previous stage. Hence, the only choice variable for each country is the R&D investment. The first-order conditions (FOC) of minimizing (3) with respect to R_i are given by

$$-\frac{\partial C(e_i, R_i + \alpha R_{-i})}{\partial K_i} = k_i. \quad (5)$$

The investments in R&D are chosen such that the marginal investment costs k_i equal the marginal benefits that result from reducing the abatement costs ($-\partial C(e_i, R_i +$

$\alpha R_{-i})/\partial K_i > 0$). Both FOCs determine the optimal Nash-equilibrium R&D levels under autarky $R_i^A(e_i, e_{-i}, \alpha)$ and $R_{-i}^A(e_i, e_{-i}, \alpha)$.

The comparative statics of the optimal values are given by

$$\frac{\partial R_i^A(e_i, e_{-i}, \alpha)}{\partial e_i} = -\frac{C_{ixK}}{(1-\alpha^2)C_{iKK}} > 0 \quad (6)$$

$$\frac{\partial R_i^A(e_i, e_{-i}, \alpha)}{\partial e_{-i}} = \frac{\alpha C_{-ixK}}{C_{-iKK}} \leq 0. \quad (7)$$

where the subscripts denote the second derivatives of the abatement cost function of the corresponding country. The R&D investment increases in the level of the country's own ERT because the higher the abatement level, the more costs can be saved by investing in R&D. The R&D investments of country i are weakly decreasing in the ERT of the foreign country. If country $-i$ increases its abatement effort, it will also invest more in R&D to satisfy cost effectiveness. Due to the R&D spillovers the effective stock of knowledge of country i increases which allows for reducing its investments in R&D.

Linking

When carbon markets are linked in the first stage, countries minimize equation (4) with respect to a_i and R_i . The FOCs are given by

$$\frac{\partial C(a_i, R_i + \alpha R_{-i})}{\partial a_i} = p \quad (8)$$

$$-\frac{\partial C(a_i, R_i + \alpha R_{-i})}{\partial K_i} = k_i. \quad (9)$$

According to the first line, the optimal abatement levels are such that the marginal abatement costs equal the permit price. This is the standard result of permit trading. The second line yields the optimal level of investments in R&D, analogously to the autarky scenario. The four FOCs together with the market clearing condition $e_i + e_{-i} = a_i + a_{-i}$ determine the five endogenous variables in the Nash equilibrium $a_i^L(e, \alpha)$, $a_{-i}^L(e, \alpha)$, $R_i^L(e, \alpha)$, $R_{-i}^L(e, \alpha)$ and $p(e, \alpha)$. Note that all variables depend on the total level

of the ERT $e = e_i + e_{-i}$. Since ETSs are linked, it is not important for the equilibrium values whether country i or country $-i$ increases its ERT. The comparative statics for the variables are given by

$$\frac{\partial a_i^L(e, \alpha)}{\partial e} = -\frac{1}{\det} \left(C_{iKK}(C_{-iaa}C_{-iKK} - C_{-iaK}^2) \right) > 0 \quad (10)$$

$$\frac{\partial p(e, \alpha)}{\partial e} = \frac{1}{\det} \left((C_{iaK}^2 - C_{iaa}C_{iKK})(C_{-iaa}C_{-iKK} - C_{-iaK}^2) \right) > 0 \quad (11)$$

$$\frac{\partial R_i^L(e, \alpha)}{\partial e} = \frac{1}{\det} \left(-C_{iaK}(C_{-iaa}C_{-iKK} - C_{-iaK}^2) + \alpha C_{-iaK}(C_{iaa}C_{iKK} - C_{iaK}^2) \right) \leq 0 \quad (12)$$

where the term $\det < 0$ is the determinant of the matrix that one obtains by totally differentiating the four FOCs and the market clearing condition. The abatement effort of each country increases in the total ERT. Clearly, if one country increases its ERT, this country will have a higher abatement effort. However, a part of the increase will be transferred through the permit market to the other country, increasing its abatement level as well. Since marginal abatement costs are increasing, the equilibrium price rises in the total level of the ERT. The effect of a higher ERT on the R&D level of a country may be positive or negative. If the spillover parameter $\alpha = 0$, then this effect is unambiguously positive. Since the abatement level of each country increases in the ERT, each country also adjusts its R&D investments upwards. This picture may change in the presence of spillovers: Given that one country has increased its R&D investment, this augments the effective knowledge level of the other country. If this increase is substantial (which is the case if α is rather large), this country may even reduce its investment in R&D despite of a higher abatement effort.⁶

⁶However, under the assumption that all third derivatives of the abatement cost function are zero, the R&D level of each country is unambiguously increasing in the ERT.

3.2 Stage 2

In the second stage, countries determine their ERTs, anticipating the reaction functions of the third stage and taking as given the decision of whether ETSS are linked or not linked.

Autarky

Under autarky, both countries simultaneously minimize their social costs given by equation (3) with respect to the emissions reduction target e_i . Taking into account the optimality conditions from the third stage, the FOCs read

$$\frac{\partial SC_i^N(\cdot)}{\partial e_i} = -d_i + \frac{\partial C(e_i, K_i)}{\partial e_i} + \alpha \frac{\partial C(e_i, K_i)}{\partial K_i} \frac{\partial R_{-i}^A}{\partial e_i} = 0 \quad (13)$$

In the absence of spillovers, each country chooses its ERT as to equalize the marginal environmental damage with the marginal abatement costs. If $\alpha > 0$, the country takes into account the adverse effect that an increase of its own ERT has on the R&D level of the other country. This increases the country's abatement costs which is why each country will reduce its ERT in the presence of spillovers relative to $\alpha = 0$. I call this effect the strategic investment effect. In equilibrium, both FOCs are satisfied simultaneously and the equilibrium values in a Nash equilibrium are given by $e_i^A(\alpha)$ and $e_{-i}^A(\alpha)$.

Linking

If ETSS have been linked in the first stage, each country minimizes its social costs given by equation (4) with respect to its ERT taking the ERT of the other country as given. Substituting the optimality conditions from the third stage (equations (8) and (9)), the FOC of country i reduces to

$$\frac{\partial SC_i^L(\cdot)}{\partial e_i} = -d_i + p + \alpha \frac{\partial C(e_i, K_i^L)}{\partial K_i} \frac{\partial R_{-i}^L(e, \alpha)}{\partial e_i} + \frac{\partial p}{\partial e}(e_i - a_i^L) = 0 \quad (14)$$

In a Nash equilibrium, this FOC is satisfied for both countries and the equilibrium values are given by $e_i^L(\alpha)$ and $e_{-i}^L(\alpha)$. To interpret the FOC, consider first the case

where $\alpha = 0$. In equilibrium, each country chooses its ERT such that the marginal environmental damage equals the marginal abatement costs given by p plus the marginal revenue effect that is caused by a marginal change of the permit price represented by the last term of equation (14). Since the permit price is the same for both countries, equation (14) reveals that the country with lower marginal environmental damage is the permit exporter whereas the country with higher damage is the permit importer. This result is also found by Helm (2003).

In the presence of spillovers, the strategic investment effect represented by the term $\alpha \frac{\partial C_i(e_i^L, K_i^L)}{\partial K_i} \frac{\partial R_{-i}^L(e, \alpha)}{\partial e_i}$ adds to the rational of each country. This term reflects the marginal change of abatement costs, originating from the technology spillovers that have altered due to a change of the R&D investments of the other country.⁷ Since a part of an increase of the own ERT is transferred via the permit market to the other country, the other country tends to increase its investments in R&D. This increases the positive spillovers which is why each country has an incentive to augment its ERT when spillovers are existent. This incentive is the higher the higher the spillover factor α . Hence, while the strategic investment effect gives rise to decrease the ERT under autarky, it leads to an increase of the ERT under linking.

Summing up both FOCs, taking into account the market clearing condition as well as equation (9) and solving for p yields

$$p = 1/2(d_i + d_{-i} + \alpha k_i \frac{\partial R_{-i}^L(e, \alpha)}{\partial e_i} + \alpha k_{-i} \frac{\partial R_i^L(e, \alpha)}{\partial e_{-i}}). \quad (15)$$

In equilibrium, the permit price is the average of the marginal environmental damage of both countries and the strategic investment effect of both countries. Provided that an increase of the ERT augments the R&D investments of both countries, the equilibrium price increases in the spillover parameter α . Since countries have an incentive to set

⁷Since from equation (9) we have $\frac{\partial C_i(e_i^L, K_i^L)}{\partial K_i} = -k_i$, this term can also be interpreted as marginal savings on own investment costs due to technology spillovers.

higher ERTs in order to benefit from the spillovers of the other country, the permit price will be increasing.

Turning to the question of which country is permit exporter, plugging equation (15) into equation (14) and solving for the number of permits traded yields

$$e_i^L - a_i^L = 1/(2) \left(\frac{\partial p(e)}{\partial e} \right)^{-1} \left(d_i - d_{-i} + \alpha k_i \frac{\partial R_{-i}^L(e, \alpha)}{\partial e} - \alpha k_{-i} \frac{\partial R_i^L(e, \alpha)}{\partial e} \right) \leq 0. \quad (16)$$

From this equation, Proposition 1 follows.

Proposition 1

Country i is permit exporter (importer) if

$$d_i + \alpha k_i \frac{\partial R_{-i}^L(e, \alpha)}{\partial e} < (>) d_{-i} + \alpha k_{-i} \frac{\partial R_i^L(e, \alpha)}{\partial e}.$$

To interpret Proposition 1, consider the incentives of each country to increase its ERT when there is no trade, i.e. when $e_i^L(\alpha) = a_i^L(e^L(\alpha), \alpha)$. In this case, the permit revenue effect vanishes. Marginally increasing its ERT incurs the same costs for each country (p). However, marginal benefits, consisting of the marginal environmental benefits and the spillover benefits differ between countries. On the margin, the country with higher marginal benefits has an incentive to increase its ERT more substantially and therefore becomes permit importer. To illustrate Proposition 1 in terms of α , consider Corollary 1.

Corollary 1

If all third derivatives of the abatement cost functions are zero, i.e. the second derivatives are constants, then country i is permit exporter if

$$\alpha < \frac{2(d_i - d_{-i})C_{KK}}{2(d_i - d_{-i})C_{KK} + C_{aK}(k_i - k_{-i})}. \quad (17)$$

Given the assumption that countries are symmetric with respect to their abatement cost function, Proposition 1 simplifies to the inequality (17). Let country i be the low damage country, then corollary 1 states that country i is always permit exporter if its marginal investment costs are higher than those of the other country ($k_i > k_{-i}$). In this case, the term on the right hand side exceeds one and the inequality is always satisfied because α was assumed to be strictly smaller than one. However, if $k_i < k_{-i}$, then there is a critical value $\tilde{\alpha}$ where country i is permit exporter for $\alpha < \tilde{\alpha}$ and permit importer for $\alpha > \tilde{\alpha}$. In the following, most of the results will be expressed by assuming country i to be permit exporter.

3.2.1 Social Costs

Countries will link their ETS if both countries agree to link, meaning both countries to be better off under permit trading. This is the case when the social costs of each country are lower under linking than under autarky. Dropping the arguments of equilibrium values for reasons of readability, the social costs difference of country i can be written as

$$\begin{aligned}\Delta_i(e_i^L, e_{-i}^L, e_i^N, e_{-i}^N) &= SC_i^L(e_i^L, e_{-i}^L) - SC_i^N(e_i^N, e_{-i}^N) \\ &= d_i(e_i^N + e_{-i}^N - e_i^L - e_{-i}^L) + C(a_i^L, K_i^L) - C(e_i^N, K_i^N) + \\ &\quad p \cdot (e_i^L - a_i^L) + k_i(R_i^L - R_i^N).\end{aligned}$$

If $\Delta^A(e_i^L, e_{-i}^L, e_i^N, e_{-i}^N) < 0$, then country i is better off under linkage than under autarky. Subtracting and adding $p \cdot (e_i^N)$ and rearranging yields

$$\begin{aligned}
\Delta^A(\cdot) = & d_i(e_i^N + e_{-i}^N - e_i^L - e_{-i}^L) + \\
& p \cdot (e_i^L - e_i^N) + \\
& C(a_i^L, R_i^L + \alpha R_{-i}^N) - C(e_i^N, R_i^N + \alpha R_{-i}^N) + p(e_i^N - a_i^L) + k_i(R_i^L - R_i^N) + \\
& C(a_i^L, R_i^L + \alpha R_{-i}^L) - C(a_i^L, R_i^L + \alpha R_{-i}^N)
\end{aligned} \tag{18}$$

The first line of equation (18) is the damage effect and describes the difference of the environmental damage between the linking and no linking scenario. The second line is, analogously to Helm (2003), the strategic price effect. This effect arises because countries asymmetrically choose different ERTs under permit trading and under autarky. In particular, a permit exporting country has an incentive to decrease its ERT under linking, causing the price effect to be negative. Equation (18)'s third line describes the efficiency gains from trade adjusted by the investments in R&D. This term is unambiguously negative and thus favors linking relative to autarky, representing the main argument in the literature that suggests linkage to be beneficial. The last line is new to the literature and is referred to as spillover effect. This effect either favors or disfavors linking depending on the size of the foreign country's R&D investments in the two scenarios

The magnitude of all four effects depends on the difference between the ERTs as well as the investment levels under linking and under autarky. In the following, I will analyze these differences in more detail.

3.2.2 Comparison of ERTs and R&D investments

I will start with a comparison between the actual abatement effort under linking (a_i^L) and the ERT under autarky (e_i^N) because this impacts, among other factors, the size of the efficiency gains from trade (see third line of equation (18)). Using equations (8) and

(13) and substituting equation (15), the difference of marginal abatement costs under linking and under autarky can be written as

$$\frac{\partial C(a_i^L, K_i^L)}{\partial a} - \frac{\partial C(e_i^N, K_i^N)}{\partial a} = 1/2(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e}) + \alpha k_i (\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e}). \quad (19)$$

For $\alpha = 0$, the right hand side of equation (19) is negative for the high damage country, but may turn positive for α sufficiently large. For the low damage country, the right hand side of this term is always positive which means that the marginal abatement costs under linking are higher than those under autarky. This is a first indicator that a_i^L may exceed e_i^N which will be confirmed in the following.

Generally speaking, a comparison of the ERTs and the R&D investment levels between linking and autarky is complicated due to the fact that the ordering of second derivatives may differ across countries. To elaborate more on that, it is helpful to define the following two expressions

Definition 1

Define \overline{SMC}_i as the *average slope of the adjusted marginal abatement costs* and \overline{ATL}_i as the *average technology level per unit abatement* of country i which are given by

$$\overline{SMC}_i \equiv \frac{\int_{e_i^N}^{a_i^L} C_{iaa}(a, K_i^L) da \int_{K_i^N}^{K_i^L} C_{iKK}(a_i^N, K) dK - \int_{e_i^N}^{a_i^L} C_{iaK}(a, K_i^L) da \int_{K_i^N}^{K_i^L} C_{iaK}(a_i^N, K) dK}{(a_i^L - e_i^N) \int_{K_i^N}^{K_i^L} C_{iKK}(a_i^N, K) dK} \quad (20)$$

$$\overline{ATL}_i \equiv - \frac{\int_{e_i^N}^{a_i^L} C_{iaK}(a, K_i^L) da / (a_i^L - e_i^N)}{\int_{K_i^N}^{K_i^L} C_{iKK}(a_i^N, K) dK / (K_i^L - K_i^N)}. \quad (21)$$

The derivation of both definitions is deferred to the Appendix. The term \overline{SMC}_i is the average slope of the marginal abatement costs which are adjusted by the optimal

investment in R&D. Given the assumptions regarding the abatement costs, this term is unambiguously positive. Moreover, note that \overline{SMC}_i is smaller than the average slope of the marginal abatement costs without adjustment of R&D investments given by $\int_{e_i^N}^{a_i^L} C_{iaa}(a, K_i^L) da / (a_i^L - e_i^N)$ which reflects the cost saving due to investments in R&D. The term \overline{ATL}_i denotes the average technology level per unit abatement of country i . In the appendix, I show that this term corresponds to $(K_i^L - K_i^N) / (a_i^L - e_i^N)$. Using Definition 1 and the results from equation (19), Proposition 2 reads

Proposition 2

Let \overline{SMC}_i be the average slope of the adjusted marginal abatement costs of country i , then the difference between actual abatement under linking and abatement under autarky is given by

$$a_i^L - e_i^N = \left(1/2(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e}) + \alpha k_i \left(\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e_i} \right) \right) / \overline{SMC}_i \quad (22)$$

Proposition 2 confirms the statement from above that the actual abatement under linking is higher than that under autarky for the low damage country. Moreover, the difference is increasing in the spillover factor α . The reason is rooted in the strategic investment effect. While an increase of the ERT positively spills back via a higher investment in R&D of the other country under linking, it leads to lower spillovers under autarky.

Comparison of country specific ERTs

Turning to the question of how countries choose their ERTs under the different scenarios, using equation (16) and some transformations of the FOCs from the last stage (equations (5) and (9)) and transforming properly yields

Proposition 3

Let \overline{SMC}_i be the average slope of the adjusted marginal abatement costs of country i ,

then the difference between the ERT under linking and under autarky is given by

$$e_i^L - e_i^N = \frac{1}{2} \left(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e} \right) \left(\frac{1}{\overline{SMC}_i} - \frac{1}{\frac{dp}{de}} \right) + \alpha k_i \left(\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e} \right) \frac{1}{\overline{SMC}_i} \quad (23)$$

The first term of the first line in equation (23) determines, according to Proposition 1, whether country i is permit exporter or importer. In the following, I will interpret Proposition 3 from the perspective of a permit exporter. If $\alpha = 0$, the low damage country is unambiguously the permit exporting country and the term $d_{-i} - d_i$ is positive. Thus, whether country i extends its ERT under linking relative to autarky depends on the sign of the second term of the first line.

This term contrasts the average slope of the marginal abatement costs (\overline{SMC}_i) with the impact of an increase of the ERT on the permit price ($\frac{dp}{de}$). To interpret this difference, consider the incentives of a country to increase its ERT under autarky and under linking from the FOCs (equations (13) and (14)). Under autarky, the marginal costs increase by \overline{SMC}_i while the marginal costs increase by $\frac{dp}{de}$ under linking. Since a part of the increased ERT is transferred via the permit market to the other country, the increase of the marginal costs under linking is - in general - lower than that under autarky and we have $0 < \frac{dp}{de} < \overline{SMC}_i$. Thus, the second term of the first line in equation (23) tends to be negative, implying the low damage country to reduce its ERT when permit markets are linked. In other words, the low damage country has an incentive to issue more allowances under trade which is referred to as 'hot air' in the literature. This point was also pointed out by Helm (2003). The reverse holds true for the permit importing country which will increase its ERT when countries allow for permit trading.

If $\alpha > 0$, the interpretation of the second term of the first line of equation (23) does not alter. However, the first term that reflects whether country i is permit importer or exporter changes. In particular, this term implicitly indicates the number of permits

traded in the trading scenario (see equation (22)). If this number increases in α , then the incentive for the permit exporting country to reduce its ERT would be even stronger. This is the case when the strategic investment effect for the permit exporting country is higher than this for the permit importing country. Otherwise, the difference in permits traded decreases and so does the incentive to reduce the ERT when permits are traded. Finally, the term in the second line of equation (23) denotes the difference of the strategic investment effect under linking and under autarky which is, in general, positive, causing countries to set a rather high ERT. In particular, if α is sufficiently high, then also the permit exporting country may increase its ERT. This result is confirmed by Corollary 2:

Corollary 2

If all third derivatives of the abatement cost functions are zero, then $e_i^L \gtrless e_i^N$ whenever

$$2C_{KK}(d_i - d_{-i})(1 - \alpha^2) - \alpha C_{aK}(k_i(3 + \alpha) + k_{-i}(\alpha - 1)) \gtrless 0 \quad (24)$$

Corollary 2 shows for $\alpha = 0$ that the low damage country reduces its ERT while the high damage country increases its ERT when permit markets are linked. For $\alpha > 0$, if $k_i > k_{-i}$, then, according to Corollary 1, the high damage country will always be permit importer and therefore will always set a higher ERT under linking. However, if the marginal investment costs in R&D of the high damage country are substantially higher than those of the low damage country ($k_i < k_{-i}$), then the high damage country will become permit exporter and may set a lower ERT under linking. Nevertheless, Corollary 2 reveals that both countries will increase their ERTs under linking when α approaches 1 regardless of whether they are permit exporter or importer.

Comparison of aggregate ERTs

For the comparison of the aggregate ERT, let us define $e^L = e_i^L + e_{-i}^L$ and $e^N = e_i^N + e_{-i}^N$ as the aggregate ERT under linking and under autarky, respectively. Summing up equation (23) from Proposition 3 over both countries yields

Proposition 4

Let \overline{SMC}_i and \overline{SMC}_{-i} be the average slope of the adjusted marginal abatement costs of country i and $-i$, then the difference between the aggregate ERT under linking and under autarky is given by

$$e^L - e^N = \frac{1}{2} \left(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e} \right) \left(\frac{1}{\overline{SMC}_i} - \frac{1}{\overline{SMC}_{-i}} \right) + \alpha k_i \left(\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e} \right) \frac{1}{\overline{SMC}_i} + \alpha k_{-i} \left(\frac{\partial R_i^L}{\partial e} - \frac{\partial R_i^N}{\partial e} \right) \frac{1}{\overline{SMC}_{-i}} \quad (25)$$

Starting the interpretation of Proposition 4 with the case $\alpha = 0$, the second line of equation (25) vanishes. The first term of the first line is positive if country i is the low damage country. The second term contrasts the average slope of the marginal abatement costs of both countries. If the average slope of the low damage country is larger than that of the high damage country, then the aggregate ERT under linking is below that under autarky. This was also pointed out by Helm (2003) and Holtsmark and Sommervoll (2012). The reason for this is the following. In the trading equilibrium the adjusted marginal abatement costs equal the permit price whereas they equal the marginal environmental damage under autarky. Hence, under permit trading, I proofed in Proposition 2 that the low damage country increases its abatement effort while the high damage country reduces the actual abatement relative to autarky. If the average slope of the low damage country exceeds that of the high damage country, then the decrease of the abatement effort by the high damage country will outweigh the increase of abatement of the low damage country, implying the overall ERT to shrink under trading.

For $\alpha > 0$, the same argumentation applies as long as the low damage country remains permit exporter, i.e. as long as the first term of the first line in equation (25) is positive. However, the terms from the second line add to the difference in ERTs. These terms reflect the incentives for investing strategically in R&D under linking and under autarky

and are, in general, positive. Hence, as the spillover factor increases, the aggregate ERT under linking tends to exceed that under autarky. Corollary 3 will confirm this statement.

Corollary 3

If all third derivatives of the abatement cost function are zero, then the overall ERT under autarky is never larger than this under permit trading and it holds that

$$e^L - e^N = (k_i + k_{-i}) \frac{\alpha}{2(1 - \alpha)} \left(\frac{-C_{aK}}{C_{aa}C_{KK} - C_{aK}^2} \right) \geq 0 \quad (26)$$

For $\alpha = 0$, we have $e^L = e^N$. If all third derivatives are zero and the abatement cost functions are symmetric, then the average slope of the adjusted marginal abatement costs is the same for both countries and the first term in equation (25) vanishes. For $\alpha > 0$, Corollary 3 indicates that the difference between the ERT under linking and under autarky is strictly positive. This reflects the strategic investment effect that causes both countries to increase its ERTs under linking. Note that this effect is the stronger, the higher is the spillover parameter α , implying the difference between e^L and e^N to be increasing in α .

Comparison of R&D investments

In order to analyze the R&D investments of the countries, I should start with comparing the technology levels K_i between the linking and no linking scenario. Since the technology level positively depends on the actual abatement effort, the technology level should be higher whenever the actual abatement effort is higher under linking than under autarky. Using equation (22) from Proposition 2 and the fact that $\frac{\partial C(a_i^L(e), K_i^L(e))}{\partial a} = k_i = \frac{\partial C(e_i^N, K_i^N)}{\partial a}$ leads to

$$\begin{aligned} K_i^L - K_i^N &= (a_i^L - e_i^N) \overline{ATL}_i \\ &= \left(1/2(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e}) + \alpha k_i \left(\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e_i} \right) \right) \frac{\overline{ATL}_i}{\overline{SMC}_i} \end{aligned} \quad (27)$$

Since the average technology level per unit abatement is positive, country i has a higher technology level under linking when its abatement effort under linking exceeds that under autarky. The difference in the technology level is the larger, the larger is the difference between the abatement efforts and the larger is \overline{ATL}_i . For a permit exporting country, the technology level will always be higher under linking relative to autarky. For low values of α , the technology level of the permit importing country decreases in response to linking whereas it may increase for high values of α due to the difference of the strategic investment effect. The difference of the technology level depends, in particular, on the size of the term $\overline{ATL}_i/\overline{SMC}_i$. This term can be interpreted as the average sensitivity of the technology level to a change in marginal abatement costs.⁸

Turning to the R&D investments of the country, manipulating equation (27) yields

Proposition 5

Let \overline{SMC}_i and \overline{SMC}_{-i} be the average slope of the adjusted marginal abatement costs and \overline{ATL}_i and \overline{ATL}_{-i} be the average technology levels of country i and $-i$, then the difference between the R&D investments under linking and under autarky is given by

$$R_i^L - R_i^N = \frac{1}{1 - \alpha^2} \left(\frac{1}{2} \left(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e} \right) \left(\frac{\overline{ATL}_i}{\overline{SMC}_i} + \alpha \frac{\overline{ATL}_{-i}}{\overline{SMC}_{-i}} \right) \right. \\ \left. + \alpha k_i \left(\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e_i} \right) \frac{\overline{ATL}_i}{\overline{SMC}_i} - \alpha^2 k_{-i} \left(\frac{\partial R_i^L}{\partial e} - \frac{\partial R_i^N}{\partial e_{-i}} \right) \frac{\overline{ATL}_{-i}}{\overline{SMC}_{-i}} \right) \quad (28)$$

The first line of equation (28) indicates the effect of the R&D levels depending on whether country i is permit importer or exporter. Suppose that country i is permit exporter, then this term is unambiguously positive and country i will increase its investments in R&D for two reasons. First, since the actual abatement exceeds the ERT of country i , this country has an incentive to make higher investments in R&D. Second, for country $-i$, the actual abatement is below its ERT, implying this country to

⁸To see this, assuming all third derivatives to be zero, the term $\overline{ATL}_i/\overline{SMC}_i$ is given by $-C_{xK}/(C_{xx}C_{KK} - C_{xK}^2)$ which is equivalent to the expression $dK/dC_x(x, K(x))$.

reduce its R&D investments. This reduces the technology level K_i which is why country i counteracts this effect by extending its R&D investments.

The second reflects the difference between linking and autarky when setting the ERT due to the strategic investment effect. According to this effect, each country has an incentive to set a higher ERT, leading initially to a higher investment level of both countries. However, an expansion of the R&D investments of country $-i$ causes country i to adjust its investment downwards which is reflected by the second term of the second line. In the most extreme case, this effect may be so large that the R&D investments of country i decrease under linking. This is the case when the strategic investment effect of country $-i$ is substantially larger than that of country i and when the number of permits traded (reflected by the term in brackets of the first line) is not too high. Corollary 4 confirms this statement

Corollary 4

If all third derivatives of the abatement cost function are zero, then $R_i^L \gtrless R_i^N$ whenever

$$2C_{aK}C_{KK}(d_i - d_{-i})(1 - \alpha^2) + \alpha C_{aK}^2(k_i + k_{-i}) + \alpha^2 C_{aK}^2(k_i - 3k_{-i}) \gtrless 0$$

From the perspective of the low damage country, the first term in Corollary 4 is positive which reflects the fact that the low damage country is the permit exporting country and therefore increases its investments. The second term is positive for both permit importing and permit exporting countries, representing the fact that the overall ERT tends to increase under linking. The last term indicates the difference in the strategic investment effects. In particular, this term is negative if $k_i < k_{-i}$. If α is sufficiently high and the difference between k_i and k_{-i} is very large, than this term may outweigh the other positive terms, implying the low damage country to reduce its R&D investments under linking relative to autarky. Perspective of high damage country

For the sake of completeness, let us turn to the aggregate investment level under

linking $R^L = R_i^L + R_{-i}^L$ and under autarky $R^N = R_i^N + R_{-i}^N$ respectively. Summing up equation (28) over both countries and rearranging yields

$$\begin{aligned}
R^L - R^N = & \frac{1}{1 + \alpha} \left[\frac{1}{2} \left(d_{-i} - d_i + \alpha k_{-i} \frac{\partial R_i^L}{\partial e} - \alpha k_i \frac{\partial R_{-i}^L}{\partial e} \right) \left(\frac{\overline{ATL}_i}{\overline{SMC}_i} - \frac{\overline{ATL}_{-i}}{\overline{SMC}_{-i}} \right) \right. \\
& \left. + \alpha k_i \left(\frac{\partial R_{-i}^L}{\partial e} - \frac{\partial R_{-i}^N}{\partial e_i} \right) \frac{\overline{ATL}_i}{\overline{SMC}_i} + \alpha k_{-i} \left(\frac{\partial R_i^L}{\partial e} - \frac{\partial R_i^N}{\partial e_{-i}} \right) \frac{\overline{ATL}_{-i}}{\overline{SMC}_{-i}} \right] \quad (29)
\end{aligned}$$

For $\alpha = 0$, the interpretation of the first line is analogous to the interpretation after Proposition 4. There I have argued that the aggregate ERT under linking is smaller than under autarky if the average slope of the marginal abatement costs of the low damage country, i.e. the permit exporting country, is below that of the permit importing country. The same logic applies here. Relative to autarky, the permit exporting country increases its abatement effort and therefore has higher marginal abatement costs while the reverse holds true for the permit importing country. Remember that the term $\overline{ATL}_i/\overline{SMC}_i$ measures the average change of the technology level due to a change of the marginal abatement cost for country i . Thus, if the average change is larger for the permit exporting country, this implies that the increase in the technology level of this country outweighs the decrease of the technology level of the permit importing country, leading to a higher aggregate technology level and to a higher aggregate investment level.

For $\alpha > 0$, the interpretation of the first line of equation (29) does not alter as long as the low damage country remains to be the the permit exporting country. However, the second line adds to the difference of the aggregate investment levels. This line reflects the difference of the strategic investments effects under linking and under autarky for both countries and is, in general, positive, implying the aggregate investments in R&D to increase in α .

If all third derivatives are zero, then the difference of the aggregate investments in

R&D is given by

$$R^L - R^N = \frac{\alpha}{1 - \alpha^2} \frac{C_{aK}^2(k_i + k_{-i})}{2C_{KK}(C_{aa}C_{KK} - C_{aK}^2)} \geq 0. \quad (30)$$

If all third derivatives are zero, then, due to the symmetry assumption of the abatement cost function, the term $\overline{ATL_i}/\overline{SMC_i}$ is the same for both countries, implying the first line of equation (29) to vanish. Thus, the difference of the aggregate investment levels only stems from the difference of the strategic investment effects which unambiguously increase the ERT and therefore also the R&D levels.

Comparison of social costs

With all the results from above, we can evaluate the difference in social costs given by equation (18). This difference finally determines whether or not countries are willing to link their ETSs in the first stage. If one country expects social costs to be higher under linking than under autarky, this country will not consent to link. In fact, countries will establish a joint ETS when both countries are better off under linking.

Generally speaking, equation (18) is hard to evaluate because of the simultaneous presence of the different effects. However, Proposition 6 draws some conclusions

Proposition 6

If $\alpha = 0$, both countries may consent to link. Even if total emissions are increasing. More or less as in Helm...

Interpretation...

In order to make some more statements about the social cost differences, I will focus on abatement cost functions where all third derivatives are zero in the following. This allows for some very clear results.

Proposition 7

If all third derivatives of the abatement cost function are zero and $\alpha = 0$, then the high

damage country is worse off under trading while the low damage country is better off under trading. The aggregate social costs are lower under linking than under autarky.

In the absence of spillovers, the spillover effect vanishes. Moreover, from Corollary 3, we have seen that the aggregate ERT corresponds to that under autarky if $\alpha = 0$ which is why also the environmental damage effect disappears, leaving the strategic price effect and the efficiency gains from trade to be non-zero. The efficiency gains from trade leads both countries to favour linking. I argued after Proposition 3 that the low damage country tends to set a smaller ERT under linking relative to autarky. Therefore the strategic price effect of this country is negative, causing the low damage country to unambiguously consent to linking. For the high damage country, the strategic price effect is positive and outweighs the efficiency gains from trade. The reason is that under the symmetry assumption regarding the abatement costs, the difference between the ERT under linking and under autarky exactly corresponds to the difference between actual abatement and the ERT under autarky. Therefore, the efficiency gains from trade can not compensate for the strategic price effect and the high damage country will always disagree with linking. In aggregate, the strategic price effects of both countries cancel out, implying the difference in aggregate social costs to be negative due to the efficiency gains from trade. Thus, linking enhances the welfare.

Turning to the case with R&D spillovers, the analysis becomes much more complex because the environmental damage and the spillover effect add to the comparison of social costs. However, Proposition 8 reports some insights

Proposition 8

If all third derivatives of the abatement cost function are zero and if countries are symmetric with respect to their investment costs in R&D, then the social costs under linking are decreasing more rapidly in the spillover parameter α than those under autarky. Moreover, if α is sufficiently close to unity, then the high damage country is unambiguously better off under linking.

Proposition 8 has the qualifier that countries are not only symmetric regarding their abatement costs, but also regarding their investment costs in R&D. This guarantees, according to Corollary 1, that the low damage is always permit exporter while the high damage country is permit importer regardless of the size of α .

To interpret Proposition 8, it is useful to analyze the change of the four effects when α increases. As stated by Corollary 3, the aggregate ERT increases in α due to the difference of the strategic investment effect. Thus, the environmental damage effect unambiguously becomes negative for both countries. This effect is the larger, the larger is the size of α . From Proposition 2, it follows that the difference between actual abatement under linking and the ERT under autarky is increasing in the spillover factor, implying the efficiency gains from trade to become larger for both countries. Evaluating Corollary 4 for $k_i = k_{-i}$ reveals that the low damage country has a higher R&D investment level under linking than under autarky. Moreover, this difference is the higher, the higher is α which is why the spillover effect for the high damage country is unambiguously increasing in absolute terms, making linking more likely as α becomes larger. The investment level of the high damage country may be increasing or decreasing in α , implying the spillover effect for the low damage country to be indeterminate. The strategic price effect is unambiguously increasing in α for the high damage country. This is because the permit price is increasing in α (by equation (15)) and the difference between the ERT under linking and under autarky becomes larger due to the strategic investment effect.⁹

From the perspective of the high damage country, the efficiency gains from trade as well as the environmental damage and the spillover effect become more negative as α increases whereas the strategic price effect works in the opposite direction. In total, I show in the appendix that the first three effects outweigh the last effect, thereby

⁹For the low damage country, the strategic price effect may be increasing or decreasing in α for α sufficiently small. This reflects the fact that on the one hand, the permit price is increasing whereas the difference between the ERT under linking and under autarky becomes smaller. However, if α is sufficiently large, then also the low damage country sets a higher ERT under linking than under autarky, implying the strategic price effect to become unambiguously larger as α increases further.

reducing the cost difference between linking and autarky. More importantly, I show that as α approaches unity the social costs under linking are below those under autarky, implying the high damage country to consent to linkage.

For the low damage country, aggregating all four effects reveals that the social costs under linking are decreasing more rapidly in α than those under autarky. Thus, the low damage country unambiguously prefers linking over autarky regardless of the size of α . Given that the social costs of both countries decline more rapidly in α in the linking scenario, also the aggregate social costs are always lower under linking. Hence, from a global perspective, it is always more efficient to link the ETSs regardless of the size of α . However, note that this welfare level is neither first, nor second best because countries determine both the ERT and the R&D spillovers non-cooperatively not taking into account the positive externalities on the other country.

4 Conclusion

This paper asks the question whether it is beneficial for two countries to link their ETSs when the ERTs are determined endogenously and R&D spillovers are present. The answer to this question crucially depends on the timing of the political decision, i.e. whether the ERTs are to be determined before or after countries decide upon linking or not linking their ETSs.

If countries first decide on linking their carbon markets and set their ERT afterwards, the permit importing country may not be willing to link in the absence of R&D spillovers. The reason is that the permit exporting country imposes a negative strategic price effect on the other country by reducing its ERT under linking relative to autarky. This allows the permit exporting country to sell more permits and increases its revenue from permit trading. The permit importing country responds by increasing its ERT to counteract the increased environmental damage suffered from the reduction of the ERT of the exporting country. This further increases the payments of buying permits for the permit importing

country. In total, the negative price effect may outweigh the efficiency gains from trade and the permit importing country may be worse off under linking relative to autarky.

The incentives to link ETSs *ex ante* become more complex in the presence of R&D spillovers due to the strategic investment effect. This effect is negative under autarky because increasing a country's ERT also increases its own investment in R&D which crowds out R&D investments of the foreign country, thereby decreasing the positive spillovers. In contrast, the strategic investment effect is, in general, positive under linking. The reason is that increasing a country's ERT boosts foreign R&D investments because a part of the domestic increase will be transferred to the foreign country via the permit market. Hence, countries set higher ERTs under linking than under autarky which reduces their environmental damage. Additionally, R&D spillovers for the permit importing country are higher under linking relative to autarky because of a higher abatement effort of the exporting country. In total, if the spillover parameter is sufficiently high, the permit importing country is better off under linking and agrees to link its ETS *ex ante*.

If countries determine their ERTs prior to the linking decision, the impact of technology spillovers on the linking decision reverses. Given that countries have already determined their ERTs, they unambiguously benefit from linking due to the efficiency gains from trade in the absence of R&D spillovers. However, if technology spillovers are relevant, the permit exporting country may not consent to link. The reason is that though benefiting from the efficiency gains from trade, the R&D spillovers for this country deteriorate under linking. The permit importing country reduces its R&D investment in response of a lower abatement effort when permit markets are linked. Hence, from the perspective of the permit exporting country there is a trade-off between the efficiency gains from trade and decreased R&D spillovers. If the spillover effect outweighs the efficiency gains, the permit exporting country will not consent to link.

The policy implication of this analysis is straightforward. Given that linking ETSs increases the joint welfare of countries, the recommendation concerning the timing de-

depends on the presence of spillovers. If spillovers do not play an important role, which holds certainly true in the case of rather small ETSs, then countries should decide upon linking their ETSs after determining its ERTs. This happened to be the case when the California ETS and the Quebec ETS established a joint ETS back in 2013. On the other hand, if R&D spillovers are relevant, which is the case when large ETSs such as the EU and China are going to link, then countries should make the decision of linking their ETSs prior to the determination of its ERTs.

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