SECTORAL LINKING OF CARBON MARKETS: A TRADE-THEORY ANALYSIS

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Abstract: The linking of emission trading systems (ETS) is a widely discussed policy option for future international cooperation on climate change. Benefits are expected from efficiency gains and the alleviation of concerns over competitiveness. However, from trade-theory it is known that due to general equilibrium effects and market distortions, linking may not always be beneficial for all participating countries. Following-up on this debate, we use a Ricardo-Viner type general equilibrium model to study the implications of *sectoral* linking on carbon emissions ('leakage'), competitiveness, and welfare. By comparing pre- and post-linking equilibria, we show analytically how global emissions can increase if one of the 'linked' countries lacks an economy-wide emissions cap, although in case of a link across idiosyncratic sectors a decrease of emissions ('anti-leakage') is also possible. If–as a way to address concerns about competitiveness–a link between the EU ETS and a hypothetical US system is established, the partial emission coverage of the EU ETS can lead to the creation of new distortions between the non-covered domestic and international sector. Finally, we show how the welfare effect from linking can be decomposed into gains-from-trade and terms-of-trade contributions, and how the latter can make the overall effect ambiguous.

Keywords: *Linking; Emission Trading; Trade Theory; Leakage; Competitiveness*

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1. Introduction

In view of the expiry in 2012 of the Kyoto Protocol's reduction obligations, the bottom-up linking of existing national or regional emission trading systems (ETS) has become a widely discussed policy option (Buchner and Carraro 2007, Flachsland et al. 2009a, b). For example, the creation of an OECD-wide carbon market that in some way becomes linked to developing countries is now a central pillar of the European Union's climate strategy (EU Commission 2009), in line with various legislative cap-and-trade initiatives in the United States and Australia that have signaled a strong willingness to link their systems (Tuerk et al. 2009).[1] In fact, after COP-15 in Copenhagen did not yield a legally binding multilateral agreement, this approach appears ever more relevant (Stavins 2009).

The merits of international emission trading are well-understood and include efficiency-gains (e.g. Tietenberg 2006), but also the alleviation of competitiveness concerns through the elimination of carbon price differentials and access to cheap abatement options in developing countries (e.g. Alexeeva-Talebi et al. 2010). Some observers, however, have cautioned that in the presence of market distortions and general-equilibrium price effects, the linking of regional emission trading systems may not always be beneficial (Babiker et al. 2004; Anger 2008), and, in addition, might facilitate undesirable international spillovers of shocks in permit markets (McKibbin et al. 2008).[2]

The present contribution follows up on this debate and employs an analytical Ricardo-Viner type general equilibrium model with international trade in goods and fossil fuel resources to study the impacts of sectoral linking on emissions, competitiveness, and welfare. The scenarios under investigation are designed to mimic the most important strategic options for permit market links between some of the major players in international climate policy, namely Europe, United States and China.

The EU has specified a comprehensive climate policy package for the time up to 2020, featuring *inter alia* an economy wide emission reduction target to be implemented on one hand by means of the EU ETS–which covers around 40% of European GHG emissions–and on the other hand by various policies and measures aimed at the remaining sectors (European Union 2009a, b). A major focus of our analysis regards the potentially adverse impacts such a segmented policy approach may entail. In contrast, if the United States were to implement a climate policy package along the lines of the Waxman-Markey draft, its economy-wide cap-and-trade system would cover about 85% of US greenhouse gas emissions (Larsen and Heilmayr 2009). For China we analyze scenarios representing the implementation of a scaled-up Clean Development Mechanism or sectoral trading scheme (EU Commission 2009, Schneider and Cames 2009), but we also take into account the possible simultaneous presence of an economy-wide intensity target.[3]

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[1] OECD regions preparing the implementation of cap-and-trade systems include the United States, Australia, Japan, South Korea, as well as individual US states and Canadian provinces organized in the Western Climate Initiative (WCI) or Midwestern Greenhouse Gas Reduction Accord.

[2] For a review of merits and demerits of linking cap-and-trade systems, see, e.g., Flachsland et al. (2009b).

[3] Prior to the COP-15 meeting at Copenhagen, China announced its intention to reduce the carbon intensity of its economy by 40-45% from 2005 to 2020.

By comparing the pre- and post-linking equilibria between two countries, we find that global emissions can rise if one of the 'linked' countries lacks a comprehensive cap on its total emissions. In this case, an increased uptake of fossil fuel resources in the non-capped sector–what we will call *linking-induced leakage* or simply *leakage* in short–would be observed.[4] However, whether or not this type of leakage actually occurs turns out to depend on which industries are linked in the joint permit market: if their respective output goods are imperfect substitutes, leakage does not occur or may even become negative (what we will denote as *anti-leakage*). As an extension of this analysis, one mechanism that is shown to be ineffective as a means to prevent leakage is an economy-wide intensity target, which has been suggested as a politically more feasible option than an absolute cap, at least for developing countries.

If the EU ETS was to establish a link with a hypothetical US system, leakage would not be an issue because both regions would face a constraint on total emissions. Besides gains-from-trade, a major driver for implementing such an option would be to address concerns about competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field' (Houser et al. 2008). However, our results indicate that due to the EU ETS' partial coverage of total EU emissions, this can only be achieved to a limited extent. As will be shown, under such circumstances linking can create (or increase) a distortion both between the EU's own sectors as well as between the EU's non-ETS sector and its US counterpart.

Finally, our analysis provides an explicit representation of the welfare effects of linking in a general-equilibrium setting. Namely, the overall effect is decomposed into a gains-from-trade and a terms-of-trade effect. Because the sign of the latter depends on which goods a country exports and imports, the net effect turns out to be ambiguous.

The remainder of this article is organized as follows: The next section reviews the relevant literature. Section 3 sets out our model. Results are derived and discussed in Section 4 and–for the special case in which one good becomes non-traded–in Section 5. Section 6 concludes.

2. Literature Review

Studies on linking different emission trading systems can roughly be divided into three categories: (i) qualitative-institutional studies, (ii) game-theoretic approaches, and (iii) numerical partial and general equilibrium analyses.

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[4] In its original meaning, leakage denotes the increase in emissions elsewhere in response to a tighter emissions policy at home. This is, strictly speaking, not what happens in our case, in which the home country does not change its level of emissons, but only links its emissions trading system to that of another country. However, because it aptly conveyes the idea of an unintended emissions increase outside the regulated system, we still chose to employ the term in the present context.

The first category contains a number of studies which have investigated the institutional aspects involved in linking, focusing on the different systems' design compatibility as well as qualitative economic and political impacts (e.g. Sterk et al. 2006, Tuerk et al. 2009, Flachsland et al. 2009a,b). They mainly provide detailed analyses of proposals for new cap-and-trade systems, identify needs for harmonization of system design features, or compare different institutional arrangements for the governance of joint carbon markets. However, due to the nature of these studies, the scope for economic analysis remains rather limited.

The second strand of more game-theoretic research focuses on strategic interactions between countries that unilaterally implement domestic trading systems and consider linking, i.e. international emission trading, as a policy option. Helm (2003) provides evidence that in such a case the anticipation of linking creates an incentive for low-damage countries to relax their cap in order to benefit from increased permit sales. Rehdanz and Tol (2005) discuss suitable instruments, in particular import quotas, which enable buyers to contain such inflationary tendencies on the sellers' side. Carbone et al. (2009) employ a computable general equilibrium (CGE) framework with international trade in goods, resources, and permits, and allow countries to anticipate the impact of their quota allocation decision. They identify the possibility of oligopolistic behaviour, i.e. that the incentive of net permit sellers to raise permit prices by increasing the stringency of their cap may outweigh their incentive to relax the cap, especially in the presence of additional positive effects on international resource markets.

Finally, with a focus on the internal dynamics of the EU ETS, Dijkstra et al. (2011) as well as Böhringer and Rosendahl (2009) analyze the partition between ETS and non-ETS sectors as a strategic game of EU countries against each other, constrained by the fixed EU ETS total emission cap. While the former specify the conditions for welfare gains and losses when additional trading sectors enter the system, the latter pursue an empirical analysis and find evidence for a strong role of political economy forces.

In the third group of studies, partial equilibrium analyses of permit markets using regionally and sectorally specified marginal abatement cost curves are employed to study the impact of carbon market linkages on allowance prices and regional abatement costs (Anger 2008, Anger et al. 2009, Stankeviciute et al. 2008, Russ et al. 2009). One main conclusion to draw from partial market modeling is that unless linking is assumed to be accompanied by the introduction of severe market distortions, it will be welfare enhancing for all countries due to the standard gains-from-trade effect (Anger 2008, Anger et al. 2009). Linking cap-and-trade systems to the CDM offers particularly high efficiency gains due to the expected large supply of low cost abatement options in developing countries. However, by definition these models ignore the general equilibrium effects of permit trade, e.g. a loss of competitiveness or carbon leakage occuring due to changes in relative prices.

To capture such effects in the context of climate policy, several CGE models were developed and first applied to assess the economic implications of the Kyoto Protocol (e.g. Bernstein et al. 1999, McKibbin et al. 1999) and, more recently, the impacts of biand plurilateral linking. For example, Babiker et al. (2004) and Paltsev et al. (2007) show that an increase in the domestic price of carbon after joining international emission trading can reinforce pre-existing distortions associated with inefficiently high fuel taxes – up to the point where the corresponding welfare losses outweigh the primary gains in efficiency from emission trade. Most closely related to our work–in terms of the issues addressed–is Alexeeva-Talebi and Anger (2007) and Alexeeva-Talebi et al. (2010): the first study finds that whenever linking the EU ETS to another country's system leads to an inefficient emission allocation between ETS and non-ETS sectors in the latter (assuming perfectly efficient policies in the no-linking case), the link is welfare decreasing for the EU partner country and has hardly any impact on EU welfare. The subsequent study analyzes the competitiveness impacts on the EU economy from unilateral climate policy, and finds them to be largely negligible if the EU ETS establishes a link with the CDM market, due to the resulting much lower allowance price. However, because of the numerical character of CGEs, such analyses can only provide limited insights on the underlying mechanisms at work, which is the objective of our contribution.

Thus, our study aims to complement previous contributions through its analytical general equilibrium framework based on trade-theory. This allows for a theoretical investigation into the economic and environmental impacts of linking carbon markets, taking into account the interplay of permit trade and trade in sectorally differentiated goods and fossil fuel resources. In that sense, our adoption of a trade-theory point of view follows the work of Copeland and Taylor (2005), although–differently from us–they used a long-run oriented Heckscher-Ohlin framework and focused on the strategic effects of trade in a model with endogenous emissions choice.

3. Model Definition

We consider an extended Ricardo-Viner model with two countries, home h and foreign f (index i), as main protagonists, and an additional country s that supplies fossil fuel resources R, which are an essential input factor for production in both h and f. This set-up allows studying the general equilibrium effects of climate policy when the supply of emission-causing fossil fuels remains outside the domain of regulation.

Each country's economy is composed of two sectors, producing goods X and Y (index j). The corresponding constant-returns-to-scale technologies, F and G, use fossil resources as well as other inputs–such as capital and labor–for production. We adopt the short- to mid-term point of view of the Ricardo-Viner (or specific factor) model (Mayer 1974, Neary 1978), where the fossil fuel resource is assumed to be perfectly mobile across sectors, while all other inputs are immobile and hence sector-specific.[5] As a consequence, the latter are only implicitly included in the specific functional forms of F and G:

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[5] This approach has the merit of avoiding the tendency towards full specialization that arises in a Heckscher-Ohlin model when production factors are tradable (Markusen 1983). So far only few scholars have considered factor trade in a Ricardo-Viner model, most notably Neary (1995), who studied the impact of capital mobility in a two country specific factor model that in its formal approach bears some similarity

$$(1) \qquad X^i = F^i(R_X^i) \qquad\qquad Y^i = G^i(R_Y^i) \quad ,$$

with strictly concave functions F^i and G^i (declining returns for each individual production factor), and $R_X^i + R_Y^i = R^i$ capturing the sectoral allocation of resource inputs in country *i*. Emissions are assumed to be identical to the amount of fossil fuel resources employed in production; the two terms are therefore used interchangeably throughout this article.

In view of the symmetry of the problem, we choose the resource as the numeraire (i.e. p_R=1), and p_x and p_y as the price of good *X* and *Y*, respectively.[6] Firms in each country maximize profits under perfect competition and hence satisfy the usual first-order conditions for the marginal product of the resource input:

$$(2) \qquad 1 = p_x\, F_R^i(R_X^i) = p_y\, G_R^i(R_Y^i) \qquad ,$$

where the subscript *R* is used to denote the derivative with respect to *R*, i.e. the marginal product. Note that as payments accrue to the other (immobile) factors of production, the value of output of *X* and *Y* exceeds the value of the resource used in their production, even though firms do not have market power. Because technologies are strictly concave, Eq.(2) can be inverted to obtain the resource demand function D^i of country *i*:

$$(3) \qquad D^i(p_x, p_y) := F_R^{i\,inv}\left(p_x\right) + G_R^{i\,inv}\left(p_y\right) \qquad .$$

In line with the short- to mid-term focus of our analysis, we ignore potential changes in the environmental damage level resulting from variations in the amount of fossil fuel combustion (i.e. emissions).[7] That is, in our model consumer preferences are represented through a utility function $U(C_x^i, C_y^i)$ which only depends on the realized consumption bundle. Furthermore, we assume that tastes are homothetic and uniform across all countries, including the resource supplier. Thus, taken prices as given, all consumers spend the same fraction η of their income I^i on good *X* and $1-\eta \equiv \tilde{\eta}$ for consumption of good *Y*, where η depends only on the parameters of the utility function and the relative price between goods, which for convenience we denote in shorthand form by $p_{x/y} \equiv p_x / p_y$. Demand for good *X* and *Y* in country *i* is thus given by, respectively, $\eta\, I^i / p_x$ and $\tilde{\eta}\; I^i / p_y$. Welfare can be expressed as a function of real income using the indirect utility function:[8]

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with ours. As one of the main findings he shows that–depending on the assumed trade pattern–trade in factors can either be a substitute or complement of trade in goods.

[6] While usually one of the goods is chosen as the numeraire, our choice preserves the symmetry between *X* and *Y* and thus allows for a more intuitive presentation of the results.

[7] Climate change is a stock pollutant problem with a significant delay between emissions and damages.

[8] We sometimes use brackets [..] to emphasize the argument of a function.

$$W^i = U\left[\frac{I^i}{\phi(p_x, p_y)}\right] \qquad , \tag{4}$$

where ϕ, a function only of p_x and p_y, is the exact price index of consumption goods. Finally, we assume that the resource supply side can be characterized by a supply function S

$$R = S[\phi(p_x, p_y)] \ , \tag{5}$$

that is strictly decreasing in ϕ. Since its nominal price is normalized to one, the supply of R is determined by its real price, i.e. the nominal price divided by the price index ϕ. As rising goods prices decrease the real price of R, its supply is negatively related to p_x and p_y, i.e. S'<0. This assumption is in line with empirical evidence showing that the supply elasticity of oil and natural gas (Krichene 2002) as well as of coal (Light et al. 1999) is positive (except perhaps on very short time scales where it tends to be close to zero) because of induced investments into extraction and exploration. It also allows taking supply-side reactions towards a demand-side driven carbon policy explicitly into account, an aspect that has been emphasized in recent discussions of the so-called ‘green paradox’ (Sinn 2008).

Formally, the functional form of Eq.(5) can be derived by assuming that the resource supplying country produces a non-traded domestic good Z, which constitutes an imperfect substitute for consumption of the imported goods X and Y (and thus the only source of utility under autarky). If consumer preferences over goods X and Y are captured through the price index ϕ, the supplier country’s welfare can be expressed as $\tilde{U}(I^s/\phi, Z)$, where $\tilde{U}$ is a homothetic function with elasticity of substitution greater than unity (so that neither good is essential). Furthermore, assume that the country faces a tradeoff between producing R and Z, such that its production possibility frontier can be described by a concave transformation function T (corresponding to convex technologies) with $R=T(Z)$. Under these assumptions, the supplier country’s problem is to choose the output level Z that maximizes $\tilde{U}(T(Z)/\phi, Z)$, which leads to the first-order condition $MRS^s[T(Z)/(\phi Z)]=-T_Z/\phi$, where MRS denotes the marginal rate of substitution and T_Z the marginal rate of transformation. Implicit differentiation then shows that $dZ/d\phi > 0$ and hence $dR/d\phi < 0$ whenever $T_Z<0$ and $T_{ZZ}<0$ holds and the elasticity of substitution is larger than unity, as we previously assumed.[9]

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[9] In an analytical trade model like ours, the supply of fossil fuel resources must necessarily be represented in a highly stylized way that neglects some aspects. First of all, resources should be differentiated according to type, i.e. coal, natural gas, and oil. This is important because only the latter two represent homogenous goods, while coal comes in different varieties and lacks a fully integrated world market (Burniaux and Oliveira Martins 2012). Moreover, while the supply of coal can be viewed as infinite, natural gas and oil are characterized by absolute scarcity. As a consequence, the extraction of the latter will be governed by intertemporal considerations, which cannot be represented within our static model. The presence of market power–often assumed but contested for the case of oil (Ramcharran 2002)–adds further complication.

Closing the model, the income I^i of countries *h* and *f* is given by output minus the costs for imported resource inputs (corresponding to the factor income of the non-resource inputs, e.g. labor), i.e.

$$(6) \qquad I^i = p_x X^i + p_y Y^i - R^i \quad ,$$

while for the resource supplying country it is simply *R*.[10] A global competitive equilibrium can now be defined by prices p_x and p_y such that (i) firms maximize profits, i.e. Eq.(2) is satisfied in both countries, (ii) consumers maximize utility, i.e. their demand is determined by the function η and their income, (iii) world markets for goods clear, i.e.

$$(7) \qquad \frac{\eta(p_{x/y})}{p_x}\left(I^h + I^f + R\right) = X^h + X^f \text{ and } \frac{\tilde{\eta}(p_{x/y})}{p_y}\left(I^h + I^f + R\right) = Y^h + Y^f$$

and, finally, (iv) the competitive resource market clears, i.e.

$$(8) \qquad S\left[\phi(p_x, p_y)\right] = D^h(p_x, p_y) + D^f(p_x, p_y) \ .$$

Eq.(8), together with the four independent conditions implied by Eq.(2), and the equation obtained by dividing through the market clearing conditions from Eq.(7) form a set of six equations allowing to uniquely determine the six independent variables p_x, p_y, and R_j^i, from which–by using $\eta(p_{x/y})$–the individual consumption levels follow directly. Note that combining Eq.(6) and Eq.(7) implies that trade is always balanced, as the value of consumed goods must by definition equal national income.

Any trade equilibrium will comprise flows of resource *R* from *s* to *h* and *f*, and flows of goods *X* and *Y* towards *s*, as well as–possibly–an exchange of *Y* and *X* between *h* and *f*. For example, the production functions of *h* and *f* could be strongly asymmetric, such that *h* produces almost only good *X*, and *f* almost only good *Y*. In this case both countries would trade with the resource supplier but also with each other. On the other side, if *h* and *f* are perfectly symmetric, they will still trade with the resource supplier but not with each other. In other words, the home and foreign country will always be net exporters of either *Y* or *X*, or of both. Note that the latter case would not be possible in a conventional Ricardo-Viner (or specific factors) model, where the mobile factor is not traded but part of the countries' endowment. Trade will then occur only in the form of an exchange of *Y*-

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[10] To keep the model tractable we assume that countries *h* and *f* do not dispose of any fossil fuel resources of their own. However, all of our results still hold if they are endowed with a limited amount of resources R_0^i, such that they both remain net resource-importers in all of the following scenarios. Eq.(3) would then refer only to the 'residual' demand, and the national income defined in Eq.(6) would only take the imported resource into account. The only effect of such a modification would be a shift of income towards countries *h* and *f*, which–given that preferences are homothetic–would leave the comparative statics of the model unchanged.

against *X*-goods between the two countries.[11]

4. Economic Impacts of Linking

The model has the aim to provide a stylized representation of the climate policies of the United States, Europe, and China. For the case of the United States we assume the adoption of the Waxman-Markey Bill as described in Larsen and Heilmayr (2009). Europe has already adopted a comprehensive climate policy package (European Union 2009a,b), and China is assumed to implement a scaled-up CDM or sector-based trading mechanism (EU Commission 2009), possibly on top of its currently proposed economy-wide intensity-target.

Focusing on the linking options from the point of view of the European Union towards the United States and China, we analyze the following linking scenarios in terms of their economic and environmental consequences (leakage), and discuss impacts on competitiveness and welfare:

1. EU ETS and sector *X* in China
2. EU ETS and sector *Y* in China
3. EU ETS and sector *X* in China, with China under national intensity target
4. EU ETS and economy-wide United States ETS

Case 1: EU ETS and China link along X-sectors (symmetric link)

The European Union officially envisages a link of its EU ETS to sectoral crediting schemes in major developing countries such as China (EU Commission 2009, Russ et al. 2009). In this scenario, we assess the economic impacts of linking the European ('home') trading scheme to sectors in China ('foreign') that are symmetric to those covered by the EU ETS, i.e. power generation and a number of emission intensive industries such as iron and steel, aluminum, and cement production.

To take into account the limited coverage of the EU ETS of only around 40% of all GHG emissions in Europe[12], we assume one sector, say *X*, to be the cap-and-trade sector with a given upper limit $\bar{R}_X^h$ on the resource intake (and an associated 'emission' price τ_x^h). The

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[11] A formally similar model to ours is employed by Eichner and Pethig (2011) to study the so-called Green Paradox (Sinn 2008). It also features two commodity-producing countries and one resource supplier. Moreover, although presented as a dynamic two-period model, it is possible to reinterpret the two periods as two sectors in a static model. In fact, in formal terms the two models only differ in the resource supply function, which–differently from us–they assume to be perfectly inelastic, i.e. there may be shifts between sectors/periods, but the total amount of supplied fossil fuel (or emissions) always remains the same. They also investigate a different question, namely the reaction of the foreign country–assumed to have no emissions constraint at all–to a tightening of the emissions cap of the home country in the first or second sector/period. The effects of emissions trading are not discussed at all. We thank the editor, Sjak Smulders, for calling our attention to this publication.

[12] The major non-covered sectors are road transport and heating fuels.

other sector, *Y*, is regulated by an adjustable command-and-control policy or resource tax τ_y^h.[13] Constraining the production in sector *X* by a fixed absolute resource cap $\overline{R}_X^h$ implies for the marginal product in this sector

$$(9) \qquad p_x\, F_R^h(\overline{R}_X^h) = 1 + \tau_x^h > 1 \quad .$$

The other sector's resource intake can then be viewed as being subject to a tax τ_y^h

$$(10) \qquad p_y\; G_R^h(R_Y^h) = 1 + \tau_y^h \quad ,$$

which is set in a way to ensure that the resource demand of sector *Y* always stays at the level needed for compliance with the economy's overall emissions cap:[14]

$$(11) \qquad R_Y^h \overset{!}{=} \overline{R}^h - \overline{R}_X^h \qquad \Rightarrow \quad \tau_y^h = p_y\, G_R^h(\overline{R}^h - \overline{R}_X^h) - 1 \quad .$$

China (as most other developing countries) currently rejects binding economy-wide emission caps, but might implement crediting mechanisms modeled on the Kyoto Protocol's Clean Development Mechanism (CDM). Since the current project-based CDM approach is plagued by doubts over additionality (Schneider 2007) and lack of scale (Stern 2008), several suggestions have been made on how an upscaling could be achieved. These include proposals for absolute or intensity-based no-lose crediting baselines for emissions on a sectoral level, and policy or programmatic approaches that bundle projects in order to reduce transaction costs (EU Commission 2009, Schneider and Cames 2009).

Within our model, these approaches are equivalent since all imply the setting of a sectoral cap against which emission reductions are credited. Hence, we represent this mechanism by an absolute sectoral business-as-usual (BAU) cap $\overline{R}_j^f$ for sector *j*, while the other sector faces no resource constraint. Since the presence of such a crediting mechanism implies that the affected sector faces an additional opportunity cost when using the resource input, it leads to the same type of first-order condition for the marginal product that holds for the EU ETS sector in Europe, Eq.(9). The difference to the European policy

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[13] The European Union aims at a 20% economy-wide emission reduction relative to 1990 by 2020. Since the policy package allows the use of CDM credits in order to achieve the envisaged reductions for the non-ETS sectors (European Union 2009a), one may argue that a crediting mechanism should also be incorporated in our model. However, since there is a comparatively low 3% limit on CDM use in the non-ETS sectors, and a total reduction target of 10% below year 2005 emission (EU Commission 2008), we assume that domestic policies–here represented by an emission tax–will nevertheless be the principle means for meeting the objective.

[14] The tax is assumed to be recycled back to households via lump-sum transfer. Note that for the purpose of our analysis, there is no need to include the tax receipts in Eq.(6) or elsewhere, since they have no influence on the country's total income, which only depends on its GDP measured in international prices.

case is the absence of an economy-wide reduction target and corresponding resource tax (or command-and-control policy) for the non-ETS sector.[15]

Proposition 1: *Let the home country be fully capped at* $\overline{R}^h$*, with an ETS in sector X holding* $\overline{R}_x^h$ *permits, and an adaptable emissions tax* τ_y^h *in sector Y that ensures a constant intake* $\overline{R}_y^h$*. If the foreign country adopts a sectoral BAU target* $\overline{R}_x^f$ *for its X-sector in order to establish an emissions-trading link with home's X-sector ('linking'), then*

- *(i) the price* p_x *of good X falls,*
- *(ii) the price* p_y *of good Y rises,*
- *(iii) the resource R appreciates in real terms,*
- *(iv) the resource intake (=emissions) in foreign's Y-sector increases, i.e. leakage occurs, and*
- *(v) the emission tax* τ_y^h *in home must rise.*

Proof: See Appendix A.1

When foreign implements a BAU cap[16] for its *X*-sector and links with home's ETS, the joint output of the two *X*-sectors rises to its efficient level. In order to absorb the increased global supply of good *X*, its price p_x must fall. But due to the homothetic preferences, consumers now also have a higher demand for good *Y*, leading to an increase in its price and creating an incentive to expand its production in foreign's uncapped sector *Y*, which causes linking-induced leakage. Because firms' incentive to produce good *Y* also increases in the home country, the corresponding resource tax τ_y^h has to be increased in order to keep the resource intake constant. For a segmented system like the EU's, this means that if the 'price of carbon' was initially equalized across trading and non-trading sectors, this will no longer be the case after linking, since the latter leads to a reduction of the permit price in home's sector *X*, and at the same time to a higher fossil resource tax in sector *Y*.

In terms of welfare, Proposition 1 implies that there are three effects of linking that must be taken into account: the direct gains-from-trade from emissions trading, the terms-of-trade effect from the fall of p_x and rise of p_y, and the expansion of foreign's *Y* sector.[17] Because only the second effect can have negative welfare implications, one arrives at the following proposition:

Proposition 2: *Under the conditions of Proposition 1, the total welfare effect of linking is ambiguous for at least one of the two 'linked' countries. A necessary condition for a loss of welfare of country i (i=home, foreign) is that its terms-of-trade effect, determined by*

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[15] Another difference consists in the non-binding character of the business-as-usual cap, which, however, is irrelevant in a model without uncertainty like ours.

[16] We focus on a BAU cap since in the context of a sectoral link with a developing country this appears to be an empirically relevant case. However, our results from Propositions 1,2,3 and 6 also hold if country 'f' has already implemented a more stringent sectoral cap before joining the linking agreement.

[17] As stated earlier, for the scope of this short-term analysis we ignore the long-run negative environmental effects associated with the increase in global fossil fuel usage.

$$\text{(12)} \qquad dW^i = \frac{U'}{\phi}\left(\left(X^i - C_x^i\right)dp_x + \left(Y^i - C_y^i\right)dp_y\right) \quad ,$$

is negative, which is always the case for at least one country. On the other side, the terms-of-trade effect is always positive for the resource supplier country.
Proof: See Appendix A.2

Linking leads to an increase in the joint output of *X*-goods. Dividing the achieved surplus between the two linked countries gives the expected positive gains-from-trade effect on welfare for both. The foreign country, in addition, reaps in the benefits from the increased production of its *Y*-sector. However, the terms-of-trade effect captured in Eq.(12) is ambiguous, and can–if it turns out to be negative and sufficiently large–outweigh the gains and lead to an overall loss of welfare from linking.

Depending on the functional specification of the production functions, the home country may be a net exporter of both or only one good (e.g. if home and foreign are ex-ante rather symmetric it will export both goods). As an inspection of Eq.(12) shows, if home is a net exporter of good *X*, or a net importer of good *Y* (or both), then the linking-induced fall of p_x and rise of p_y can result in a deterioration of home's terms-of-trade and thus–somewhat resembling the well-known immiserizing growth effect–in an overall loss of welfare from linking. Conversely, to ensure that home (or, likewise, foreign) will gain from linking it must be a net exporter of good *Y* and a net importer of good *X*.

Hence, the specific changes of the countries' terms-of-trade depend on the prevailing trade pattern; however, since terms-of-trade adjustments represent a zero-sum-game at the global level, and because the supplier country always improves its position (the resource price appreciates in real terms, otherwise supply would not increase), home's and foreign's combined terms-of-trade effect must be negative, implying that one of them experiences improving and the other deteriorating terms-of-trade, or that they deteriorate for both. Interestingly, the latter case means that there is a theoretical possibility that both countries suffer a loss of welfare from linking. This would be the case if the resource appreciates strong enough so as to dominate all other effects.

Therefore, in the present scenario of symmetric linking the resource supplier is the only guaranteed winner. Home and foreign both realize efficiency gains, the distribution of which will depend on the functional specification of the production functions. In addition, the foreign country also benefits from the increase in p_y by expanding its *Y* sector, a possibility from which the home country is excluded due to its economy-wide emissions cap. With regard to terms-of-trade, no more than one of the two countries can benefit, which–in the face of a falling price for good *X* and a rising price for good *Y*–will be the country that is relatively more specialized in the production and export of good *Y*.

Case 2: EU ETS and China link between X and Y sector (asymmetric link)

In view of the previous analysis, a natural question is to ask whether it would make any difference if the link between the EU ETS and Chinese sector is established in an anti-symmetric manner, i.e. from sector *X* in the European Union to sector *Y* in China. The following proposition confirms that this is indeed the case:

Proposition 3: *If, under the same conditions for the home country as in Proposition 1, the foreign country adopts a sectoral BAU target* $\overline{R}_y^f$ *for its Y-sector, such that the link for emission trading is established between sectors X in the home and Y in the foreign country, then*

- *(i)* *the price* p_x *of good X falls,*
- *(ii)* *the price* p_y *of good Y rises,*
- *(iii)* *the resource R depreciates in real terms,*
- *(iv)* *global resource intake (=emissions) is reduced, i.e. negative leakage occurs, and*
- *(v)* *the emission tax* τ_y^h *in home must rise.*

Proof: See Appendix A.3

In principle, asymmetric linking produces the same kind of effects as symmetric linking: sector *X* in the home country imports ‘emission permits’ and expands, thereby increasing the world supply of good *X* and inducing a fall of p_x. The difference is that foreign has to reduce the output of *Y* in order to enable the profitable generation and sale of credits to home’s capped sector *X*. In this case the fall of p_x gives foreign’s *X* sector an incentive to reduce its production and, hence, its usage of resources. This reduction in both of foreign’s sectors–while emissions remain controlled at the ‘cap-plus-credits’ level in the home country–leads to what may be termed linking-induced ‘anti-leakage’.

In practical terms this scenario may represent a hypothetical sector crediting mechanism implemented in China’s transport or heating sector, which on the one hand would induce cost-effective emission reductions in these sectors, and on the other lead to lower European Allowance (EUA) prices in the EU ETS. European ETS industries will expand their production in the presence of lower EUA prices, thereby lowering world prices for these products, with the effect of crowding out some industrial production in China.

Hence, from an environmental perspective an asymmetric linking to crediting schemes appears preferable to a symmetric one, since it avoids the leakage effect discussed before. However, as in the symmetric case the rise of p_y necessitates an increase in the fossil resource tax τ_y^h at home, which can aggravate distortions stemming from the different values of the marginal resource product in home’s *X* and *Y* sectors.

In terms of welfare, the implications from symmetric *X*-*X* linking largely carry over to the present case. In fact, the overall welfare impact is again determined by the sum of the same effects: gains-from-trade, changes in the terms-of-trade, and (for foreign only) output adjustment. If one of the countries engaged in linking–due to its trade specialization–experiences a terms-of-trade deterioration, then the overall welfare impact becomes again ambiguous for this country. However, since under asymmetric linking the supplier's terms-of-trade deteriorate, this can be the case only for either home or foreign, or for none of them. In other words, in contrast to symmetric linking it is not possible that both home and foreign lose from linking, but instead they could both gain. As the direction of the price changes is the same as for symmetric linking, the same specialization favorable under an *X*-*X* link is favorable under an *X*-*Y* link, i.e. a country's terms-of-trade position will improve if it is an exporter of *Y* and importer of *X*.

As a consequence of the similarity of the induced effects, it is also not possible to derive general conclusions about which type of linking, symmetric or asymmetric, countries would prefer. For example, China would in both cases reap in some of the efficiency gains generated by trading the resource *R*, and would in both cases be affected by the fall of p_x and rise of p_y. The difference between the two types of linking is that under symmetric linking China increases its output of good *Y*, but it must also pay a higher real price for the input *R*, whereas under asymmetric linking its *X*-sector contracts, but in turn it benefits from the depreciation of *R*. Also because the specific rise or fall of the real price of *R* in part depends on the supplier's function *S*, one cannot a priori tell which of the two types of linking dominates the other in terms of welfare.

Case 3: Symmetric link between EU ETS and China, with intensity target in China

Although China's position on the non-acceptance of a binding absolute emission target has remained firm, its government recently announced that it plans to reduce the carbon intensity of the national product (i.e. CO_2 emissions per unit of GDP) by 40 – 45% below its 2005 level by the year 2020. If implemented, any type of crediting mechanism would operate in parallel to this domestic intensity policy. In our model, this can be represented by introducing the additional constraint

$$(13) \qquad \overline{R}^f(\bar{\gamma}) = \bar{\gamma}\, I^f \quad ,$$

where $\bar{\gamma}$ represents the policy-imposed intensity level.

In view of the possibility for symmetrical sectoral links to induce leakage discussed in case 1, the question arises of whether the implications of Proposition 1 could be averted if China's total emissions are constrained by an intensity target, or, in other words, whether or not an intensity target could serve as a safeguard mechanism against unintended leakage. To assess this question, we consider a symmetric link between the *X*-sectors of home and foreign just as in case 1, but assume that in addition a binding but not too stringent (to ensure foreign is an exporter of permits) intensity target for total emissions is implemented in the foreign country.[18]

Proposition 4: *Let home's total emissions be capped at* $\overline{R}^h$*, with an ETS in sector X endowed with* $\overline{R}_x^h$ *permits, and an adaptable emission tax in sector Y. Furthermore,*

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[18] There is no need to discuss output-based sectoral intensity targets, i.e. limits on the emissions per unit of sector output. In our framework the choice of production technologies is fixed in the short-term, and hence an absolute cap $\overline{R}_x$ in the *X*-sector is fully equivalent to a sectoral intensity target of $\bar{\gamma}_x = \overline{R}_x / F(\overline{R}_x)$.

assume foreign's total emission level to be constrained by a binding intensity target $\overline{R}^f = \bar{\gamma} \cdot I^f$*, which, however, implies a lower emission price than in home's ETS. In order to establish an emission trading link with home's X-sector, resource use in foreign's X-sector now becomes capped at its pre-linking level* $\overline{R}_x^f$*. An adaptable emission tax is levied in foreign's Y-sector to ensure compliance with its intensity target. In this case,*

- *(i) the price* p_x *of good X falls,*
- *(ii) the price* p_y *of good Y rises, and*
- *(iii) resource intake (=emissions) in foreign's Y-sector can increase or decrease (i.e. positive or negative leakage), depending on the net effect of linking on foreign's GDP.*

Proof: See Appendix A.4

As in case 1, linking home's ETS to foreign's less strongly constrained *X*-sector results in an efficiency-enhancing reallocation of resource inputs to the home country, raising the global output of *X* while keeping the combined resource use of both countries' *X*-sectors constant at $\overline{R}_x^h + \overline{R}_x^f$. As a consequence of the increased supply of good *X*, good *Y* will become relatively more expensive, creating an incentive for firms in both countries to increase their production of *Y*.

The difference to the standard symmetric linking of case 1 is that in presence of a binding intensity target, foreign's *Y*-sector cannot expand unless its GDP has grown due to linking. Under an intensity target, the allowed emission level is proportional to GDP, meaning that any additional emissions would exceed the target unless GDP has grown. As discussed before, gains-from-trade in the *X*-sector in combination with the ambiguous terms-of-trade effect due to the changing prices p_x and p_y mean that foreign's GDP might be both higher or lower than in the no-linking case. Therefore, positive or negative leakage equal to the intensity target times the change in foreign's GDP occurs, demonstrating that the intensity target cannot substitute a comprehensive absolute emissions cap as an effective safeguard against linking-induced leakage.[19]

Case 4: Link between EU ETS and United States ETS

This scenario involving two fully capped systems can be interpreted as a stylized representation of a hypothetical link between the current EU ETS and a Waxman-Markey like US system (now denoted as '*f*'). A US cap-and-trade system based on the latter would cover 85% of US greenhouse gas emissions and can therefore be modeled as an economy-wide cap-and-trade system with an upper bound $\overline{R}^f$ on national emissions.[20] As

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[19] We do not consider the case of asymmetric linking with an intensity target. As we have demonstrated in case 2, asymmetric linking leads to negative leakage. In this case, an additional 'emissions per GDP' intensity target would simply become non-binding and hence irrelevant.

[20] Sectors not covered by the cap-and-trade system envisaged by Waxman-Markey are: (i) sources below the ETS compliance threshold, (ii) land-use and land-use change, (iii) landfill gases, (iv) HFC, (v) CFCs, (vi) nitrous oxide from nitric acid plants, and (vii) coal mine methane emissions. Given that sectors (ii) to (vii) do not use fossil fuel resource inputs, we assume them to be negligible in the context of our analysis.

a consequence, this policy always leads to an efficient domestic sectoral burden sharing of the abatement effort, which in formal terms means that in both sectors the same gap τ^f arises between the value of the marginal product and the (normalized) world price of the resource:

$$(14) \qquad p_x\, F_R^f\,(R_X^f) = p_y\; G_R^f\,(\overline{R}^f - R_X^f) = 1 + \tau^f > 1 \quad .$$

One would expect the US to become a net exporter of permits in this case, given that the EU Commission (2008) expects a year 2020 EU allowance price of 30€/tCO_2, while a study by the EPA (2009) suggests a lower price of about 16$/t$CO_2$ for US allowances. Besides efficiency gains, the main motivation for such a linking project would be to harmonize the price of emissions across regions and thereby address the issue of competitiveness. Because both regions have binding national emission targets, there is no concern with regard to linking-induced leakage in this case. However, the fact that the EU's policy is built on an internal segmentation with a trading and non-trading sector gains particular relevance.

Proposition 5: *Let foreign have an economy-wide cap-and-trade system and home a cap on total emissions implemented through a sectorally segmented policy, with an ETS in the X-sector and an adaptable emission tax τ_y^h in the Y-sector. Suppose the (implicit) price of emissions in home's two sectors is initially the same, and higher than in the foreign country. If the two countries establish a link between foreign's ETS and home's X-sector,*

- (i) *the price p_x of good X falls,*
- (ii) *the price p_y of good Y rises,*
- (iii) *the permit price in home's X-sector decreases, while the emission tax in its Y-sector must increase, and*
- (iv) *the emission tax differential between home's and foreign's Y-sector may become greater (competitiveness), e.g. if foreign's post-linking output of Y has increased with respect to the pre-linking level.*

Proof: See Appendix A.5

The proposition shows that linking may fail to 'level the carbon playing-field'. With an internally inefficient policy such as the EU's, the first-best prescription of creating a joint market in order to harmonize emission-permit prices actually enlarges the internal domestic distortion between trading and non-trading sector, and might increase the gap in competitiveness between home's and foreign's *Y*-sector. The latter formally depends on the details of the production and utility functions, but in the plausible scenario where the gains in global efficiency are used to increase the global output of both *Y* and *X*, the assertion always holds.[21] This can be seen by recalling that before linking the marginal product G_R^i in the *Y*-sector is higher at home than in the foreign country, implying that a uniform global increase in p_y would already widen the emission-tax gap (which is given by the difference of the *value* of the marginal products: $p_y\, G_R^h - p_y\, G_R^f$). If, in addition,

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[21] The efficiency gains from linking allow re-producing the global pre-linking output without having to use all resources. Unless *X* and *Y* are close substitutes, the extra *R* will be used to obtain more units of both.

foreign's Y-sector expands, thereby further decreasing its marginal product G_R^f, the gap becomes even larger.

In terms of welfare, the results of Proposition 2 carry over in a straightforward way: both countries benefit from the gains-from-trade associated with the linking of their emission trading schemes, but they might nevertheless lose welfare if their terms-of-trade deteriorate very strongly. In fact, since in the present case the supplier's terms-of-trade remain unchanged (otherwise the global supply of R would not remain constant), they must improve for one of the two countries–the one more specialized on good Y–and necessarily deteriorate for the other–the one more specialized on good X.

To see that in this case one of the two countries, say home, might indeed lose welfare from linking, consider the special case in which home is fully specialized on the production of good X, and foreign on the production of good Y. After linking, home will have some additional X-goods as its share of the gains-from-trade surplus, but at the same time the value of its output decreases due to the fall of p_X. Since the former, i.e. home's share of the gains-from-trade, is mainly determined by the characteristics of the production functions, it is well possible that it becomes too small to compensate for the latter, the negative price effect. This would imply a loss of income for home, which–given that the price index ϕ of Eq.(4) remains constant under EU-US linking–amounts to a reduction of welfare.

5. Extension: The Case of Non-Traded Goods

The above discussed model with two main countries and traded goods is oriented on the standard approach in trade economics and allows developing an intuition about the potential effects and forces at work. Admittedly, the stylized character of these models–indispensable for an analytical treatment–is often at odds with the idiosyncrasies of reality. In this section, we explore a formal modification of the model aiming to acknowledge the empirical fact that a large share of emissions arises in the production and consumption of goods–such as electricity–that are not heavily traded, at least not between far distant regions such as Europe and China. Specifically, we are referring to the transport and building (i.e. heating) sectors, and in particular to the energy sector (mainly electricity), which in total make up about 65% of all CO_2 emissions in the EU (EEA 2009). Prominent sectors that are emission intensive and characterized by heavy trade include, e.g., the cement, steel, and aluminum industries.

In view of a potential linking proposal involving such 'domestic' sectors, the question arises in how far the previously derived results still hold. E.g. the EU could link its ETS to China's electricity sector, or the transport sector, as suggested by Schneider and Cames (2009). To explore such a scenario, we modify the general model by assuming that the sector Y is a purely domestic industry in both countries. As a consequence, the price for good Y will in general be different across countries, and trade between h and f will not occur in the absence of linking. In formal terms, a competitive equilibrium in this model is now described by the following equations for the prices p_x and p_y^i: (i) profit maximization, i.e.

(15) $$p_x\, F_R^i(R_X^i) = p_y^i\, G_R^i(R_Y^i) = 1 \quad ,$$

(ii) consumers maximize utility, i.e. their demand is determined by $\eta^i := \eta\left(p_x / p_y^i\right)$, (iii) each country's income I^i is given by its GDP, i.e. $I^i = p_x\, X^i + p_y^i\, Y^i - R^i$, (iv) markets for all goods clear, i.e.

(16) $$\eta^h I^h + \eta^f I^f + R = \left(X^h + X^f\right) p_x \quad ,$$

(17) $$\tilde{\eta}^i I^i = Y^i p_y^i \quad ,$$

for good *X* and good *Y*, respectively, and

(18) $$S\left(p_x\right) = D^h(p_x) + D^f(p_x)$$

with $S' < 0$ for the resource market. Note how the resource supply function in Eq.(18) has simplified, since it is now an argument only of the relative price p_x of good *X*. In fact, because goods of type *Y* are not internationally traded, their prices p_y^i play a role only for internal accounting, but do not matter at the international level. On the other hand, the share η^i of income spent on good *X* can now be different across regions, since it depends on the ratio of the international price p_x and the country-specific price p_y^i of the domestic good.

To analyze the impacts of linking, it is assumed that an 'emission market' for trade in *R* is established between the EU ETS and one of China's sectors, either the one integrated in international trade or the domestic sector.

Proposition 6: *Let the home country be fully capped at* $\overline{R}^h$, *with an ETS in sector X having* $\overline{R}_x^h$ *permits, and an adaptable emission tax in sector Y that ensures a constant intake of* $\overline{R}_y^h$. *If the foreign country adopts a sectoral BAU target* $\overline{R}_x^f$ *for its X-sector and an emission trading link with home's X-sector ('linking') is established, then*

- *(i) the price* p_x *of good X falls,*
- *(ii) resource intake (=emissions) in foreign's Y-sector increases, i.e. leakage occurs across sectors.*

If instead foreign's Y-sector is capped at the BAU level and linked to home's X-sector,

- *(iii) global resource intake remains constant, i.e. leakage does not occur.*

Proof: See Appendix A.6

The intuition essentially remains the same as in the model where both goods are traded internationally: Linking the *X*-sectors has the direct gains-from-trade effect of increasing the amount of available *X*-goods in the foreign country. This changes the marginal rate of substitution of its consumers, which then prefer to renounce at some *X*-goods in order to increase their consumption of *Y*-goods. As a consequence, the country responds by expanding production in its *Y*-sector and paying for the additional resource intake–i.e. leakage–with some of its *X*-goods obtained from emission trading. The leakage effect will, however, be relatively weaker than in the case where both goods are traded, since the foreign country expands its *Y*-sector only to supply its own consumers, and not also those of the other country.

In case of an asymmetric link from home's *X* to foreign's *Y*-sector, the foreign country receives additional *X*-goods as 'compensation' for the amount δR that is re-allocated from foreign's domestic *Y*-sector to home's *X*-sector. Foreign's only degree of freedom is to adjust its *X*-sector, since the *Y*-sector is held fixed as part of the linking agreement. However, the first-order condition 'resource price equals value of marginal product' for efficient production in the *X*-sector remains unaltered by the linking-induced trade in *R*. In fact, positive leakage would necessarily require a rise of p_x, in contradiction to the supply side relation Eq.(18), which necessarily requires p_x to fall in order for global resource supply to grow. Hence, the foreign country becomes 'stuck' in a corner solution (consumers would like to exchange some *X* for some *Y*-goods but cannot do so), which in this case prevents the occurrence of leakage.

Overall, the introduction of a domestic good has led to a certain weakening of our results, but qualitatively they remain valid. This effect is in line with intuition, in as much as all of our results are driven by trade effects, which can be expected to become weaker when one good is by definition excluded from trade, as in this section. Nevertheless, it was shown that our principal results are robust against this modification of the model framework.

6. Conclusions

This paper has analyzed the impacts of linking emission trading systems on carbon leakage, competitiveness, and welfare within a tractable Ricardo-Viner general equilibrium model with international trade in goods and resources. The considered scenarios were designed to mimic the strategic options for future permit-market linkages between some of the major players in international climate policy, namely Europe, United States, and China.

By analytically comparing pre-linking and post-linking market equilibria, we have shown that a link involving an economy without national emissions cap can provoke leakage in form of an expansion and increased fossil fuel use in the non-capped sector. However, the actual occurrence of this linking-induced leakage depends on which industries are linked to form the joint permit market: in case of asymmetric linking, i.e. when the respective output goods are imperfect substitutes, leakage is prevented and may even become negative. These results were shown to prevail qualitatively even in the presence of a non-tradable good.

Hence, from the point of view of environmental integrity, a link of the EU ETS to a sectoral trading system in China (or elsewhere) that covers similar sectors bears some negative implications. Linking across asymmetric sectors (e.g. transport, heating, and in fact any sector producing non-tradable goods) tends to reduce global emissions and thus appears favorable from the EU perspective.

One approach for regulating economy-wide emissions in developing countries is the intensity target, which was recently adopted as a voluntary policy by China. However, our analysis has shown that such a target does not constitute a substitute for an absolute cap, i.e. it does not prevent the occurrence of leakage when one of China's sectors is linked to the EU ETS, and–in terms of policy implications–should therefore not be viewed as an instrument to facilitate participation in emissions trading.

If the EU ETS establishes a link with a hypothetical US system, their total emissions will remain constant since both regions have an economy-wide cap. The main motivation for pursuing this policy option would be to address concerns over competitiveness, i.e. the idea of harmonizing permit prices in order to 'level the carbon playing-field'. However, our results indicate that due to the EU ETS' internal segmentation this can only be partially achieved, as linking can create and increase distortions both between the EU's two sectors as well as between the EU's non-trading sector and its US counterpart.

The modeling analysis of Böhringer et al. (2009) of the EU 2020 climate policy package suggests that non-ETS sectors face higher marginal abatement costs than the EU ETS sectors. Linking the EU ETS to a US system could intensify such concerns. An obvious remedy is to include all EU sectors in the EU ETS. Alternatively, the segmented caps can be adjusted to harmonize marginal abatement costs across sectors. In the context of our model this implies tightening the EU ETS cap after linking to a US system (e.g. in form of a buy-back of permits by the EU regulator), a step that may require *ex ante* policy coordination if e.g. the resulting increase of the US allowance price raises political concerns.

Finally, the analysis allowed to recognize the potentially ambiguous welfare effect of linking in a general-equilibrium setting. Each country's welfare change can be decomposed into an always positive gains-from-trade effect, and a terms-of-trade effect, where the sign of the latter depends on the country's trade specialization, i.e. its export and import position. In the presence of strongly deteriorating terms-of-trade, the welfare impact of linking on the individual country can then become negative, following a logic similar to that of immiserizing growth. Such a possibility of losing welfare from emissions trading is a characteristic feature of our model set-up and contrasts with the established findings for the standard Ricardo-Viner model, where individual sectors may lose, but the country as a whole always gains when engaging in international trade. However, this is fully consistent in view of the fact that our model differs from conventional trade models in two fundamental ways, namely by *(i)* introducing trade in inputs and *(ii)* comparing two equilibria which both comprise international trade in output goods.

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Appendix

A.1 – Proof of Proposition 1

Emission trading–in our model in the equivalent form of resource trading–will take place since the home country's binding resource constraint implies that the value of its marginal resource product is higher than in the foreign country. In the post-linking equilibrium marginal products become equalized, i.e. $F_R^h(\overline{R}_X^h + \delta R) = F_R^f(\overline{R}_X^f - \delta R)$, thus determining the amount of traded resource $\delta R > 0$ (δ denoting some finite change, as opposed to infinitesimal changes indicated by *d*), as well as the resulting increase in the world supply of good *X*, denoted with a superscript *w* for 'world' by δX^w: $\delta X^w = F_R^h(\overline{R}_X^h + \delta R) + F_R^f(\overline{R}_X^f - \delta R) - (F_R^h(\overline{R}_X^h) + F_R^f(\overline{R}_X^f))$. In the following, we can therefore treat both quantities as given–yet undetermined–positive constants.

By taking the ratio of the global clearing conditions for the *Y*- and *X*-markets given in Eq.(7), we obtain for the post-linking equilibrium

$$\text{(A1)} \qquad \frac{\tilde{\eta}\, p_{x/y}}{\eta} = \frac{\overline{Y}^h + Y^f}{\overline{X}^w} \qquad ,$$

where a bar indicates a constrained, fixed variable. Since sector *X* is fixed after linking, i.e. it does not respond to price movements (assuming, as we do, that the constraint remains still binding after linking), the post-linking equilibrium can be characterized by investigating the comparative statics of the last equation, and of the supply side relation implied by Eq.(8)

$$\text{(A2)} \qquad S[\phi(p_x, p_y)] = \overline{R}_X^w + \overline{R}_Y^h + D_Y^f(p_y)$$

with respect to an exogenously given small increase dX^w–the effect of linking–in the world supply of *X* (where $D_j^i(p_j)$ represents the resource demand of sector *j* in country *i*, as obtained by inverting Eq.(2)). The left hand side of Eq.(A1) is a function only of the prices p_x and p_y, while the world supply Y^w depends only on p_y, and hence one obtains for the total differential

$$\text{(A3)} \qquad \sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{1}{Y^w}\frac{\partial Y^f}{\partial p_y}dp_y - \frac{dX^w}{X^w} \qquad ,$$

where σ>0 denotes the elasticity of substitution of the underlying utility function. Likewise, written in differential terms Eq.(A2) becomes

(A4) $$S'\phi_x dp_x = \left(\frac{\partial D_Y^f}{\partial p_y} - S'\phi_y\right) dp_y \quad \Rightarrow \quad \frac{dp_x}{p_x} = \frac{\left(p_y\left(\partial D_Y^f / \partial p_y\right) - \phi S'\tilde{\eta}\right)}{\phi S'\eta} \frac{dp_y}{p_y}$$

where we used the relationship

(A5) $$\frac{p_x \phi_x}{\phi} = \eta \qquad \text{with} \quad \phi_x := \frac{\partial \phi}{\partial p_x}$$

derived from Roy's identity. In view of *S'*<0 and the positive dependence of the foreign *Y*-sector's resource intake on the price p_y, the first term on the right-hand-side must be negative. This implies that dp_y and dp_x have always opposite signs. Substituting Eq.(A4) into Eq.(A3) yields

(A6) $$\frac{dX^w}{X^w} = \left(\frac{p_y}{Y^w}\frac{\partial Y^f}{\partial p_y} + \frac{\sigma}{\eta}\left(1 - \frac{p_y\left(\partial D_Y^f / \partial p_y\right)}{\phi S'}\right)\right)\frac{dp_y}{p_y} \quad ,$$

which demonstrates that linking (dX^w>0) always leads to a positive dp_y and negative dp_x, given that the term in parenthesis is unambiguously positive. Moreover, since the resource intake in foreign's *Y* sector depends positively on p_y, $dp_y>0$ is a sufficient condition for leakage to occur and–by Eq.(10)–for the need to increase the resource tax τ_y^h in order to keep the resource intake in home's *Y* sector constant. Finally, in order for Eq.(5) to be consistent with an increased global supply, the real price of the resource must rise. □

A.2 – Proof of Proposition 2

Following Proposition 1, the impact of linking on each country consists of a direct gains-from-trade effect and the effect from changes in p_x and p_y. In addition, the foreign country also increases its output in the *Y*-sector, which obviously represents a positive welfare contribution for foreign, given that p_y rises in the course of linking.

The gains-from-trade effect can be represented as an increased availability of *X* for both countries. To see this, let us first note that the permit price, say p_E, does not need to be taken into account explicitly, since it is fully determined by the value of the marginal product in the *X*-sector, and hence directly coupled to p_x:

(A7) $$1 + p_E = p_x F_R^h(\bar{R}_x^h + \delta R) = p_x F_R^f(\bar{R}_x^f - \delta R) \quad ,$$

where δR can be interpreted as the number of permits (and, simultaneously, resources) that are traded in the course of linking. For home, the partial effect on income associated with the gains-from-(emissions)-trade can thus be expressed as

$$\text{(A8)} \qquad \begin{aligned} \Delta I^h &= \left(p_x\, F^h(\overline{R}_x^h + \delta R) - (1 + p_E)\,\delta R\right) - p_x\, F^h(\overline{R}_x^h) \\ &= p_x \left(F^h(\overline{R}_x^h + \delta R) - \delta R\, F_R^h(\overline{R}_x^h + \delta R) - F^h(\overline{R}_x^h)\right) =: p_x\, \delta X_T^h \end{aligned}$$

i.e. as a fixed increase of available *X*-goods denoted by $\delta X_T^h > 0$, the size of which depends only on the properties of the production functions F^i. This effect is, therefore, always positive. For the foreign country we get δX_T^f in complete analogy.

With welfare as a function of real income as defined in Eq.(4), the terms-of-trade effect on home/foreign can be computed by evaluating:

$$\text{(A9)} \qquad dW^i = \frac{\partial W^i}{\partial p_x} dp_x + \frac{\partial W^i}{\partial p_y} dp_y = \frac{dW^i}{d(I^i/\phi)} \left(\frac{\partial (I^i/\phi)}{\partial p_x} dp_x + \frac{\partial (I^i/\phi)}{\partial p_y} dp_y \right).$$

Applying the envelope theorem and Eq.(A5), we obtain the following expression, valid for both countries:

$$\text{(A10)} \qquad \phi\, dW^i = U' \cdot \left(\left(X^i - C_x^i\right) dp_x + \left(Y^i - C_y^i\right) dp_y \right) \quad .$$

The two terms in parenthesis represent the net exports of good *X* and *Y*, respectively. Hence, if home is a net exporter of good *X* or a net importer of good *Y* (or both), then the linking-induced fall of p_x and rise of p_y can lead to a terms-of-trade deterioration and thus to a negative welfare contribution. Given that the other contributions are always positive, the negative terms-of-trade effect constitutes a necessary condition for an overall loss of welfare due to linking.

Finally, to see that at least one country (between home and foreign) must experience a negative terms-of-trade effect, consider the sum of the terms-of-trade contributions for home and foreign from Eq.(A10):

$$\text{(A11)} \qquad \left(X^h - C_x^h + X^f - C_x^f\right) dp_x + \left(Y^h - C_y^h + Y^f - C_y^f\right) dp_y = C_x^s\, dp_x + C_y^s\, dp_y \quad .$$

Apart from a reversed sign, this expression represents the terms-of-trade effect experienced by the resource supplier country, and thus illustrates how terms-of-trade adjustments constitute a zero-sum-game at the global level. Since the right-hand-side of Eq.(A11) can be written as $I^s\left(\eta\, dp_x / p_x + \tilde{\eta}\, dp_y / p_y\right)$ which–by invoking the supply side relation Eq.(5) and Eq.(A5)–results to be negative when global resource supply increases, i.e. $dS > 0 \;\Rightarrow\; \eta\, dp_x / p_x + \tilde{\eta}\, dp_y / p_y < 0$, we can conclude that the supplier country's terms-of-trade always increases due to linking. As a consequence, the terms-of-trade of either home or foreign, or both, must deteriorate. □

A.3 – Proof of Proposition 3

In this case, home imports resources *R* from foreign until the price-weighted marginal products becomes equalized, i.e.

$$\text{(A12)} \qquad p_x\, F_R^h(\overline{R}_X^h + \delta R) = p_y\, G_R^f(R_Y^f - \delta R) \quad .$$

Thus, the exact amount of traded permits δR now depends not only on the property of the functions F^h, and G^f, but also on the price ratio $p_{x/y}$. However, as we assume that the foreign country was without emissions constraint before linking, a new equilibrium necessarily requires that some positive amount of resource trade from foreign to home actually takes place, i.e. $\delta R>0$ (because of continuity $p_{x/y}$ cannot suddenly jump and reverse the trade direction). As a consequence, there will be an increase by δX^h in *X*-output at home and a corresponding fall by δY^f in *Y*-output abroad. To determine the implied change in foreign's *X*-output, consider again Eq.(A1) written in differential form as in Eq.(A3), now modified for the case of *X*-*Y* linking:

$$\text{(A13)} \qquad \sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{dY^f}{Y^w} - \frac{dX^h}{X^w} - \frac{1}{X^w}\frac{\partial X^f}{\partial p_x}dp_x \quad ,$$

which can be rearranged to

$$\text{(A14)} \qquad \left(\sigma + \frac{p_x}{X^w}\frac{\partial X^f}{\partial p_x}\right)\frac{dp_x}{p_x} = \frac{dY^f}{Y^w} - \frac{dX^h}{X^w} + \sigma\frac{dp_y}{p_y} \quad ,$$

where the term in parenthesis is always positive, and–by assumption–we also have dX^h >0 and dY^f <0. It follows that if p_y falls, then also p_x must fall. Next, consider the clearing condition for the resource market, and its total differential, in analogy with Eq.(A4):

$$\text{(A15)} \quad S\big[\phi(p_x, p_y)\big] = \overline{R_X^h + R_Y^f} + \overline{R}_Y^h + D_X^f(p_x) \quad \Rightarrow \quad \left(\eta - \frac{p_x}{S'\phi}\frac{\partial D_X^f}{\partial p_x}\right)\frac{dp_x}{p_x} = -\tilde{\eta}\frac{dp_y}{p_y}$$

Because the last parenthesis is always positive, it follows that dp_y and dp_x must have opposite signs. But then p_y cannot fall, since this would also require p_x to fall, by Eq.(A14). Therefore p_y must rise, which, by Eq.(A15), means that p_x falls. Finally, since the resource intake of foreign's *X* sector only depends on p_x, and p_x falls, the resource intake and output of this sector must fall, i.e. negative sectorial leakage occurs. In contrast to the case of *X*-*X* linking, the relative rise of p_y is in this case less pronounced, i.e. it does not overcompensate the fall of p_x, and thus leads to a net increase of the cost ϕ

for one unit of utility (i.e. $\eta\, dp_x / p_x + \tilde{\eta}\, dp_y / p_y > 0$) and–consistent with negative leakage–a drop of the (real) price of *R*. □

A.4 – Proof of Proposition 4

In principle, this proof follows the same line of argumentation as the one for Proposition 1. Again, the amount of resource traded between foreign's and home's *X*-sector in the course of linking is fully determined by the condition of marginal product equalization, i.e. it is only a function of $\overline{R}_X^h, \overline{R}_X^f$, and the production technologies, as in Eq.(A8). Also as before, the global efficiency gains in the production of good *X* imply a fall of p_x and a simultaneous rise of p_y.

A rising price for *Y* constitutes an incentive for firms in the foreign country to increase their production of this good and thus use more resources, such that leakage would occur. However, for a scenario in which foreign has adopted an intensity target, the supply side relation Eq.(A2) has to be rewritten as

$$\text{(A16)} \qquad S\left[\phi(p_x, p_y)\right] = \overline{R}_X^w + \overline{R}_Y^h + \min\left\{D_Y^f(p_y), \overline{\gamma} \cdot I^f - \overline{R}_X^f\right\} \quad ,$$

implying that in the present case a higher resource intake is only consistent with the intensity target if foreign's income has become higher in the course of linking. In fact, the emission-of-GDP intensity target may even become non-binding, if the increase of foreign's income is sufficiently high. In this case, however, the scenario with intensity target would simply reduce to case 1, i.e. Proposition 1 holds. On the other side, if linking has an adverse effect on foreign's GDP, the intensity target tightens the constraint on emissions and leads to negative leakage.

Specifically, let us consider gross domestic product (as defined by the expenditure method), which is given by the value of consumption plus exports minus imports:

$$\text{(A17)} \qquad I^f = p_x X^f + p_y Y^f - \overline{R}_X^f - R_Y^f \quad .$$

Hence, in presence of a binding emission-per-GDP target $\overline{\gamma}$, resource use in foreign's *Y*-sector can be expressed as:

$$\text{(A18)} \qquad R_Y^f = \overline{\gamma}\left(p_x X^f + p_y Y^f - \overline{R}_X^f - R_Y^f\right) \quad ,$$

which in differential terms implies (denoting the income from the gains-of-trade in emissions trading by dX_T^f)

$$\text{(A19)} \qquad dR_Y^f = \frac{\overline{\gamma}}{1+\overline{\gamma}}\left(p_x dX_T^f + X^f dp_x + Y^f dp_y + p_y\, G_R^f\, dR_Y^f\right)$$

and, by rearranging,

$$\text{(A20)}\qquad \left(1-\frac{\bar{\gamma}}{1+\bar{\gamma}}\, p_y\, G_R^f\right) dR_Y^f = \frac{\bar{\gamma}}{1+\bar{\gamma}}\left(p_x dX_T^f + X^f dp_x + Y^f dp_Y\right) \quad .$$

The term $\bar{\gamma}\, p_y\, G_R^f$ represents the marginal increase in foreign's emission allowances 'generated' by the intensity target if sector *Y* increases its resource input by one marginal unit. Clearly, with a binding intensity target a *ceteris paribus* expansion of the *Y*-sector (and thus GDP) must lead to fewer new allowances than would be needed to fully cover the additional resource consumption. Therefore we can conclude that $\bar{\gamma}\, p_y\, G_R^f$ must be smaller than one and, accordingly, that the parenthesis on the left hand side of Eq.(A20) is always positive. The parenthesis on the right hand side represents the partial (i.e. when holding the production of *Y* constant) income effect arising from linking in form of gains-from-trade and price changes. Thus, foreign's production of *Y* increases (decreases) and positive (negative) emission leakage occurs, if the income effect induced by linking is positive (negative). □

A.5 – Proof of Proposition 5

Since foreign has by assumption the lower permit price, the initial effect of linking is that home buys 'permits' and imports resources into its *X*-sector. If the barred variables denote pre-linking allocations, then the post-linking equilibrium is characterized by a common implied resource tax τ in all but home's *Y*-sector:

$$\text{(A21)}\qquad 1+\tau = p_x\, F_R^h(\bar{R}_X^h + \delta R_X^h) = p_x\, F_R^f(\bar{R}_X^f + \delta R_X^f) = p_y\, G_R^f(\bar{R}_Y^f + \delta R_Y^f)$$

subject to $\delta R_X^h + \delta R_X^f + \delta R_Y^f = 0$, as the trading system is neutral with respect to total resource use. Because foreign has an economy-wide ETS, the last part of Eq.(A21) is valid at all times, also during the linking process, and can thus be used for comparative statics. In differential terms it becomes:

$$\text{(A22)}\qquad \frac{p_x}{p_y} = \frac{G_R^f(R_Y^f)}{F_R^f(R_X^f)} \quad\Rightarrow\quad \frac{dp_x}{p_x} - \frac{dp_y}{p_y} = \frac{G_{RR}^f}{G_R^f}\, dR_y^f - \frac{F_{RR}^f}{F_R^f}\, dR_x^f \quad .$$

At the same time, the differential of the global supply-demand constraint Eq.(A1), in analogy with Eq.(A3), is given by

$$\text{(A23)}\qquad \sigma\left(\frac{dp_x}{p_x} - \frac{dp_y}{p_y}\right) = \frac{dY^f}{Y^w} - \frac{dX^w}{X^w} = \frac{G_R^f}{Y^w}\, dR_y^f - \frac{F_R^f}{X^w}\, dR_x^f - \frac{F_R^h}{X^w}\, dR_x^h \quad .$$

Substituting Eq.(A22) into Eq.(A23) leads to the following expression:

(A24) $$\left(\sigma\frac{G^f_{RR}}{G^f_R}-\frac{G^f_R}{Y^w}\right)dR^f_y=\left(\sigma\frac{F^f_{RR}}{F^f_R}-\frac{F^f_R}{X^w}\right)dR^f_x-\frac{F^h_R}{X^w}dR^h_x \qquad .$$

The factors in parenthesis are clearly negative. Hence, given our assumption that home will be a net importer of resource permits, i.e. $dR^h_x>0$, the term dR^f_x cannot be positive, since this would imply also a positive dR^f_y, which in turn would mean foreign is a net importer of permits. Therefore, linking must lead to a reduction of foreign's production of good *X*. Although for foreign's *Y*-sector the change in output remains ambiguous, the change in the price ratio $p_{x/y}$ is uniquely determined: if $dR^f_y>0$, then the right-hand-side of Eq.(A24) becomes negative, and hence $d(p_{x/y})<0$. If, on the other hand, $dR^f_y<0$, then $dY^w<0$ and $dX^w>0$ follow, which means that the middle-part of Eq.(A23) becomes negative, and again $d(p_{x/y})<0$ must hold. Moreover, since total global resource supply must remain constant under the considered cap-and-trade system, the cost of utility function ϕ, which actually represents the inverse of the real price of one unit of the resource, must also stay constant, which by Eq.(5) and Eq.(A5) requires $\eta\, dp_x/p_x+\tilde{\eta}\, dp_y/p_y=0$, i.e. the change in p_y and p_x must be of opposite signs. Therefore we can conclude that p_x falls and p_y increases, which proves assertion (i) and (ii).

Given the rise in p_y, it also becomes evident that the tax τ^h_y in home's *Y*-sector must be increased in order to keep this sector's total resource intake constant, as the latter is governed by $1+\tau^h_y=p_y\,G^h_R(\bar{R}^h_y)$. On the other hand, if home's *X*-sector is to expand, despite the falling price of p_x, then the corresponding resource tax (or emission permit price) must have decreased due to linking, thus completing the proof of assertion (iii).

It remains to show that it is possible and plausible for the gap between the emissions prices in home's and foreign's *Y*-sector to increase. In formal terms, this requires

(A25) $$d\tau^h_y=G^h_R(\bar{R}^h_y)\,dp_y\ >\ d\tau^f=G^f_R(\bar{R}^f_y)\,dp_y+p_y\,G^f_{RR}(\bar{R}^f_y)\,dR^f_y$$

to be true. Given that we have $G^h_R>G^f_R$ by assumption, the inequality holds whenever dR^f_y is positive, or negative but sufficiently close to zero, i.e. whenever linking leads to an expansion or only small contraction of foreign's *Y*-sector. Conversely, a closing of the emissions-price gap can only occur if foreign's *Y*-sector contracts sufficiently. This would correspond to a case in which resources from both foreign sectors are reallocated to home's *X*-sector. Although theoretically possible, such a scenario is not very plausible, as it would mean that all efficiency gains realized in the global production of good *X* are used to produce more only of good *X*, and that the global production of *Y* actually decreases. Eq.(A24) implies that this could happen if *X* and *Y* are very close substitutes, since for $\sigma\to\infty$ one infers that the sign of both dR^f_x and dR^f_y must be negative.

Conversely, if X and Y are perfect complements, i.e. $\sigma \to 0$, Eq.(A23) requires that both dX^w and dY^w must be positive, and thus $dR_y^f > 0$. □

A.6 – Proof of Proposition 6

Consider first a symmetric X-X link. As before, we assume that the foreign country sells some amount δR of resource to the home country, receiving an amount of δX in return which exceeds the loss of domestic X production and which is defined solely by the condition of marginal product equalization, and hence does not depend on any prices. Prior to linking, the foreign country's firms and consumers–taking the price p_x as given–implicitly maximize

$$\text{(A26)} \qquad \max_{R_x^f, R_y^f} U^f \left[F^f(R_x^f) - \frac{\left(R_x^f + R_y^f\right)}{p_x}, G^f(R_y^f) \right] \quad .$$

Regarding the optimal choice for sector Y, a homothetic utility implies

$$\text{(A27)} \qquad \frac{\partial_x U^f}{\partial_y U^f} =: MRS\left(\frac{C_y^f}{C_x^f} \right) = p_x \, G_R^f \qquad ,$$

where MRS denotes the marginal rate of substitution. After linking to the home country's X-sector, the maximization problem in Eq.(A26) is simplified to one of a single variable, namely R_y^f, because foreign's X-sector is now fully determined by the condition of marginal product equalization. Foreign's general equilibrium reaction to a positive 'shock' δX can thus be evaluated by considering the comparative statics of Eq.(A27), written as

$$\text{(A28)} \qquad MRS\left(\frac{G^f(R_y^f)}{\overline{X}^f + \delta X - \left(\overline{R}_x^f + R_y^f\right)/p_x} \right) = p_x \, G_R^f \quad ,$$

where the pre-linking equilibrium defines the parameters $\overline{X}^f$ and $\overline{R}_x^f$. Computing all derivatives yields

$$\text{(A29)} \quad \left(\frac{\partial\left(C_y^f / C_x^f\right)}{\partial X^f} dX^f + \frac{\partial\left(C_y^f / C_x^f\right)}{\partial R_y^f} dR_y^f + \frac{\partial\left(C_y^f / C_x^f\right)}{\partial p_x} dp_x \right) MRS' = G_R^f \, dp_x + p_x \, G_{RR}^f \, dR_y^f \quad .$$

Noting that the derivative MRS' is positive and since, evidently, we have

(A30) $$\frac{\partial\left(C_y^f / C_x^f\right)}{\partial X^f} < 0 \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial R_y^f} > 0 \qquad \frac{\partial\left(C_y^f / C_x^f\right)}{\partial p_x} < 0$$

the equation can be written in a qualitative way (‘neg’ denoting negative terms, ‘pos’ positive ones) as

(A31) $$\left(G_R^f - [...neg...]\cdot MRS'\right)dp_x + \left(p_x\, G_{RR}^f - [...pos...]\cdot MRS'\right)dR_y^f = [...neg...]\cdot MRS'\, dX^f$$

The still needed relation linking dp_x and dR_y^f can be obtained from the resource supply relation Eq.(18). With a binding constraint, the resource intake for all sectors except foreign’s *Y*-sector remains constant, and thus any change in the global supply must be due to a change in R_y^f :

(A32) $$dS = dR_y^f = S'\, dp_x \quad .$$

Substitution into Eq.(A31) yields

(A33) $$dp_x = \frac{[...neg...]\cdot MRS'}{\left(G_R^f - [...neg...]\cdot MRS' + p_x\, S' G_{RR}^f - [...pos...]\cdot S'\, MRS'\right)}dX^f \quad ,$$

which–given the unambiguous negative sign of the coefficient–demonstrates that linking leads to a fall in the price p_x. By virtue of Eq.(A32), it follows that foreign’s *Y*-sector expands, i.e. leakage occurs. Finally, the efficiency condition $p_y^f\, G'(R_y^f) = 1$ also implies that the price p_y^f increases.

In case of an asymmetric link from home’s *X* to foreign’s *Y*-sector, the foreign country receives additional goods *X* as ‘payment’ for the amount δR of resource that is traded from its domestic *Y*-sector to home’s *X*-sector. Foreign’s only degree of freedom is to adjust its *X*-sector, since the *Y*-sector has become ‘fixed’ as part of the linking agreement. However, the first-order condition for efficient production in the *X*-sector remains unaltered by the linking-induced trade in *R*, since foreign’s maximization problem after linking

(A34) $$\max_{R_x^f} U^f\left[F^f(R_x^f) + \delta X - \frac{\left(R_x^f + \bar{R}_y^f\right)}{p_x}, G^f(\bar{R}_y^f - \delta R)\right]$$

only implies the equalization of resource price and value of marginal product:

(A35) $$p_x\, F_R^f(R_x^f) = 1 \quad .$$

Therefore, foreign's *X*-sector expands only if p_x increases. But since the supply relation Eq.(A32) allows an increase in global resource supply only for a decrease in p_x, this cannot happen, allowing to conclude that global resource use must remain unaltered. □

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