Carbon Leakage with International Technology Spillovers

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Summary

In this paper we study the effect of international technology spillovers on carbon leakage. We first develop and analyse two simple competing models for carbon leakage. The first model represents the pollution haven hypothesis. It focuses on the international competition between firms that produce energy-intensive goods. The second model highlights the role of a globally integrated carbon-energy market. We calculate formulas for the leakage rates in both models and, through meta-analysis, show that the second model captures best the major mechanisms reported in the CGE literature on carbon leakage. We extend this model with endogenous energy-saving technology and international technology spillovers. This feature is shown to decrease carbon leakage. We build-in the endogenous energy-saving technology in a large CGE model and verify that the results from the formal model carry over. Carbon leakage becomes negative for moderate levels of international technology spillover.

Keywords: Carbon-Leakage, Climate Policy, Induced Technological Change; Trade and Environment

JEL Classification: F18, O39, Q25, Q4

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1. INTRODUCTION

Cutting the emissions of the greenhouse gas carbon dioxide (CO_2) has become a major political challenge for the coming decades. The political feasibility of the enterprise is hampered by global disagreement on the preferred level of abatement and its distribution over countries. Because of the close connection between CO_2 emissions and fossil fuel use, countries that want to pursue a more restrictive policy with respect to their emissions worry that their energy-intensive industries will suffer from international competition from industries in countries that follow a laxer climate change policy. Abating countries will see their reduction efforts be offset to some extent by increasing emissions in non-abating countries, while income and employment leak away to those countries. Not only does this carbon-leakage phenomenon render emission reduction costly and ineffective, it also generates an extra incentive for free-riding behaviour, jeopardizing the scope for international climate agreements. It has been suggested that carbon leakage may require environmental policies to adjust from a generic approach with a carbon tax equal among sectors towards carbon taxes that are differentiated among sectors, sheltering those sectors that are threatened to loose most from international competition (Hoel 1996). Carbon leakage has thus significant political weight and many computable general equilibrium (CGE) models have been used to determine its size and its relationship with key economic parameters. [4, 6, 7, 8, 17, 28].[2]

Felder and Rutherford [17] develop a recursively dynamic CGE and conclude that the integration of the world market of fossil fuels is most important in explaining carbon leakage. In their model, a reduction in fossil fuel demand in abating countries leads to lower prices on the world energy market, which subsequently leads to an increase in energy demand in non-abating countries. Along the same line of argument, Burnieaux and Oliveira Martins [8] conclude that, for integrated markets, carbon leakage is decreasing in the world elasticity of supply. An inelastic supply by definition means that quantities of supply will not adjust; all adjustment goes through prices. Consequently, a reduction in fossil fuel demand in abating countries must be exactly offset by an equal increase in other countries. Bohringer et al. [6], Bollen et al [7], and Paltsev [27] emphasize a different transmission channel for carbon leakage. They show that carbon leakage is increasing with the intensity of international competition in energy-intensive goods. Strong international competition implies that increased energy costs in abating countries lead to an increased price for energy-intensive goods, and the stronger the international competition for these goods, the more production will move to countries with lower energy costs. This

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[2] In this paper, we abstract from endogenous environmental policy as in Golombek and Hoel [18] and Copeland and Taylor (13). In line with the typical CGE analyses, in our analysis we take environmental policies as an exogenous parameter.

mechanism is known as the pollution haven hypothesis. Within this spectrum of competing transmission channels, Babiker [4] calculates the consequences of an extreme position when one assumes perfect substitution between energy-intensive goods produced in different countries, as in the Heckscher-Ohlin model. In this case, the international relocation of production of energy-intensive goods is almost complete, and when the non-abating countries are less energy efficient than the abating countries, carbon leakage may even exceed 100%.

In this paper, we build on this literature and extend it with a formal analysis on technology spillovers. We foresee that a major stream in the coming CGE literature will be directed to the incorporation of new features in CGE models such as strategic behaviour, imperfect markets, and technological change. In applied analysis, the question is how these new features affect the quantitative results. We focus on technological change, specifically on the role of an internationally shared technology base, that is, international technology spillovers, and its effect on carbon leakage. The central idea throughout our analysis is that abatement policies may change the direction of technological change, not only domestically, but also internationally. There are many arguments for a substantial international R&D spillover [11]. There is empirical evidence for the international spillover of technological change, the diffusion of environmental technologies [23], and specifically for energy-saving innovations [14, 28]. Based on this line of reasoning, some authors go so far as to assume that carbon leakage will be negative [20]. We may consider our analysis as an assessment of technology conditions under which this optimistic assumption may hold.

Our approach is as follows. First, in Section 2 we develop two stylized models that each describes a particular transmission channel for carbon leakage. Grossman and Krueger [19] present a helpful decomposition of emissions reductions that can also be used for decomposing carbon leakage, where changes in emissions are attributed to changes in the overall economic scale, the sectoral composition of the economy, and the production technology employed (see Kuik and Gerlagh [22] for such a decomposition of carbon leakage). For CO_2 emission reductions policies, the scale effects of climate change policy are typically negligible compared to the other two effects. We can therefore limit our analysis to the relative importance of the composition effect versus the technique effect. For carbon leakage the composition effect follows from the pollution haven hypothesis. When there is strong competition in the world market for energy-intensive goods, carbon-energy intensive industries will move from CO_2-abating countries to non-abating countries, and high carbon leakage results. Our first model, labelled the “pollution haven model”, describes this phenomenon.

That part of carbon leakage that can be attributed to the technique effect is not caused by international trade in energy-intensive goods, but by international trade in energy commodities. When, in abating countries, firms substitute other inputs for carbon-energy, global carbon-energy demand decreases. Assuming an integrated global carbon-energy market (and a less than fully elastic global of supply of carbon-energy), global carbon-energy prices fall. In turn, energy demand in the non-abating countries will increase as in these countries carbon-energy substitutes for other inputs. We simply label this model the "energy market model". For both stylized models we assess the dependence of carbon leakage on their parameters, and in Section 3 we test both models by comparing the parameter dependence in the formal model with the results from a meta-analysis based on the CGE carbon-leakage literature. We specifically consider parameters describing the international competition in energy-intensive goods, and the global supply elasticity of carbon-energy. We extend the meta-analysis to a controlled experiment where we create a sample of simulations employing the GTAP-E model [10]. The meta-analysis is used to select a preferred formal model for further analysis.

In Section 4 we further develop the formal model to include endogenous technological change and international technology spillovers. Our stylized description of technological change resembles Nordhaus's [26] and Sue Wing's [30] approach. Both describe a substitution frontier between carbon-energy and other inputs as possibly arising from two different mechanisms, either through a regular input-substitution frontier, or alternatively, through a technology variable that varies with prices and production choices.

Section 5 illustrates the formal analysis through an experiment with the CGE model GTAP-E. Whereas the brief formal model has the advantage of analytical rigor and independence of data, the large-scale CGE model better describes the many feed backs in an integrated economy. Together, the evidence developed in this paper offers a rich picture of the scope for technological change and its international spillover to affect carbon leakage. We conclude in Section 6.

2. TWO MODELS FOR EXPLAINING CARBON LEAKAGE

In this section we set up two models that represent two different transmission channels for carbon leakage: the pollution haven model and the energy market model. The pollution haven model developed here may be considered a stylized form of the model used in Di Maria and Smulders [15] and Di Maria and van der Werf [16]. Consider two countries, denoted by subscript $i=A,B$. The two countries are identical in structure; they are only different in size and CO_2 reduction policy. Let θ denote the share of country A in the world economy, and let country A implement a carbon-energy tax to reduce carbon-energy use, while country B implements no CO_2 reduction policy. To maintain the model structure as simple as possible, we only describe firms operating in the energy-intensive sector, which is assumed competitive so that firms are price takers. We describe output for this sector, carbon-energy use, and trade, and take prices of labour and other production factors as constant.

Under price-taking behaviour, a joint perfect substitution in the international markets for carbon-energy and for energy-intensive goods would lead to extreme equilibrium responses following a policy change in country A. Any carbon-tax in country A would increase the production costs in country A and all production would move to country B. To prevent such extreme responses, we either assume an integrated market with perfect substitution for the energy-intensive output good, or for the carbon-energy input good, but not jointly.

In the pollution haven model, we assume perfect substitution in the international markets for energy-intensive goods. There is one world market price for energy-intensive goods, q. World output Y is equal to world demand, and demand depends on the price through the elasticity of demand ε:

$$\theta Y_A + (1-\theta) Y_B = -\varepsilon q, \tag{1}$$

where all variables are in log-differences, so that Y_i is the *relative* change in output in country i, and q is the relative change in the energy-intensive goods price. We assume competitive producers implying that output prices change proportionally to input prices and taxes, multiplied by weights for input shares. All other production factor prices are assumed constant, so that output prices only depend on carbon-energy prices, plus a carbon-tax in country A.

$$q = \alpha(p_A+\tau_A)\ , \tag{2}$$

$$q = \alpha\, p_B, \tag{3}$$

where α is the share of carbon-energy in value added, p_i is the relative price change of carbon-energy in country i, and τ_A is the carbon-energy tax. Competitive production implies that carbon-energy demand E_i is proportional to output and proportional to the price difference between output and input prices

$$E_A = Y_A + \mu(q-p_A-\tau_A), \tag{4}$$

$$E_B = Y_B + \mu(q-p_B)\ , \tag{5}$$

where μ is the elasticity of substitution between carbon-energy and other production factors. Finally, the model is closed by the carbon-energy supply functions,

$$E_A = \psi p_A, \tag{6}$$

$$E_B = \psi p_B, \tag{7}$$

where ψ is the elasticity of supply. We have 7 equations that determine the 7 variables, Y_A, Y_B, q, p_A, p_B, E_A, E_B as a function of τ_A. Since all equations are linear in all variables, all variables are all proportional to τ_A. We now define the carbon leakage rate as the increase in absolute emissions in country B divided by the decrease in absolute emissions in country A:

$$LR = -\frac{1-\theta}{\theta}\frac{E_B}{E_A}\,. \tag{8}$$

For the pollution haven model, the leakage rate can be solved as[3]

$$LR = \frac{(1-\theta)\psi}{(1-\theta)\psi + \alpha\varepsilon + (1-\alpha)\mu}. \tag{9}$$

We state the dependence of the leakage rate on the parameters as a proposition:

PROPOSITION 1. In the pollution haven model (1)-(7), carbon leakage is decreasing with the size of the country abating, θ, and zero for $\theta=1$. The leakage rate is increasing in the elasticity of carbon-energy supply, ψ, zero for inelastic carbon-energy supply, $\psi=0$, and 100% for fully elastic carbon-energy supply, $\psi=\infty$. Carbon leakage is decreasing in the elasticity of demand for energy-intensive goods, ε, and in the elasticity of substitution between carbon-energy and other inputs, μ.

Formally, the proposition follows directly from (9). The intuition needs some explanation. The dependence of the carbon leakage on the size of country A, $\partial LR/\partial\theta<0$, is obvious. When country A would comprise the world, $\theta=1$, then by definition there can be no carbon leakage. In a continuous setting, it is then clear that the carbon leakage rate will decrease with the size of the country. For the other parameters, the dependence of the carbon leakage on the parameters is not obvious but dependent on the underlying model. We therefore first describe and analyze the second model, and only then discuss jointly for both models the intuition for the relation between parameters and carbon leakage.

The second model we develop assumes a fully integrated carbon-energy market characterized by one global carbon-energy price. In terms of the model, this means that equations (6) and (7) are replaced by (12). In return, we need to loosen the assumed perfect competition on the international market for energy-intensive goods, and instead, consider two separate markets; equation (1) is replaced by (13) and (14). All other equations remain the same, though country-specific carbon-energy prices p_i are replaced by one world carbon-energy price p, and the single world output price q is differentiated for both countries into q_i.

$$E_A = Y_A + \mu(q_A - p_A - \tau_A) \tag{10}$$
$$E_B = Y_B + \mu(q_B - p_B) \tag{11}$$
$$\theta_E E_A + (1-\theta_E)E_B = \psi p \tag{12}$$
$${}_A = -\varepsilon q_A \tag{13}$$
$${}_B = -\varepsilon q_B \tag{14}$$
$${}_A = \alpha_A\,(p+\tau_A) \tag{15}$$

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[3] We have used Mathematica software to solve formally for the leakage rates. The Mathematica code is available from the corresponding author upon request.

$$_B = \alpha_B \, p \tag{16}$$

For the energy market model, we can calculate the leakage rate (8) as

$$LR = 1 - \frac{\psi}{\psi + (1-\theta)(\alpha\varepsilon + (1-\alpha)\mu)} . \tag{17}$$

PROPOSITION 2. In the energy market model (10)-(16), the carbon leakage is decreasing with the size of the country abating, θ, and zero for $\theta=1$. The leakage rate is decreasing in the elasticity of carbon-energy supply, ψ, 100% for inelastic carbon-energy supply, $\psi=0$, zero for fully elastic carbon-energy supply, $\psi=\infty$, increasing in the elasticity of demand for energy-intensive goods, ε, and in the elasticity of substitution between carbon-energy and other inputs, μ.

Noticeably, in the energy market model, for all parameters but θ, dependence of the carbon leakage rate on the parameters has changed sign. This makes the two models well suited for testing in the next section. We can find out which of the two stylized models best reflects the mechanisms at play in typical CGE models used for the calculation of carbon leakage. This is the subject of the next section. First, we will describe the different mechanisms in the two models. Since in both models, only parameter ψ can move the carbon leakage rate over its entire range [0,1], this parameter is the most promising for comparing the two models.

The more elastic is the elasticity of carbon-energy supply, ψ, the more responsive is the carbon-energy supply to its price. In the pollution haven model, the two countries are linked through the market for energy-intensive goods, while the carbon-energy market is domestic. Thus, the higher the supply elasticity, the higher the potential for a carbon supply and use response in country B, thus $\partial LR/\partial\psi>0$. When carbon-energy supply is fully elastic, $\psi=\infty$, then carbon-energy prices in country B will be constant, $p_B=0$ (7), global output prices q will be constant, $q=0$ (3), there will be no change in overall demand, $\theta Y_A+(1-\theta)Y_B$ (1), and no input substitution in country B (5). Thus, any decrease in carbon-energy in country A is exactly offset by a proportional decrease in its share in output, an increase in output in country B, and a proportional increase in carbon-energy inputs in country B.

In the energy market model, the two countries are linked through the energy market, and the effect of the global carbon-energy supply elasticity on carbon leakage is more direct. When country A reduces carbon-energy consumption, the change can be accommodated either through in increase in demand in country B (leakage) or a decrease in supply (no leakage). The higher the elasticity of supply, the stronger the adjustment of supply, the lower is the leakage, $\partial LR/\partial\psi<0$.

In the pollution haven model, carbon leakage depends negatively on the elasticity of demand, $\partial LR/\partial\varepsilon<0$. When country A reduces carbon-energy consumption, the higher the elasticity of demand, the higher is that part of the decrease in carbon-energy that can be accommodated through a decrease in overall demand of energy-intensive goods. In contrast, in the energy market model, the higher the elasticity of demand, the stronger the response of the consumers in country *B* and carbon-energy demand in country *B* thus compensates for a larger part of the decrease in demand in country *A*, $\partial LR/\partial\varepsilon>0$.

Similarly, in the pollution haven model, a higher elasticity of substitution between carbon-energy and other inputs accommodates alternative ways of reducing carbon-energy use by shifting it to country *B*, hence $\partial LR/\partial\mu<0$. In the energy market model, however, the higher the elasticity of substitution, the stronger the response of the firms in country *B* and carbon-energy demand in country *B* thus compensates for a larger part the decrease in demand in country *A*, $\partial LR/\partial\mu>0$.

3. CARBON LEAKAGE IN CGE MODELS

CGE estimates of the size of carbon leakage vary considerably. Table 1 lists a number of studies. The first column entry presents estimates of the leakage rate (*LR*); they range between 2 percent in OECD's GREEN model to 21 percent in a model by Light *et al.* (1999) and even 115 percent in a specific simulation by the MIT-EPPA model. This section investigates the relation between the carbon leakage rates and the model parameters, listed in the other columns.

First, Table 1 reports the models' assumptions on the share of global emissions of abating countries (θ) in 2010, and the assumed policy regime (*P*) which is 1 in the case of international emissions trading among abating countries and 0 otherwise. Second, the supply elasticities of fossil fuels indicate the rate of decreasing returns in their production. There is some disagreement among the models with respect to the relative elasticity of coal and oil versus gas. While GREEN and MIT-EPPA assume an elastic supply response for coal and a less elastic supply for gas, WorldScan assumes the reverse. We have calculated an avarage supply elasticity of carbon-energy (ψ) as the output-and-carbon-intensity-weighted average of the models' supply elasticities of coal, crude oil and gas. Third, we list the elasticity of substitution between imported and domestically produced energy commodities, v_e, and imported and domestically produced energy-intensive goods, v_y. In case models assumed different trade substitution elasticities for different energy goods, we have calculated the average trade elasticity for the carbon-energy good as the trade-and-carbon-intensity-weighted average of the trade elasticities of coal, crude oil, and gas.

Finally, Table 1 reports the models' substitution elasticity between energy and other factors of production (μ) and the substitution elasticity between energy-intensive goods and other goods in consumption (ε).

TABLE 1. *Key results and elasticities in CGE literature*[4]

Model and paper	*LR*	*P*	θ	ψ	ν_e	ν_y	μ	ε
DEEP (Kallbekken, 2006)	0.06	1	0.35	1	4	4	0.5	1
G-Cubed (McKibbin et al., 1999)	0.06	0	0.52	1	1	1	0.5	1
GEM-E3 (Bernard and Vielle, 2000)	0.13	0	0.52	1	6	3	0.3	1
GEM-E3 (Bernard and Vielle, 2000)	0.04	1	0.62	1	6	3	0.3	1
GREEN (Burniaux *et al.*, 2000)	0.05	0	0.52	8	4	4	0.4	n.a.
GREEN (Burniaux *et al.*, 2000)	0.02	1	0.62	8	4	4	0.4	n.a.
GTAP-E (Burniaux and Truong, 2002)	0.04	0	0.52	5	19	2	0.5	0.8
GTAP-E (Burniaux and Truong, 2002)	0.04	1	0.61	5	19	2	0.5	0.8
GTAP-E (Kuik and Gerlagh, 2003)	0.16	0	0.52	1	7	2	0.5	0.8
GTAP-E (Gerlagh and Kuik, this paper)	0.14	1	0.62	0.6	5	2	0.5	0.8
GTAP-EG (Paltsev, 2001)	0.11	0	0.52	1	4	4	0.5	1
Light (Light et al., 1999)	0.21	0	0.52	0.5	4	4	1	1
MIT-EPPA (Babiker and Jacoby, 1999)	0.06	0	0.52	2.9	3	3	0.5	n.a.
MIT-EPPA (Babiker, 2005)	0.20	1	0.51	0.8	8	8	0.5	n.a.
MIT-EPPA, Babiker, 2005)	1.15	1	0.51	0.8	∞	8	0.3	n.a.
MS-MRT (Bernstein et al., 1999)	0.19	0	0.52	1.5	4	4	0.3	1
MS-MRT (Bernstein et al., 1999	0.16	1	0.61	1.5	4	4	0.5	1
WorldScan (Bollen, 2004)	0.17	0	0.26	3	10	3	1	n.a.

n.a. is not available, meaning that we could not find the elasticity in the model descriptions.

Based on the sample, we try to explain the leakage rate on basis of the parameter choices. That is, we estimate

$$LR_i = a_0 + a_1 P + a_2 \theta + a_3 \psi + a_2 \nu_e + a_2 \nu_y + a_2 \mu + e, \tag{18}$$

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[4] *LR* = Rate of carbon leakage, *P* = Policy regime (1 if international emissions trading; 0 otherwise), θ = Global CO_2 emissions share of abating countries, ψ = Elasticity of supply of carbon-energy, ν_e = Armington trade elasticity of energy goods, ν_y = Armington trade elasticity of energy-intensive goods, μ = Elasticity of substitution between carbon-energy and other inputs, ε = Elasticity of substitution between energy-intensive and other consumption goods.

where e is the error term, assumed white noise. We use OLS to estimate the parameters' contribution, and leave out the outlier Babiker (2005) study with leakage rate above 100%. This produces a sample of 17 observations. Results are listed in Table 2. The sample is small and insufficient to determine the coefficients for all parameters at a significant level. Also, we did not have values for ε, the elasticity of substitution between energy-intensive and other consumption goods, for all simulations. Omitting all parameters with insignificant coefficient from the regression, we end with two parameters, explaining 42% of the variation in leakage rates. For comparison, in the first two columns of Table 2 we added the signs of the coefficients of the supply elasticity of carbon-energy, $\psi_,$ that are predicted by the pollution haven model and the energy market model, respectively (see Propositions 1 and 2). Over the CGE sample, we find carbon leakage to be negatively related to ψ, and positive related to v_y, (regression (1)). As the first two column entries of the table show, this finding is inconsistent with the pollution haven model, but consistent with the energy market model.

Since our sample contains more observations than models, we can extend the analysis with fixed effects coefficients. That is, we add independent dummy variables for each model, and the coefficients for these dummies capture the model-specific features that affect carbon leakage, independently of the parameters included in the analysis. Results are shown in regression (2). Using fixed effects implies that we have to drop all single model observations, leaving us with a sample size of 13. In this reduced sample, only the coefficient for the elasticity of carbon-energy supply remains significant. The result again supports the global energy market as the major transmission channel for carbon leakage, and it does not support the pollution haven hypothesis. Therefore, we conclude that the energy market model offers a better description of carbon leakage in CGE models than the pollution haven model.

TABLE 2. *Dependence of carbon leakage (LR) on elasticities in CGE models*[5]

	Pollution Haven	*Energy Market*	(1)	(2)	(3)
ψ	+	–	–1.5***	–2.8**	–10.6***
v_y			1.6*		0.5***
v_e					0.3***
v_o					0.1***
μ	–	+			8.1***
N			17	13	100
Fixed effects			No	Yes	n.a.
Degrees of freedom			14	7	94
R^2_{adj}			0.42	0.77	0.98

OLS; significance at p=0.05 marked with **, p=0.01 with ***.

As a final check, we set up a controlled experiment with GTAP-E. We ran the model 100 times, varying the major parameters around their central value, plus-minus half their value, independently. This produced a database of 100 observations, which enabled us to check the results of the literature meta-analysis, as reported in column entry (3). Of those parameters varied, only the parameter ε was found insignificant, and left out of the table.

4. INPUT-SAVING TECHNOLOGY

We now proceed with the formal analysis of the energy market model (10)-(16), extending the model with endogenous technological change. In the base model, the parameter μ describes the elasticity of substitution between carbon-energy and other inputs in production. Now, these substitution possibilities may arise because of substitution between factors for given technology, but they may also relate to switching between technologies, or development of new technologies dependent on factor prices. The role of technology in substitution in such models is extensively described in Nordhaus (2002) and Sue Wing (2006). In formal terms, let us denote by σ the elasticity of substitution including technological change, and let μ be that part of the substitution opportunities that are not due to technological change. Let the parameter γ denote the share of substitution possibilities due to technological change, so that $\mu=(1-\gamma)\sigma$. We can think of μ as describing the substitution between carbon-energy intensive and extensive firms within the

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[5] See footnote 4 for description of parameters. v_o = Armington trade elasticity of other goods, that is, non-energy and non-energy-intensive goods.

sector, using energy-saving equipment that is available for the benchmark technology. Figure 1 illustrates the concept.

In Figure 1, the iso-output curve I depicts all input pairs (X_1,X_2) with constant output, for given technology. At the reference case, the input mix is at point *A*. When the second input factor, say carbon-energy, becomes more expensive, non-carbon energy factors will substitute, and input will move along curve I. Technology will also adjust and will become more carbon-energy saving, shifting the iso-output curve I to curve II. Curve III captures both direct and technology-induced factor substitution. The input mix will move along this curve to point *B*. In terms of our model, σ describes the inverse curvature of curve III, while μ describes the inverse curvature of curves I and II. The parameter γ describes the contribution of moving from curve I to curve II, relative to moving along curve I or curve II. The same idea is – in a dynamic context – presented in Figure 6 in Sue Wing (2006).

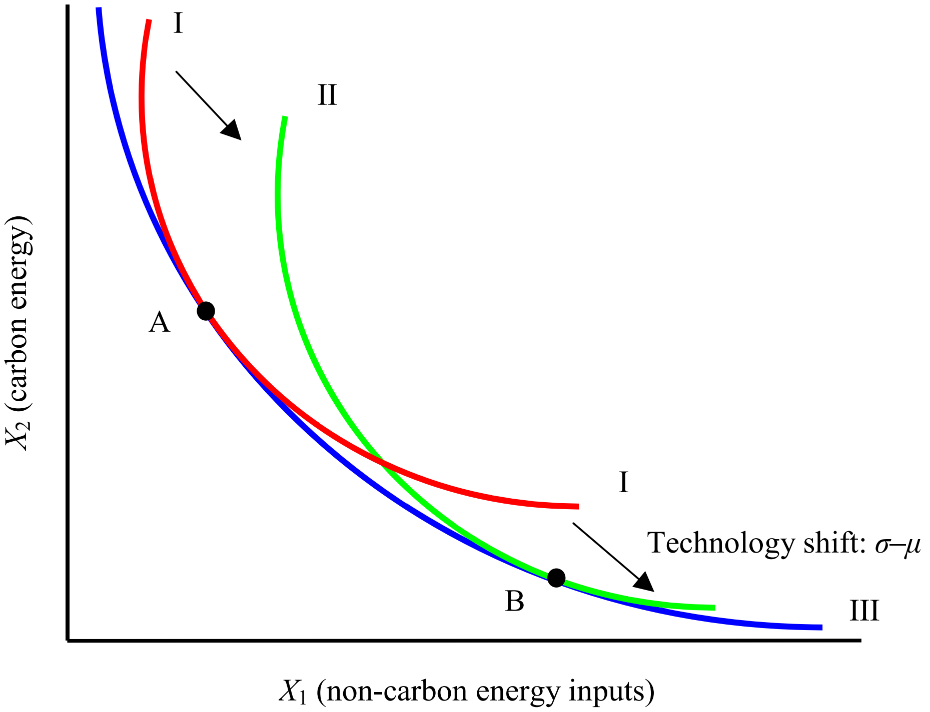

FIGURE 1. *Graphical illustration of technology-driven and non-technology substitution*

We now specify this mechanism within our stylized model. We start with a standard description of curve III as a CES production function. Let output *Y* depend in inputs X_i, and technology vector ζ, with elasticity of substitution σ:

$$Y = \left(\sum_i \zeta_i \left(X_i \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{19}$$

Now, we introduce an endogenous technology vector A in the production function, and we assume that for given technology A, the elasticity of substitution is reduced to $(1-\gamma)\sigma$: That is, for constant A, the function describes curve I, or curve II (for different A).

$$Y = \left(\sum_i \left(A_i X_i \right)^{\frac{(1-\gamma)\sigma-1}{(1-\gamma)\sigma}} \right)^{\frac{(1-\gamma)\sigma}{(1-\gamma)\sigma-1}} \tag{20}$$

The first order conditions for both the production functions are given by

$$\frac{p_i}{q} = \zeta_i \left(\frac{X_i}{Y} \right)^{-\frac{1}{\sigma}} \text{ , and} \tag{21}$$

$$\frac{p_i}{q} = \left(A_i \right)^{-\frac{(1-\gamma)\sigma-1}{(1-\gamma)\sigma}} \left(\frac{X_i}{Y} \right)^{-\frac{1}{(1-\gamma)\sigma}}, \tag{22}$$

respectively. Demanding consistency between the two price equations gives

$$A_i = \left(\zeta_i \right)^{\frac{(1-\gamma)\sigma}{(1-\gamma)\sigma-1}} \left(\frac{X_i}{Y} \right)^{\frac{\gamma}{(1-\gamma)\sigma-1}} \tag{23}$$

This equation ensures that curves I and II indeed move along curve III. When we substitute H_i for $A_i^{1-(1-\gamma)\sigma}$, we can derive a set of relatively simple equations determining the level of technology H_i and demand X_i, for given prices (p_i, q) and output Y:

$$H_i = \zeta_i^{\mu} (X_i / Y)^{-\gamma} \tag{24}$$

$$X_i = (Y / H_i)(p_i / q)^{-\mu} \tag{25}$$

The second of the two equations shows that H_i can be considered as pure input-saving technology, while the first equation presents the dependence of H_i to the input-mix and it shows that the elasticity of technological change with respect to the input change is γ.

We insert this type of technological change in our energy market model (10)-(16), and assume full international technology spillovers, so that we can replace (10) and (11) by

$$E_A = Y_A - H + \mu(q_A - p - \tau_A) \tag{26}$$
$$E_B = Y_B - H + \mu(q_B - p) \tag{27}$$
$$H = \gamma[\theta(Y_A - E_A) + (1-\theta)(Y_B - E_B)] \tag{28}$$

The new equations say that energy demand is decreasing proportionally to energy-specific technology H, while technology is increasing if the share of carbon-energy input decreases. Endogenous technology changes the carbon leakage rate from (17) into

$$LR = (a-b)/(a-b+c) = 1-c/(a-b+c) \tag{29}$$

where for convenience of notation, we use $a>0$, $b>0$, and $c>0$ according to

$$a = (1-\theta)[\alpha\varepsilon+(1-\alpha)\mu][(1-\gamma)\alpha\varepsilon+(1-\alpha)\mu] \tag{30}$$
$$b = (1-\theta)(1-\alpha)\gamma\mu\psi \tag{31}$$
$$c = \psi[(1-\gamma)\alpha\varepsilon+(1-\alpha)\mu)] \tag{32}$$

The leakage rate formula has become more complex, but we can easily see that for $\gamma=0$, we have $b=0$ and the previous equation (17) is found.

The dependence of the leakage rate on technology spillover γ, is stated in the following proposition:

PROPOSITION 3. In the energy market model with endogenous technological change (12)-(16), (26), (27), (28), we have that (i) carbon leakage is decreasing in the level of global endogenous technology, γ, and (ii) for all positive and finite parameters α, ε, μ, ψ, there exists a γ such that the leakage rate is negative.

Proof. (i) From (31) we see that b is increasing and proportional in γ. From (30) and (32) we see that a and c are decreasing in γ, but they are proportional to $(1-\gamma)$. Consequently, the numerator in the last term of equation (29) will be decreasing proportionally with $(1-\gamma)$, while the denominator will be decreasing faster than proportional with $(1-\gamma)$. Hence, the ratio will increase, and the leakage rate will fall.

(ii) It follows from (29), (30) and (31) that the carbon leakage rate is negative if

$$\gamma > (\alpha\varepsilon+(1-\alpha)\mu)^2/[(1-\alpha)\mu\psi], \tag{33}$$

which can be calculated as a finite number. Q.E.D.

The equation gives a simple formula for the required technology spillover to find negative carbon leakage [cf. 20]. For example, when carbon-energy has a value share in production α=0.1, when the elasticity of demand and elasticity of substitution are both set to conservative values ε=0.5, μ=0.5, and when the elasticity of supply is set to ψ=2, then the required technology share in substitution needs to be γ>0.28. When carbon-energy supply is very inelastic, however, e.g. ψ=0.1, then when we apply the same values for the other parameter, we would need a very high level of technology spillover, γ>5.56, far beyond the maximum level of 1.

The analysis so far is, however, conservative, as a symmetric technology spillover between abating and non-abating countries is improbable. Most probably high-income countries will abate more compared to low-income countries. Also, high-income countries tend to invest more in innovation, and technologies in developed countries are more often copied in developing countries than the other way around. The asymmetry in technology spillover would give extra support to the argument for decreasing carbon leakage [5, 11, 29]. In our model, the asymmetry can be included through an adjustment of the technology equation (28) into

$$H = \gamma(Y_A - E_A) \tag{34}$$

Solving for the leakage rate under this specification, we find the same equation (17) but now with

$$b = [(1-\theta)/\theta](1-\alpha)\gamma\mu\psi \tag{35}$$
$$c = \psi((1-\gamma)\alpha\varepsilon + (1-\alpha)(1+[(1-\theta)/\theta]\gamma)\mu)) \tag{36}$$

It can easily be seen that both c is larger and $a-b+c$ is smaller with one-sided spillovers compared to the situation with symmetric spillovers. Thus the leakage rate is smaller. We state this result as a proposition.

PROPOSITION 4. With one-sided technology spillovers from the abating country to the non-abating country, carbon leakage is less compared to the situation with symmetric spillovers.

Proof. In text.

5. INCLUDING CARBON-ENERGY SAVING TECHNOLOGY IN GTAP-E

To test the analytical model developed in Section 4 against real data, we inserted endogenous carbon-energy saving technology in GTAP-E, an existing multi-region, multi-sector CGE model of international trade and carbon emissions [10]. We used the GTAP-E model before to simulate carbon leakage in the context of the Kyoto Protocol [22].

GTAP-E has a nested CES production structure, with substitution possibilities between energy commodities and other commodities (capital, labor) on the one hand, and between different energy commodities on the other hand. In line with the theory developed in this paper, we have assumed that substitution between these commodities is partly due to technical change, and partly due to "classical" input substitution. In our representation, technical change can go in either direction. If a commodity is used more, the technology of its use improves and its unit cost decreases. If a commodity is used less, the reverse occurs. A price increase of carbon-energy induces input-saving technical change for carbon-energy, and input-augmenting technical change for other commodities. Technological change is modelled such that the overall effect of technical change on the costs of the final product is zero. In other words, induced technical change does not affect overall productivity in a sector or economy; it just changes the direction of productivity. Including technological change, without international technology spillovers, and without changing the overall elasticity (for which we used the parameter σ in Section 4), has no effect on simulated scenarios.[6] This result serves as a check that induced technological change, in itself, has no effect on carbon leakage. Induced technological change only makes a difference with the standard GTAP-E model when technological change can spill over from one country to other countries to augment their production possibilities (see Annex I for a detailed discussion of the model adjustments).

To test the model, we used an 8x8 aggregation of GTAP's version 6 database, augmented by Lee's CO_2 emissions data of November 2005. The eight regions in the model are the Annex I countries of Europe, Japan, Canada and New Zealand; USA and Australia; countries of the former Soviet Union; and five developing country or Non-Annex I regions (see Table 3). The eight commodities are coal, crude oil, gas, petroleum products, electricity, energy-intensive goods, other goods and services, and capital goods. We used projections of the Energy Information Administration of the U.S. Department of Energy (EIA/DOE, 2005) in its International Energy Outlook 2005 "Reference Scenario" (IEO2005RS) to update the database to 2010. In order to approximately replicate the CO_2 emissions projections of EIA/DOE we carried out a forward-calibration of the GTAP-E database with a rise in the world market oil price, increased Gross Domestic Product (GDP) per region, and decreased overall energy-intensity per region. In IEO2005RS the world market price of crude oil rises from about US$30 per barrel in 2004 to more than US$40 in 2005 to decline gradually to US$31 in 2010. In the IEO2005RS scenario, world GDP rises by 43% in the period 2001-2010, energy-intensity decreases by 18%, and CO_2 emissions increase by 25%. CO_2 emissions rise faster in Non-Annex I countries (52%) than in Annex I countries (12%), so that the share of Non-Annex I countries' CO_2 emissions increases from 39% in 2001 to 47% in 2010. Table 3 shows that our CO_2 emissions projections are fairly close to those of IEO2005RS.

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[6] In the formal model of Section 4, if technological change is country specific, so that H is split in H_A and H_B, and (34) is specified for both countries, then the leakage rate is given by (17), where σ should substitute for μ.

Table 3. *CO_2 emissions projections for the period 2001-2010* (% increase)

	IEO2005RS	GTAP-E adjusted data
Annex I	12	12
Non-Annex I	47	52
World	25	26
Europe, Japan, Canada, and New Zealand	5	7
USA and Australia	16	16
Former Soviet Union	17	12
Energy-exporting developing countries	31	35
China and India	65	75
Dynamic East-Asian countries	27	28
Dynamic Latin-American countries	26	20
Rest of the world	35	36

We constructed two policy scenarios. In the first scenario, KYO1, both the Annex I countries and the USA and Australia comply with their Kyoto targets and reduce CO_2 emissions by 13, respectively 30 percent below baseline in 2010. There is emissions trading between the two abating regions, so that the carbon permit price is equal for both regions. The countries of the former Soviet Union do not abate emissions, nor do they sell surplus emissions permits ("hot air") to other countries. In the second policy scenario, KYO2, the USA and Australia do not participate in the Kyoto agreement, and do not abate emissions.

In the standard solution of GTAP-E the rate of carbon leakage of participating Annex I countries to Non-Annex I countries is 13.8 percent in KYO1 and 16.8 percent in KYO2. The increase in leakage in KYO2 over KYO1 confirms the element of Proposition 2 that states that carbon leakage is decreasing with the size of the country abating.[7] If endogenous technical change and spillovers are included in the model, the rate of carbon leakage decreases in proportion to the relative strength of endogenous technical change (γ). In the figures below, the relationships between the relative strength of technical change (on the X-axes) and the rates of carbon leakage (on the Y-axes), are shown for the two scenarios. The left panel shows the KYO1 scenario, whereas the right panel shows the KYO2 scenario. Within each scenario, we vary the rate of international technology spillover from 0 to 40%. We calculate the leakage rates both for symmetric technology spillovers between OECD and non-OECD countries, and for asymmetric spillovers when technology only spills over from OECD countries to non-OECD, but not the other way round.

The figures below show that the rate of carbon leakage becomes negative for levels of γ between 0.2 and 0.3. That is, if 20 to 30 percent of the CGE-predicted input-substitution that is induced by CO_2 reduction policy would be due to input-saving technical change and if this technical knowledge would

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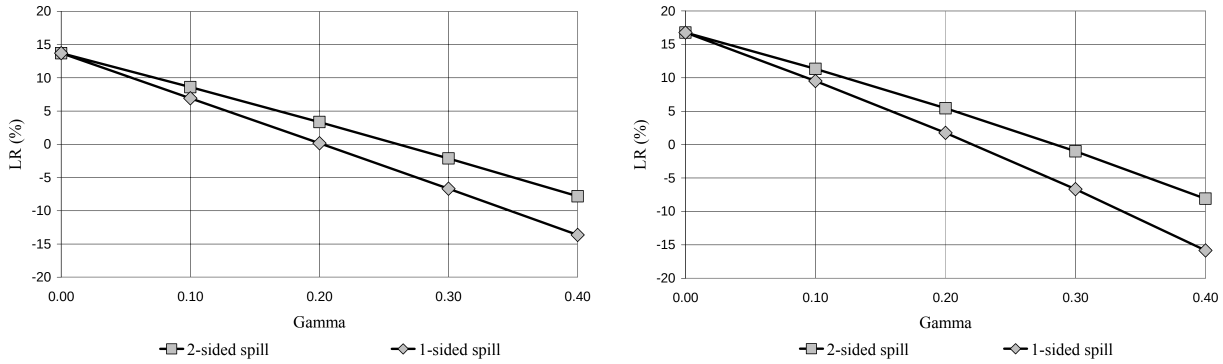
[7] $\theta_{KYO1} = 0.52 > \theta_{KYO2} = 0.26$, hence $LR_{KYO1} = 13.8 < LR_{KYO2} = 16.8$

freely spill over between countries, than carbon leakage could become zero or even negative. Figure 2 shows that carbon leakage is most reduced by a one-sided spillover, confirming Proposition 4, but the fact that there is technology spillover is more important than its direction (from OECD to non-OECD or two-sided). Assuming a smaller abating region as in KYO2 (in the right panel of Figure 2) shifts the curves up, but when technology spillover becomes a substantial effect, the size of the abating country seems to become less important.



(KYO1) (KYO2)

i

FIGURE 2. *Carbon leakage and international technology spillovers*

We also looked into the distribution of carbon leakage over the Non-Annex I regions and found that the position of China-India is remarkable. In the standard solution, about 50 percent of total leakage is related to the increase in emissions in this region. But at the same time, emissions in China-India are more-than-average sensitive to technology spillovers, and the turning-point at which the change in emissions becomes negative in China-India is reached before the overall leakage rate becomes negative. The transfer of technology to China and India seems most important for achieving negative leakage rates.

6. CONCLUSION

Our analysis suggests that, under standard assumptions of optimizing behavior of economic agents, technological spillovers can lead to small or even negative rates of carbon leakage. We developed a simple, formal model of carbon leakage, that was shown, through meta-analysis, to be qualitatively equivalent to the large-scale CGE models that have been used to compute leakage rates. We extended this simple model with endogenous energy-saving technical change and international spillovers. From this extended model, a reduced-form equation for the rate of carbon leakage was derived. This equation shows that carbon leakage decreased in the level of spilled-over endogenous technology and that the leakage rate can indeed become negative. Applying the theoretical insights of our formal model to a large-scale CGE model, we simulated carbon leakage under (variants of) the Kyoto Protocol. The results tentatively suggested that carbon leakage could become negative even under moderate levels of technological spillover.

While we consider our analysis an important step forward from earlier work on this issue, which either missed theoretical rigor or focused on the pollution haven model of carbon leakage, we do acknowledge that our analysis leaves room for further extensions. Obvious improvements would include a fully dynamic representation of energy-saving technical change supported by empirical evidence, and a detailed analysis of international technical spillover, taking into account all kinds of political, institutional, cultural and economic barriers. We do think, however, that our simple model can be useful in structuring this future research.

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APPENDIX

In this Appendix, the adjustments to GTAP-E to simulate endogenous carbon-energy-saving technical change and international spillovers are briefly explained. The authors are happy to share the source code with anyone interested. The most important adjustments to the GTAP-E model are regarding the production functions of its industries. The production functions account for several substitution possibilities between energy commodities and other inputs, and between different types of energy commodities. A graphical illustration of GTAP-E's nested production function is given in Figure 3.

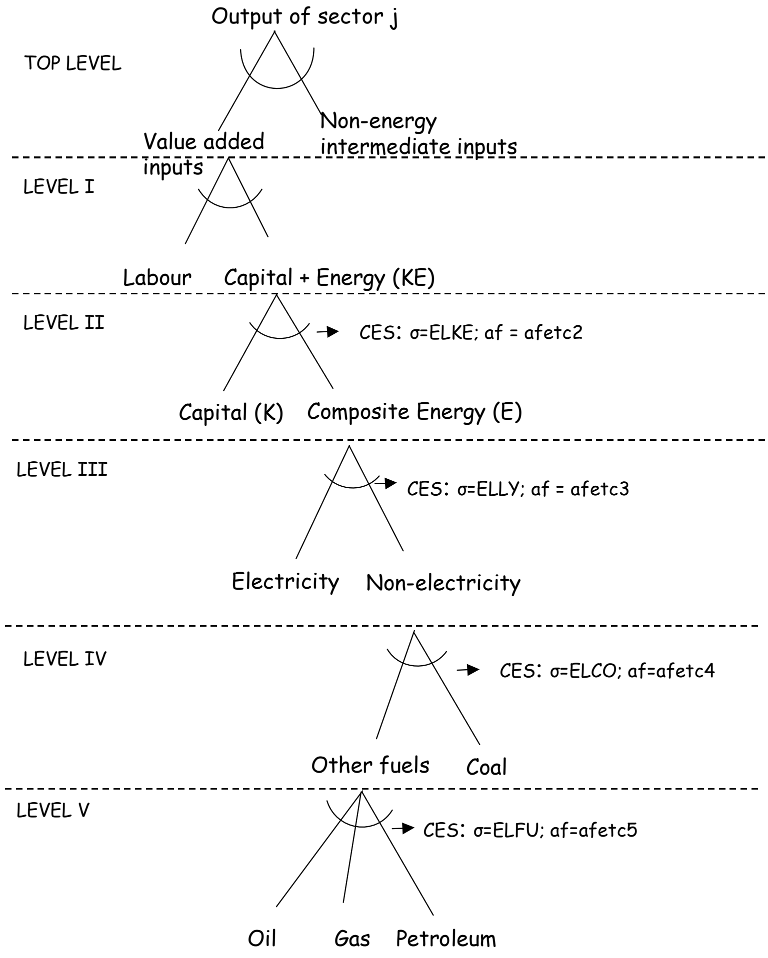

FIGURE 3. *A graphical illustration of GTAP-E's nested production function (the afetc parameters are not part of GTAP-E's original parameters; they are explained in the text below)* .

In GTAP-E's nested production function, the composite capital-energy good, *KE*, in Level I, is a CES aggregate of capital, *K*, and energy, *E*, of Level II of the production function. All else being equal, if the relative price of energy increases, producers will substitute capital for energy in the production of the capital-energy good. The rate of substitution is given by GTAP-E's exogenous elasticity of substitution: σ=*ELKE*. GTAP-E is written in log-linear form, so that its variables represent percentage changes. An industry's conditional input demand is given by:

$$qE = -af + qKE - ELKE * (pE - af - pKE) \qquad \text{(A1)}$$

where q and p denote percentage changes in quanities and prices, respectively, and af is an exogenous technical change parameter, which has as an index both the country, the sector, and the input at the considered level of the CES tree. Equation (A1) says that the share of energy in the capital-energy composite good will diminish if i) the relative price of energy, pE, increases, ii) if energy-saving technological change occurs, or iii) if both occur.

We now make energy-saving technological change, af, endogenous by assuming that a fraction, γ, of the relative, price-induced change in demand for energy ($qKE - qE$) is due to technical change. We call this endogenous technical change parameter $afetc$. In GTAP-E, the technology adjustment is then given by:

$$afetc = \gamma/[1 - (1 - \gamma)ELKE] * (qKE - qE). \tag{A2}$$

By analogous reasoning, technical change for capital is

$$afetc = \gamma/[1 - (1 - \gamma)ELKE] * (qKE - qK). \tag{A3}$$

Notice that $afetc$ has an index for the country, sector, and for capital vs. energy. With a price increase of energy, $pE > 0$, $afetc$ for energy will be positive and $afetc$ for capital will be negative. If one substitutes the $afetc$'s for the af's in Equation (A1), one sees that a price increase of energy will reduce the conditional demand for energy through a substitution effect, $-ELKE*(pE - pKE)$, as well as through induced energy-saving technological change (through the $afetc$'s).

Because of GTAP-E's specific nesting structure and the fact that the technical change parameters are assigned to the individual commodities (capital (K), electricity (EL), coal (CO), and Oil, gas and petroleum (F_i)), and not the compositie commodities (capital-energy (KE), energy (EN), non-electricity (NEL), and non-coal (NCO)), care must be taken to avoid double-counting if one wants to implement endogenous technical change in all levels of the production function. The level-specific $afetc$ parameters for the individual commodities are presented in the following table:

	Capital	Electricity	Coal	Oil, gas, petroleum
Level II: *afetc2*	$\alpha ELKE^{-1}\ (qKE - qK)$	$\alpha ELKE^{-1}\ (qKE - qEN + afetc2)$	$\alpha ELKE^{-1}\ (qKE - qEN + afetc2)$	$\alpha ELKE^{-1}\ (qKE - qE + afetc2)$
Level III: *afetc3*		$\alpha ELLY^{-1}\ (qEN - afetc2 - qEL)$	$\alpha ELLY^{-1}\ (qEN - qNEL + afetc3)$	$\alpha ELLY^{-1}\ (qEN - qNEL + afetc3)$
Level IV: *afetc4*			$\alpha ELCO^{-1}\ (qNEL - afetc2 - afetc3 - qCO)$	$\alpha ELCO^{-1}\ (qNEL - qNCO + afetc4)$
Level V: *afetc5*				$\alpha ELFU^{-1}\ (qNCO - afetc2 - afetc3 - afetc4 - qF_i)$

N.B. $\alpha = \gamma/[1 - (1 - \gamma)]$

The technical change parameters *afetc* which have now become endogenous play a role in GTAP-E's input price equations, which keep their original form. The (effective) price of the *KE* composite good is determined by the equation:

$$pKE = \theta\,(pK - afetc2) + (1 - \theta)\,(pE - afetc2) \qquad \text{(A4)}$$

where θ is the original input cost share. It can be shown that $\theta afetc2 + (1{-}\theta)afetc2 = 0$, so that endogenous technical change in our model does not affect the price of the composite *KE* commodity, nor the price of the end product. Endogenous technical change does only affect the input mix in the direction of more capital and less energy. Further down the production structure, a carbon tax will increase technical change in the less-carbon intensive energy commodities, and decrease technical change in the more-carbon intensive energy commodities.

Next we come to international technology spillovers. Let the indices *r* and *s* represent the domestic country and the foreign country respectively. We assume that the domestic country *r* abates CO_2 emissions and that by doing so it increases its knowledge on low-CO_2 technologies. In the case of one-sided international technology spillovers, this induced technical knowledge is frictionless transferred to foreign countries. Hence for country *s*:

$$afetc(s) = \Phi afetc(r) \qquad \text{(A5)}$$

Where $\Phi = 1$ if there is an international technology spillover and $\Phi = 0$ if there is not.

In our model, however, endogenous technical change is not exclusive for the country abating emissions. Because of changes in relative world prices, country *s* can also experiences technical change – usually in the opposite direction from country *r*. To capture the two-sided international technology spillover (or multi-sided in case of more than two countries), the spillover parameter Φ is made a continuous, country-specific parameter on the domain (0,1) with $\Phi(r) + \Phi(s) = 1$. We let $\Phi(r)$ and $\Phi(s)$ be the shares in gross world product of countries *r* and *s*, reflecting the 'strengths' of the technological knowledge spillovers from these countries.

Including the spillover parameter in the *afetc* equations, yields the endogenous input-saving technology paramater *afetc* in level # of the production function of sector *j* as a function of γ and σ, and of the GDP-weighted policy-induced conditional input demand changes, $(qA - qB)$, in all countries *s*. In formula:

$$Afetc\#(r) = \gamma/[1 - (1 - \gamma)\sigma] * \Sigma\, \Phi(s)\,(qA - qB) \qquad \text{(A6)}$$

Equation (A6) presents the general form in which the endogenous technical change parameters are implemented in GTAP-E.

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