Discussion Papers No. 591, September 2009
Statistics Norway, Research Department

Knut Einar Rosendahl and Jon Strand

Carbon leakage from the clean development mechanism

Abstract:
The Clean Development Mechanism (CDM) is an offset mechanism designed to reduce the overall cost of implementing a given target for greenhouse gas (GHG) emissions in industrialized Annex B countries of the Kyoto Protocol, by shifting some of the emission reductions to Non-Annex B countries. This paper analyzes how CDM projects may lead to leakage of emissions elsewhere in Non-Annex B countries, taking into account also potential (negative) leakage effects from less emission reductions in Annex B. Leakage occurs because emissions reductions under a CDM project may affect market equilibrium in regional and/or global energy and product markets, and thereby increase emissions elsewhere. We find that overall leakage typically will be positive and sizeable, thus leading to an overall increase in global GHG emissions when CDM projects are undertaken. The leakage rate is greatest when the different fossil fuel markets are more segregated.

Keywords: Carbon leakage, Clean Development Mechanism, Kyoto protocol

JEL classification: F18, H23, Q41, Q54

Acknowledgement: We are grateful for valuable comments from Christoph Böhringer, Mads Greaker, Cathrine Hagem and Michael Toman. Financial support from the Petrosam program of the Research Council of Norway is appreciated. Rosendahl also thanks Resources For the Future in Washington DC, where much of the work for this paper was carried out, for its hospitality.

Address: Knut Einar Rosendahl, Statistics Norway, Research Department.
E-mail: knut.einar.rosendahl@ssb.no

Jon Strand, The World Bank, DECRG, Environment and Energy Team
E-mail: jstrand1@worldbank.org

Discussion Papers comprise research papers intended for international journals or books. A preprint of a Discussion Paper may be longer and more elaborate than a standard journal article, as it may include intermediate calculations and background material etc.

Abstracts with downloadable Discussion Papers
in PDF are available on the Internet:
http://www.ssb.no
http://ideas.repec.org/s/ssb/dispap.html

For printed Discussion Papers contact:

Statistics Norway
Sales- and subscription service
NO-2225 Kongsvinger

Telephone: +47 62 88 55 00
Telefax: +47 62 88 55 95
E-mail: Salg-abonnement@ssb.no

1. Introduction

The Clean Development Mechanism (CDM) has been introduced into the Kyoto Protocol for two main purposes. For the so-called Annex B countries, the purpose has been to reduce the overall costs of implementing their target for greenhouse gas (GHG) emissions.[1] This is accomplished by shifting some mitigation costs from high-cost Annex B countries to low-cost Non-Annex B countries. For the Non-Annex B countries, the purpose has been to secure sustainable development through financing of projects and programs that simultaneously reduce their GHG emissions and support development, particularly in the energy sector.

It is important to emphasize that the CDM is an offset mechanism, and does not intend to reduce global GHG emissions. Rather, when a party in an Annex B country pays a party in a Non-Annex B country to reduce its emissions, the Annex B party is credited for this emissions reduction. In other words, for every GHG emissions reduction achieved through a CDM project in Non-Annex B, the total cap on GHG emissions within Annex B is lifted accordingly.[2]

In this paper we argue that using the CDM will typically tend to increase global emissions. Several problematic issues have been discussed in relation to the CDM, such as defining the appropriate baseline (would the project have taken place anyway?), avoiding perverse incentives to inflate emissions (to achieve/sell more credits), and providing disincentives to introduce environmental policies in Non-Annex B countries. These problems have been widely discussed in previous literature, including Bohm (1994), Hagem (1996), Wirl et al (1998), Fischer (2005), Wara (2008), and Rosendahl and Strand (2009). This literature concludes that there is a significant risk of overestimating the emission reductions from several types of CDM projects; thus global GHG emissions increase as a consequence of these projects.

Our focus here is on a separate but related issue, namely (carbon) leakage, which has been less studied in relation to the CDM. When a CDM project reduces the consumption of fossil fuels in a Non-Annex B country, fossil fuel markets will be affected. As a consequence, fossil fuel consumption elsewhere in Non-Annex B may change. Such spillover effects are often referred to as (carbon) leakage. Although

---

[1] Annex B countries are higher-income countries with binding commitments for GHG emissions under the protocol. Non-Annex B countries are middle- and lower-income countries without such binding commitments.

[2] It could be argued that the overall commitment in the Kyoto Protocol would have been less stringent without the CDM, in which case the *existence* of this mechanism has contributed to reduced global emissions. In our paper we focus on the *use* of the CDM.

CDM projects are required to account for leakage, (indirect) market leakages are generally neglected (cf. Vöhringer et al., 2006).[3]

The story above is only half-way told, however. A CDM project increases the effective cap on emissions within Annex B. Thus, consumers in Annex B will typically consume more fossil fuels than without the CDM project. This will also affect fossil fuel markets, and may lead to higher prices of fossil fuels and thus, possibly, *negative* spillover effects in Non-Annex B. Any net leakage must occur in Non-Annex B, because total emissions in Annex B are given by the (increased) cap. The effect on global GHG emissions of a CDM project (or the sum of all CDM projects) depends on the sum of the two types of leakage in Non-Annex B.

Our paper studies analytically how leakage from CDM projects depends on different characteristics of the fossil fuel markets. We provide numerical examples to illustrate the possible size of carbon leakage. The analysis shows that the overall leakage effects depend highly on the global character of fossil fuel markets. If these markets are "close" to being globally unified with one single price per fuel, leakage tends to be small and of less concern. If (some) fossil fuel markets are more segregated, so that domestic consumers to some degree favour domestic over imported fuels (e.g., due to high transport costs), leakage will in most cases be positive and sometimes significant. We show that the size of leakage depends highly on demand and supply responsiveness, especially in Non-Annex B, but also on supply responsiveness in Annex B. In some cases, leakage could be negative. Still, we find that CDM projects in the energy sector most likely lead to significant and positive leakage, and thus to increased global GHG emissions.

This paper models leakage effects in fossil fuel markets only, and not in product markets. Note, however, that leakage may occur also through product markets, notably for energy-intensive products. A CDM project that reduces production of an energy-intensive product will likely raise the output price in that sector, inducing other firms to increase their outputs, and thus emissions. These other firms could be domestic firms (in the country where the CDM project is carried out), firms in Non-Annex B more generally, or even firms in Annex B (depending in particular on the degree of international competition).

The traditional understanding of leakage is related to the effects of unilateral environmental policy, and there exists a substantial literature on this issue, including both theoretical and empirical studies.

---

[3] Direct leakage effects, e.g., increased emissions associated with constructing a wind mill, are sometimes accounted for.

Considering first analytical work, Copeland and Taylor (2005) analyze leakage effects through trade in "dirty" goods, and distinguish between substitution and income effects from price changes on the world market.[4] Hoel (1996) considers differentiated carbon taxes versus other trade measures to counteract leakage. Effects of technological spillovers are examined by Golombek and Hoel (2004), Gerlagh and Kuik (2007) and Di Mario and van der Werf (2008). Babiker (2001) investigates how restrictions on capital mobility may affect leakage, whereas Eichner and Pethig (2009) look into dynamic behaviour by non-renewable resource owners. We however take this literature several steps further in new directions, by explicitly separating between regional fuel markets, and between (two) types of fossil fuels. In particular, in the "standard" model, with only one fuel and one global fuel market with a unified fuel price, we show that there is no leakage. For that reason, this "standard" model is not useful for studying the leakage issue. Our extended model, with some fuels not being fully global, then enables us to identify a variety of sources of (positive or negative) leakage.

Existing empirical studies have largely focused on leakage resulting from climate policies being pursued in OECD (or Annex B) countries but not in other (Non-Annex B) countries (cf., e.g. Babiker (2005), Demailly and Quirion (2006, 2008), Grubb and Neuhoff (2006), Houser et al (2008), Reinaud (2005)).[5] The assessed size of carbon leakage from unilateral climate policies varies substantially between studies. It is interesting to note that leakage from unilateral OECD policies will typically be highest if fossil fuel markets are global in character, because demand outside OECD is then more affected by demand reductions within OECD. As noted above, we show that leakage from CDM projects is highest if fossil fuel markets are more segregated. The reason for this disparity is that with unilateral OECD policy abatement activity and net leakage take place in different regions (OECD and Non-OECD, respectively), whereas with CDM projects both abatement activity and net leakage must take place in the same region (i.e., Non-Annex B where there is no cap on emissions).

Only a small number of empirical studies on leakage related to CDM, or offset mechanisms in general, currently exist. A study by Böhringer et al (2003), of CDM projects in the electricity sector in India,

---

[4] They also consider leakage through effects on other countries' environmental policies; this has been studied also e.g. by Hoel (1991).

[5] There is also a complementary literature on economic policy measures for reducing the problem of leakage, in particular the use of free allowances, border taxes or other trade-related instruments; see Ismer and Neuhoff (2004), Fischer and Fox (2009), Pauwelyn (2007).

indicates a rate of leakage of 50-60%, due to market repercussions in the rest of the economy.[6] The study does not consider the possibility of negative leakage effects from increased cap in Annex B, however. Bollen et al. (1999) and Kallbekken (2007) use global CGE models to analyze leakage from CDM, taking into account the effects of increased cap in Annex B. Bollen et al. find positive leakage effects caused by lower energy prices in Non-Annex B, while Kallbekken finds negative leakage effects. He finds negative leakage even when he only considers the emission reduction in the CDM host country, and not increased cap in Annex B and payment for the CDM credits. This result is driven by reduced output in the CDM host country, following higher prices of other goods than fossil fuels (e.g., electricity). None of these papers provides an analytical study of leakage from CDM projects.

Our discussion relates to the CDM, but our findings are relevant to offset mechanisms in general. Any project that reduces emissions through reduced use of fossil fuels will have an impact on fossil fuel consumption elsewhere. The exception is if the project reduces emissions from a (presumably unregulated) sector that is part of a national emissions cap.

In the next section we consider the case of one fossil fuel only, where domestically produced and imported fuels are imperfect substitutes. We look into different assumption about substitutability and trade between Annex B and Non-Annex B. A CDM project is here assumed to simply reduce consumption of fossil fuels in a Non-Annex B firm. Section 3 considers two different fossil fuels, with different characteristics with respect to global trade. Finally, in Section 4 we conclude.

2. Carbon leakage from international trade in fossil fuels[7]

Fossil fuels are traded in international markets, but fuel markets are not fully global with one single price for all consumers of the world (even when accounting for tax differences). For instance, import prices of coal differ significantly across countries (IEA, 2008), and most trade in coal occurs between countries in the same region.[8] This is partly due to relatively high transport costs for coal,[9] and partly

---

[6] A related study by Glomsrød and Taoyuan (2007) finds that investing in coal cleaning in China, which has a negative direct effect on carbon emissions, could lead to increased overall carbon emissions in China due to substantial rebound effects from efficiency gains in the power and transport sectors. Although coal cleaning is not a specific CDM project, it shows that reducing emissions through efficiency investments may have adverse rebound effects if not controlled by the CDM Executive Board.

[7] As our focus here is on leakage, we disregard the so-called additionality problem. That is, we assume that the emissions reductions from the CDM project would not have taken place without the CDM.

[8] International coal trade accounted for 16 percent of global coal consumption in 2007, and a majority of international trade takes place within Annex B or Non-Annex B (IEA, 2008; EIA, 2009).

[9] For instance, according to calculations presented in CERC (2006), ocean freight rates from Australia to India accounted for about 30 per cent of total import costs in the period 1999-2005, with an increasing trend. Over the last couple of years, freight rates have been very volatile due to the escalation and then plunge in energy prices.

due to different coal qualities. A small shock to the market will typically have strongest effects on prices and demand/supply close to the source of the shock. For instance, a CDM project that reduces consumption of coal from an installation in India will most likely have stronger effects on coal supply and demand in India than in Germany. The oil market can in contrast be characterized as being close to global, whereas gas markets are mostly regional due to significant transport costs, and relation-specific investments.[10]

International trade of a particular commodity (or class of commodities) is typically modelled by assuming that commodities from different regions are imperfect substitutes. For instance, domestically produced commodities are considered as imperfect substitutes with imported commodities, and commodities imported from different countries/regions are considered as imperfect substitutes for each other. This assumption is e.g. used (also for fossil fuels) in most global CGE models based on the GTAP database.[11] The respective substitution elasticities are often referred to as Armington elasticities (Armington, 1969).

We consider trade in fossil fuels between Annex B and Non-Annex B. In this section we consider only one (aggregate) fuel. In Section 3 we will analyze the effects of having more than one fuel (within a simpler model). We assume that fuels produced in Annex B and Non-Annex B are imperfect substitutes. Besides quality differences, this assumption can be motivated by considering trade between Annex B and Non-Annex B as an aggregate of bilateral trade between countries or regions throughout the world. If we consider coal, and a price reduction in South African coal export, some countries (in Annex B and Non-Annex B) may want to increase their coal import from South Africa. Other countries do not import coal from South Africa at all because of too high transport costs, and will therefore remain unaffected by the price reduction. Consequently, on an aggregate level, coal produced in Non-Annex B is an imperfect substitute for coal produced in Annex B, both for consumers in Annex B and for consumers in Non-Annex B. The size of the substitution elasticity as well as initial trade flows determine the degree of globalization of the fossil fuel market.

We consider a marginal CDM project that reduces the use of fossil fuels in a specific firm in Non-Annex B (B) by cdm_B units of carbon, and simultaneously increases the cap on Annex B (A) emissions

---

[10] Some interregional trade takes place also in the gas market, and this long-distance trade is expected to grow in the future (see e.g. Aune et al., 2009).

[11] The GTAP database (https://www.gtap.agecon.purdue.edu/default.asp) contains complete bilateral trade information. The GTAP CGE model is documented in Hertel (1997). Examples of energy- and climate-related analysis using the GTAP CGE model or other CGE models using the GTAP database are Hertel et al. (2009), Fischer and Fox (2009), Banse et al. (2008), Babiker (2005) and Böhringer and Lange (2005).

by cdm_B units. Our purpose is to examine the effects on global emissions, through changes in the fossil fuel market. We measure fossil fuel use in carbon units. Assume that Annex B countries as a group abide by the Kyoto Protocol so that their aggregate GHG emissions are exactly as required by the agreement, adjusted for possible offsets. We also assume that the cap on emissions in Annex B is implemented through a uniform price of carbon (τ_A). Market equilibrium before the CDM project is carried out is then given by equations (1) – (5) below.

(1) $$E_i = \sum_{j=A,B} C_{i,j} + cdm_i \qquad i = A, B$$

Equation (1) states that emissions in region i, E_i, equal the sum of consumption ($C_{i,j}$) in region i of fossil fuels produced in each of the two regions A and B, *plus* the emissions from the CDM project to be implemented (which is not included in $C_{i,j}$). Obviously, $cdm_A = 0$. Due do the binding cap on emissions in Annex B, we have $E_A = \widehat{E_A}$.

(2) $$S_i = S_i^0 \left(\frac{P_i}{P_i^0} \right)^{\gamma_i} = C_{A,i} + C_{B,i} + \alpha_i cdm_B \qquad i = A, B$$

Equation (2) is the requirement that total consumption of fuels produced in region i, also including a share α_i of the CDM project consumption, must equal supply in region i (S_i). Supply is an increasing function of its price (P_i), γ_i being the supply elasticity. Note that superscript 0 denotes baseline levels of the endogenous variables.

(3) $$C_{i,j} = C_{i,j}^0 \frac{TC_i}{TC_i^0} \left[\frac{PR_i}{PR_i^0} \frac{P_j^0 + \tau_i^0}{P_j + \tau_i} \right]^{\sigma_i} \qquad i, j = A, B$$

Equation (3) states that consumption in region i of fuels produced in region j increases with total consumption in region i (TC_i), and falls with the relative consumer price of fuels produced in region j ($P_j + \tau_i$), compared to the regional consumer price in region i (PR_i). The (Armington) substitution elasticity σ_i between fuels produced in Annex B and Non-Annex B influences on the effects of relative price changes. Note that the carbon tax is part of the consumer price of fossil fuels in region A, but is zero in region B (i.e., $\tau_B = 0$).

(4) $$\left[\left(\theta_i \frac{P_A+\tau_i}{P_A^0+\tau_i^0}\right)^{1-\sigma_i} + \left((1-\theta_i)\frac{P_B+\tau_i}{P_B^0+\tau_i^0}\right)^{1-\sigma_i}\right]^{\frac{1}{1-\sigma_i}} = \frac{PR_i}{PR_i^0} \qquad i = A, B$$

Equation (4) expresses the regional consumer price as a CES aggregate of the consumer prices of fuels produced in the two regions. θ_i denotes the initial market value shares of the domestically-produced fuel.

(5) $$TC_i = TC_i^0 \left[\frac{PR_i}{PR_i^0}\right]^{\delta_i} \qquad i = A, B$$

Finally, equation (5) is the demand function, where total consumption is a decreasing function of the regional consumer price, with δ_i being the demand elasticity.

Except for the inclusion of CDM and emissions, the model above is a standard trade model. We see that there are 12 equations and 12 endogenous variables (E_B, $C_{i,j}$, TC_i, P_i, PR_i, τ_A).

We will now examine the effects of removing cdm_B from the market *and at the same time* increasing the cap $\widehat{E_A}$ by cdm_B units. To simplify, let $cdm_B = 1$. Furthermore, we normalize all initial prices to 1, and total consumption in Annex B to 1 (thus, TC_B denotes total consumption in Non-Annex B relative to total consumption in Annex B). To simplify, we also assume that $\sigma_A = \sigma_B = \sigma$, which means that the rate of substitution between domestic and imported fuels is assumed to be identical in the two regions. Finally, we assume that $\theta_d \geq ½$ and $\alpha_B \geq ½$, i.e., import shares do not exceed 50%.[12]

Our main interest is in carbon leakage (L), i.e., how much fossil fuel consumption increases elsewhere, per unit reduction through the CDM project. The leakage rate is simply $L=\Sigma_s dS_s$, which again depends on how the two prices P_s change. We take the total differential of the equation system (1) – (5), and after some tedious calculations arrive at the following expression for the price effects:[13]

[12] This is consistent with overall net trade between Annex B and Non-Annex B for both oil, coal and natural gas.

[13] In the appendix we show the expression for Δ, which can be shown to be non-negative, and strictly positive except in very special cases.

(6) $$dP_A = \frac{1}{\Delta}(\theta_A + \alpha_B - 1)(\gamma_B(1-\theta_A) + \theta_B TC_B(\gamma_B - \delta_B))$$

(7) $$dP_B = -\frac{1}{\Delta}(\theta_A + \alpha_B - 1)(\gamma_A\theta_A + (1-\theta_B)TC_B(\gamma_A - \delta_B))$$

As long as θ_A > ½ or α_B> ½, from equations (6) and (7), the effects of the CDM project are to strictly increase the price of fossil fuels produced in Annex B, and strictly reduce the price of fossil fuels produced in Non-Annex B. It follows that fossil fuels output in Annex B increases, whereas output in Non-Annex B falls. The explanation is that consumption in Annex B increases when the cap is lifted, and demand for fuels produced in Annex B increases more than demand for fuels produced in Non-Annex B (and vice versa for the reduced consumption in Non-Annex B outside the CDM project).

The effects on carbon leakage can then be calculated as follows:

(8) $$\begin{aligned} &L = \gamma_A S_A^0 dP_A + \gamma_B S_B^0 dP_B = \\ &-\frac{1}{\Delta}\delta_B TC_B(\theta_A + \alpha_B - 1)\left[(\theta_A + \theta_B - 1)\gamma_B + \theta_A\theta_B(\gamma_A - \gamma_B) + \theta_B TC_B(1-\theta_B)(\gamma_A - \gamma_B)\right] \end{aligned}$$

The sign of this expression is in general ambiguous, and depends on the sign of the last (square) parenthesis. The other factors are jointly positive. The sign of the square parenthesis depends in particular on the relationship between the supply elasticities in Annex B and Non-Annex B. If the supply elasticity in Annex B is at least as high as that in Non-Annex B ($\gamma_A \geq \gamma_B$), L is non-negative and strictly positive unless $\gamma_A = \gamma_B$ and θ_d = ½, or $\theta_A = \alpha_B$ = ½. On the other hand, if γ_B is high compared to γ_A, and θ_d are not too close to one, leakage may in fact be negative. We state these findings in the following proposition.

Proposition 1:
In a fossil fuel market with imperfect substitution between fuels produced in Annex B and Non-Annex B, a CDM project will lead to non-negative carbon leakage if the supply elasticity in Annex B (γ_A) is at least as high as that in Non-Annex B (γ_B). Leakage is strictly positive if also import shares are less than one half (θ_A > ½ or θ_B, α_B > ½). *Carbon leakage* can *be strictly negative if* $\gamma_A < \gamma_B$ and *import shares are sufficiently large.*

It is of interest to consider a few special cases. First, consider the case where $\theta_d = \alpha_B$ =1, i.e., there is no trade in fossil fuels between Annex B and Non-Annex B. Note that there cannot be any (negative) leakage from Annex B in this case, simply because any net leakage must take place in Non-Annex B, and leakage from Annex B to Non-Annex B is not possible when the fossil fuel markets are separated. As shown in the Appendix, the leakage rate then reduces to the following simple expression:

(9) $$L = \frac{-\delta_B}{\gamma_B - \delta_B}$$

In this case carbon leakage is strictly positive and depends only on the relationship between the demand and supply elasticities in Non-Annex B. For instance, if the two elasticities have the same absolute values, the leakage rate is ½. Put otherwise, the net emission reduction is then exactly half the gross reduction from the project. If demand is more (less) elastic than supply, the leakage rate is higher (lower) than ½. Further, if the demand elasticity is close to zero while the supply elasticity is larger, leakage is insignificant. This could be the case if prices are regulated and the producers meet the demand of the consumers. On the other hand, if the supply elasticity is close to zero, the leakage rate is close to 100%, and so there is no net emission reduction resulting from the CDM project. This could be the case if production is regulated by the government.

Intuitively, the CDM project reduces local demand for the fossil fuel. In order to restore market equilibrium, either supply must decrease, demand from other users must increase, or (most likely) a combination of the two. With price-responsive supply and demand, the final outcome will be a combination with reduced supply, increased demand from other users, and lower price, entailing a positive carbon leakage.

Next, consider $\theta_A = \alpha_B = ½$, i.e., Annex B consumers import the same quantity as they buy from their domestic producers, and the same applies to the CDM firm. Then it follows straightforwardly from (8) that carbon leakage is exactly zero. The first-order effects of reduced consumption in Non-Annex B (i.e., from the CDM project) is in this special case exactly counteracted by increased consumption in Annex B (i.e., from lifting the cap on emissions). Thus, market equilibrium is maintained with no changes in prices, supply in the two regions or demand in Non-Annex B (outside the CDM project). Consequently, there is no net leakage of the CDM project.

If the substitution elasticity tends to infinity ($\sigma \to \infty$), it is easily seen that $\Delta \to \infty$, so that $L \to 0$ (cf. the Appendix). This is the case with a single unified fuels market for Annex B and Non-Annex B, with a single global fuel price. This case also implies zero carbon leakage. The explanation is similar to the above situation. From equations (6) and (7) we see that the fuel price must remain unchanged, which again follows because reduced consumption by the CDM project exactly matches the increased consumption in Annex B.

Although the special cases discussed above are not in themselves very realistic, they are useful as benchmark cases. Thus, we sum them up in the following corollary:

Corollary 1:

a) *If fossil fuels in Annex B and Non-Annex B are perfect substitutes in consumption ($\sigma \to \infty$) or the import shares equal 50% ($\theta_A = \alpha_B = ½$), then there is no carbon leakage from a CDM project.*

b) *If there is no trade in fossil fuels between Annex B and Non-Annex B ($\theta_d = 1$), then the carbon leakage rate only depends on elasticities in Non-Annex B, and equals* $-\delta_B/(\gamma_B-\delta_B) > 0$.

Econometric studies of price elasticities vary a lot, and it is difficult to conclude unambiguously whether demand or supply elasticities are greater in absolute values. The same ambiguity applies to elasticities in Annex B vs. Non-Annex B. In the special case of $\theta_d = 1$, we see straightforwardly from (9) that the leakage rate increases with the (absolute value of the) demand elasticity, and decreases with the supply elasticity (in Non-Annex B). In the general case, we first note that the demand elasticity in Annex B does not affect leakage at all (δ_A does not enter into (8)). The reason is that total emissions in Annex B are exogenously determined by the cap, and so δ_A only affects the size of τ_A, i.e., the tax needed to comply with the emissions cap.

In the Appendix we show how the leakage rate varies with the other elasticities. First, we find that the absolute value of the leakage rate increases strictly in the absolute value of the demand elasticity in Non-Annex B, i.e., $d|L|/d|\delta_B| > 0$ (except when $L = 0$ initially). Second, we find that $dL/d\gamma_B < 0$ and $dL/d\gamma_A > 0$ (except when $\theta_A = \alpha_B = ½$), i.e., carbon leakage decreases with the supply elasticity in Non-Annex B, but increases with the supply elasticity in Annex B. The explanation for the latter result is that a high supply elasticity in Annex B tends to reduce the negative leakage from less mitigation in Annex B. Third, if we multiply all supply and demand elasticities by the same factor $k > 1$, then the absolute value of the leakage rate increases (except in the special cases referred to in Corollary 1). In order to explain this, we have to consider the effects of changing the substitution elasticity, σ.

As stated in Corollary 1, there is no leakage in the limit when σ goes to infinity. It is also straightforward to show that the absolute value of the leakage rate is strictly decreasing in σ, cf. the Appendix (note that σ appears only in Δ in equation 8). A low σ means that a CDM project, mainly reducing consumption of fuel produced in Non-Annex B (assuming $\alpha_B > ½$), tends to reduce the price of fuel produced there relative to fuel produced in Annex B. Still, consumers in Annex B will not switch significantly towards fuel produced in Non-Annex B, e.g., because of transport costs. Thus, other consumers in Non-Annex B will tend to increase their consumption of domestically produced fuel, resulting in carbon leakage. If all supply, demand and substitution elasticities are multiplied by the same factor k, leakage is unchanged. The intuition is that when both producers and consumers become more price-responsive, also with respect to relative prices, the leakage rate is drawn in opposite directions, and the net effect is status quo. It follows from this that increasing only the demand and supply elasticities is equivalent to decreasing the substitution elasticities, which we have seen increases the absolute value of L.

The effects of changing the market shares θ_d are less straightforward, as θ_d occurs also in the numerator of equation (8). However, if we assume that $\theta_d = \alpha_B = \theta$ and that $\gamma_s = \gamma$ (which implies that leakage is strictly positive for $\theta > ½$), we show in the Appendix that the leakage rate is strictly increasing in θ. Thus, the more segregated the fossil fuel market is, the more carbon leakage will there be from a CDM project.

We sum up these findings in the following proposition:

Proposition 2:
In a fossil fuel market with only one fuel, and imperfect substitution between fuels produced in Annex B and Non-Annex B,

a) the carbon leakage of a CDM project increases with the supply elasticity in Annex B and decreases with the supply elasticity in Non-Annex B

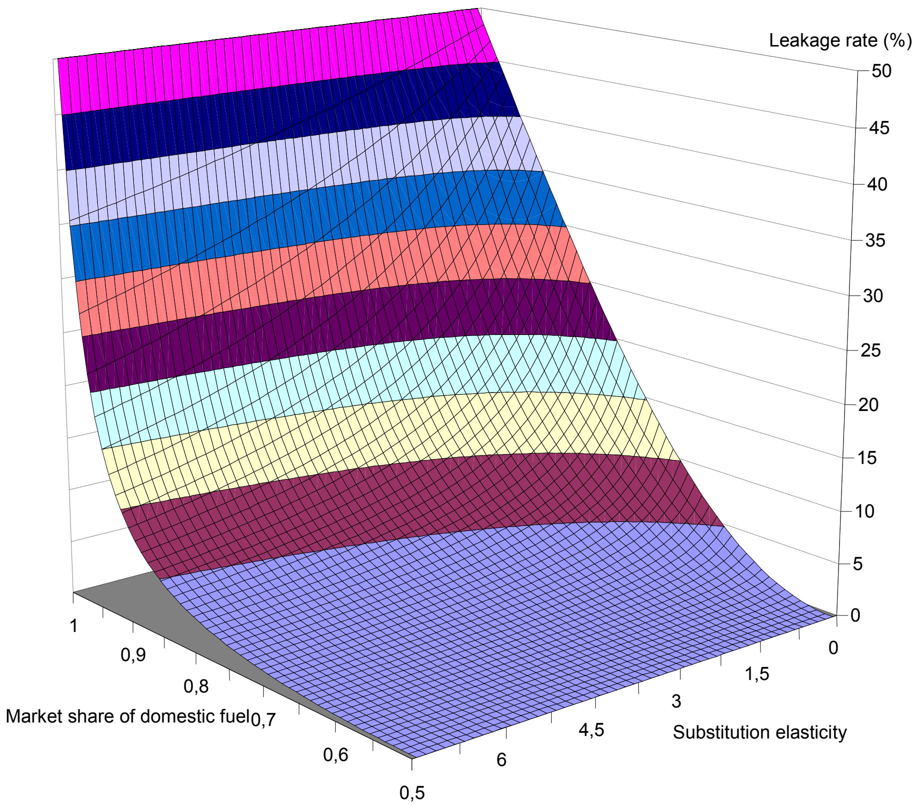
b) the absolute value of the carbon leakage increases with the demand elasticity in Non-Annex B, and decreases with the substitution elasticity

c) Given $\theta_d = \alpha_B = \theta$ and $\gamma_s = \gamma$, carbon leakage increases with the market shares of domestic suppliers.

Figure 1 exemplifies how θ and σ may affect the carbon leakage rate. In this case we have assumed that all supply and demand elasticities equal ½ (in absolute value). Then we know from (9) that $L = ½$

whenever $\theta = 1$, and, from Corollary 1, that $L = 0$ whenever $\theta = ½$. The figure also confirms the findings in Proposition 2 that L increases when σ falls or θ increases. Note that this result is the opposite of the outcome of unilateral climate policy in Annex B countries, in which case leakage increases with the substitution elasticity (see e.g. the scenarios in Babiker, 2005). As explained in the introduction, the reason for this disparity is that in the latter case abatement activity and net leakage take place in different regions (Annex B and Non-Annex B, respectively), whereas with CDM projects both abatement activity and net leakage take place in the same region (Non-Annex B).

Figure 1: Leakage rates for different values of σ and θ



In global CGE models based on GTAP (cf. footnote 11), a standard substitution elasticity between imported and domestically produced natural resources (including coal) is 2.8, and the substitution elasticity between imports from different countries are typically twice that level (i.e., 5.6). Econometric analysis in Hertel et al. (2004) finds quite similar estimate of the latter elasticity for coal (i.e., 6.1 with standard deviation 2.4). Given these elasticities, a reasonable estimate for the substitution elasticity between Annex B and Non-Annex B may be in the range 3-5.5.[14] Coal trade between Annex B and Non-Annex B constitutes about 5% of global coal production (IEA, 2008). Thus, if we for instance assume that $\theta = 0.95$ and $\sigma = 4.5$, then the leakage rate is 20%.

The model we have used is relevant if the CDM project simply reduces consumption of e.g. coal in one particular firm. Another typical CDM project is to replace coal with renewable resources as inputs into electric power production. As shown in Appendix D, this will tend to reduce the leakage rate somewhat. For instance, in the special case with no fossil fuel trade between Annex B and Non-Annex B ($\theta = 1$), and equal magnitude of supply and demand elasticities, the leakage rate is between 33% and 50%, compared to 50% in the model above (cf. equation 9). On the other hand, if the fossil-based plant is closed down and *not* replaced by a renewable plant, the leakage rate is between 50% and 75% (if all elasticities have the same absolute size).

The intuition here is the same as above. When a coal power plant is replaced by a renewable plant, demand for coal is reduced. Thus, the coal price declines, coal supply decreases, and coal demand outside the CDM project increases. On the other hand, electricity prices are unchanged (as a first order effect). However, some of the increased coal demand comes from other coal power producers, leading to increased electricity supply and subsequently lower prices of electricity. The carbon leakage rate depends on how much coal demand increases outside the CDM project relative to the reduction brought about by the CDM project itself.

As shown in Appendix D, numerical simulations suggest that the leakage rate now depends significantly on the supply elasticity of fossil fuel and the demand elasticity of fossil fuel from consumers outside the electricity market (given that its share of fossil fuels is significant). The elasticities in the electricity market are of lesser importance, which seems intuitive as the electricity price is only indirectly affected (because a new renewable power plant replaces the old fossil-based power plant). Moreover, the share of fossil fuels going to the power market is important for the leakage rate, whereas the share of fossil based power in the electricity market is less important. Again, this seems intuitive as the price effect in the electricity market is only indirect through the fossil fuel market.

[14] On the one hand, these substitution elasticities may seem low for coal, as coal is a fairly homogeneous product (despite quality differences). On the other hand, transport costs between Annex B and Non-Annex B typically account for a substantial fraction of wholesale prices for coal (cf. footnote 9), favouring regional producers.

3. Carbon leakage with one global and one regional fossil fuel

In this section we consider the effects of having two fossil fuels with different trade characteristics. We will make the extreme assumption that one fuel is traded only in regional markets ($j=R$) with no trade between Annex B and Non-Annex B markets, and the other is traded freely in a global market ($j=G$), with one common price. Moreover, we disregard any substitution possibilities between the two fossil fuels.[15] The purpose here is to investigate the effects of reducing emissions of a regionally traded fuel (cdm^R) vs. a globally traded fuel (cdm^G) through a CDM project. As before, we examine the effects on global emissions of undertaking an additional CDM project, assuming that the CDM project increases the cap on Annex B emissions equivalently: If a CDM project gives cdm^j credits, then the Annex B cap is increased by cdm^j units.

Following the model setup represented by equations (1) – (5), we assume that $\theta^R = 0$ and $\sigma^G \to \infty$. Market equilibria before the CDM project is carried out are then given by (both fossil fuels are measured in carbon units):

$$(10) \qquad \widehat{E_A} = C_A^R + C_A^G$$

$$(11) \qquad E_B = C_B^R + C_B^G + cdm^R + cdm^G$$

$$(12) \qquad \sum_{i=A,B} S_i^G = \sum_{i=A,B} \left(S_i^{G,0} \left(\frac{P^G}{P^{G,0}} \right)^{\gamma_i^G} \right) = \sum_{i=A,B} \left(C_i^{G,0} \left(\frac{P_i^R + \tau_i}{P_i^{R,0} + \tau_i^0} \right)^{\delta_i^R} \right) + cdm^G = \sum_{i=A,B} C_i^G + cdm^G$$

$$(13) \qquad S_i^R = S_i^{R,0} \left(\frac{P_i^R}{P_i^{R,0}} \right)^{\gamma_i^R} = C_i^{R,0} \left(\frac{P_i^R + \tau_i}{P_i^{R,0} + \tau_i^0} \right)^{\delta_i^R} + cdm^R = C_i^R + cdm^R \qquad i = A, B$$

We assume that either cdm^R or cdm^G is zero, and normalize the remaining cdm^j to one. We can easily see that the leakage rate is $L=(\Sigma_j dC^j_B)$, where dC^j_B depends on the price effects in Non-Annex B (remember that consumption changes in Annex B are exactly matched by consumption reductions in

[15] Substitution possibilities are important for coal versus gas (mainly in electricity production), but not so important for oil versus gas or coal (since oil is mainly a transportation fuel which gas and coal are not). Significant substitution possibilities would reduce the distinction between the globally traded and the regionally traded fuel.

the CDM project). By differentiating the equations above and solving for dP_B^R and dP^G we obtain (initial prices still being normalized to one):[16]

(14) $$dP_B^R = -\frac{1}{(\gamma_B^R - \delta_B^R)C_B^{R,0}} < 0 \qquad \text{(if } cdm^R = 1\text{)}$$

(15a) $$dP^G = \frac{1}{\Delta}\left[\alpha_A \delta_A^G (\gamma_A^R - \delta_A^R)\right] > 0 \qquad \text{(if } cdm^R = 1\text{)}$$

(15b) $$dP^G = -\frac{1}{\Delta}\frac{C_A^R}{C_A^G}\left[\gamma_A^R \delta_A^R\right] < 0 \qquad \text{(if } cdm^G = 1\text{)}$$

where

$$\Delta = \Big[C_A^R \delta_A^R \gamma_A^R \left(\beta_A \gamma_A^G + (1-\beta_A)\gamma_B^G - \alpha_A \delta_A^G - (1-\alpha_A)\delta_B^G\right) +$$
$$C^G \alpha_A \delta_A^G \left(\beta_A \gamma_A^G \gamma_A^R + (1-\beta_A)\gamma_A^R \gamma_B^G - (1-\alpha_A)\gamma_A^R \delta_B^G - \beta_A \delta_A^R \gamma_A^G - (1-\beta_A)\delta_A^R \gamma_B^G + (1-\alpha_A)\delta_A^R \delta_B^G\right)\Big] < 0$$

and α_A and β_A denote Annex B's market shares of demand and supply, respectively, in the global market.

The price effect for the regional fuel in Non-Annex B is clearly positive as long as the CDM project reduces consumption of this fuel. Moreover, equation (14) yields:

(16) $$dC_B^R = \frac{-\delta_B^R}{\gamma_B^R - \delta_B^R} \qquad \text{(if } cdm^R = 1\text{)}$$

which we recognize from equation (9) above.

From equations (15a-b) we see that the price of the globally traded fossil fuel decreases if the CDM project reduces the use of this fuel, and increases if the CDM project reduces use of the regional fossil fuel.

---

[16] In order to simplify the expressions somewhat, we assume from now on that the initial emissions tax in Annex B is small compared to the prices of fossil fuels. The main conclusions still hold if we relax this assumption.

The effects on carbon leakage can now be expressed in the following way:

(17a) $$L = \frac{-\delta_B^R}{(\gamma_B^R - \delta_B^R)} + \frac{C^G}{\Delta}\alpha_A(1-\alpha_A)\delta_A^G\delta_B^G(\gamma_A^R - \delta_A^R) \quad (\text{if } cdm^R = 1)$$

(17b) $$L = -\frac{1}{\Delta}C_A^R\frac{1}{\alpha_A}(1-\alpha_A)\gamma_A^R\delta_A^R\delta_B^G \quad (\text{if } cdm^G = 1)$$

In (17b), $L > 0$: a CDM project that reduces consumption of the global fossil fuel unambiguously increases global emissions. In (17a), however, the two terms have opposite signs, and we cannot immediately say which term is larger. Thus the impact on emissions of a CDM project that reduces consumption of the regional fossil fuel is ambiguous.

This result may seem surprising, given the findings for one fossil fuel in Section 2, where leakage was positive given no trade between Annex B and Non-Annex B ($\theta = 0$), and zero with one global fuel ($\sigma \to \infty$). Intuitively, when the cap in Annex B is raised due to the CDM project, the first-order effect is to increase consumption of *both* fossil fuels. However, since consumption of the global fossil fuel in Annex B increases less than the decreased energy use due to the CDM project, the global fossil fuel price falls. This leads to increased consumption of this fuel in the rest of Non-Annex B, explaining the leakage effect. Note that the regional market in Non-Annex B is unaffected in this case.

In order to say more about the effects of a CDM project for the regional fossil fuel, we need to combine the two terms in front in equation (17a). A sufficient but not necessary condition for positive leakage effect of a CDM project for the regional fossil fuel is then shown to be:

(18) $$\frac{\beta_A\gamma_A^G + (1-\beta_A)\gamma_B^G}{(1-\alpha_A)\delta_B^G} \geq \frac{\gamma_B^R}{\delta_B^R}$$

For instance, if the ratios of supply to demand elasticities are the same for the two fossil fuels in Non-Annex B, and Non-Annex B is *not* a net importer of the global fossil fuel, then the condition is fulfilled and leakage is strictly positive.

The intuition in this case is the following: When a CDM project takes place in a regional market, we can distinguish between the effects in this regional market and the effects elsewhere (due to the assumption that the regional market in Non-Annex B is not connected to other markets), cf. the two terms in equation (17a). In the regional Non-Annex B market we get positive leakage effects along the lines discussed before (e.g., in relation to equation (9)). Thus, if e.g. supply and demand elasticities are equal in absolute value, this leakage amounts to 50% of the CDM project. When the cap on Annex B emissions is increased, consumption of both fossil fuels increases here. This leads to *negative* leakage in Non-Annex B for the global fossil fuel. However, if the cap increase is e.g. equally divided between the two fuels, the increased consumption of the global fossil fuel in Annex B amounts to only half of the CDM project. Consequently, even if the leakage rate for this particular consumption were e.g. 50%, relative to the original CDM project, the negative leakage effects amount to merely 25%. Thus overall leakage is positive, and equals (50-25)% = 25% in this case.

Although equation (17a) in general indicates that positive leakage is more likely than negative leakage, one cannot rule out the possibility of negative leakage. This follows from the argument in the previous paragraph: If positive leakage effects in the regional market are small (due to either high supply elasticity or low demand elasticity), and the negative leakage effects in the global market are big, the overall result may be negative leakage.[17]

Table 1 below shows leakage rates, based on equations (17a) and (17b), for a CDM project reducing the use of either the regionally or the globally traded fossil fuel. As before, in the base case we assume that all demand and supply elasticities have the same absolute value (only relative elasticities matter for the leakage rates as multiplying all elasticities in equations (17a) and (17b) by a constant leaves L unchanged). We also assume equal market sizes and market shares in the base case.[18]

As seen from Table 1, in the base case the leakage rate is 30% when the CDM project reduces consumption of the regional fuel, and 20% when it reduces consumption of the global fuel. However, the table further shows that the leakage rate depends significantly on assumptions about elasticities and market shares/sizes.

[17] This may be seen from equation (17a) with either a sufficiently high supply elasticity (γ_B^R) or sufficiently low demand elasticity (δ_B^R) of the regional good.

[18] That is, demand in the global market equals combined demand in the two regional markets, which themselves are equal in size.

Table 1: Leakage rate with one globally and one regionally traded fossil fuel

	cdm^R	cdm^G
Base case	**30%**	**20%**
$\gamma_A^j = \delta_A^j = 2\gamma_B^j = 2\delta_B^j$ (Annex B elast. = 2 · Non-Annex B elast.)	36%	14%
$\delta_i^j = 2\gamma_i^j$ (Demand elasticities = 2 · Supply elasticities)	33%	22%
$\gamma_i^j = 2\delta_i^j$ (Supply elasticities = 2 · Demand elasticities)	22%	15%
$\gamma_i^G = \delta_i^G = 2\gamma_i^R = 2\delta_i^R$ (Elast. in glob. market = 2 · Elast. in reg. market)	25%	13%
$C^G = 2(C_A^R + C_B^R)$ (Global market size = 2 · Sum of regional market sizes)	25%	13%
$(\alpha_A C^G + C_A^R) = 2((1-\alpha_A)C^G + C_B^R)$ (Annex B cons. = 2 · Non-Annex B cons.)	36%	11%
"Oil and coal"[a]	31%	11%
"Fossil and non-fossil"[b]	-20%	20%

[a] Oil is the global fuel and coal the regional fuel. Market shares are 60/40 and 40/60 for respectively oil and coal demand in Annex B vs. Non-Annex B. Equal elasticities.

[b] Fossil is global and non-fossil is regional with no market response in Non-Annex B.

In the second-to-last row of Table 1 we assume that oil is the global fuel and coal the regional fuel, and have used approximate market shares/sizes from 2007.[19] A CDM project that reduces consumption of the regional fuel, coal, here has a leakage rate of 31%. In the last row we have assumed that regional demand in Non-Annex B is completely unresponsive to demand ($\delta_B^R = 0$). This could illustrate the effects of assuming global fossil fuel markets combined with mitigation of other greenhouse gases. If a CDM project reduces emissions of methane, other emissions in Non-Annex B are unaffected by this project. However, reduced mitigation in Annex B will have negative leakage effects in Non-Annex B, explaining the negative leakage effect in the table.

Above we concluded that the leakage rate could be negative when the CDM project reduces consumption of the regional fuel, whereas a CDM project that reduces consumption of the global fuel always gives positive leakage. Nevertheless, from Table 1, the leakage rate is highest in the former case in all scenarios listed except the last one. The intuition is that the first order leakage effect within Non-Annex B is lower when the market is global, as some of the market response takes place within Annex B (where total emissions are capped).

Finally, what if either both markets are regional or both markets are global? In the former case we get the same conclusion as with one regional fuel, cf. Section 2. If both markets are global (denoted *G1*

[19] There is of course some trading in coal between Annex B and Non-Annex B countries, but one cannot speak of one global coal market in the same way as for oil (mainly because of much higher transport costs relative to the value of the fuel). Still, this scenario should only be considered as illustrative.

and *G2*), leakage depends on the relative elasticities in the two markets. It can be shown that a CDM project that reduces consumption of fossil fuel *G1* has a positive leakage effect if and only if:[20]

$$(19) \qquad \frac{\beta_A^{G1}\gamma_A^{G1} + \beta_B^{G1}\gamma_B^{G1}}{\beta_A^{G2}\gamma_A^{G2} + \beta_B^{G2}\gamma_B^{G2}} < \frac{\alpha_B^{G1}\delta_B^{G1}}{\alpha_B^{G2}\delta_B^{G2}}$$

We see immediately that if the two markets are equal, there is no leakage (as with only one market). More generally, leakage is positive (negative) if the CDM project takes place in the market with the less (more) elastic global supply and more (less) elastic demand in Non-Annex B The explanation is as follows: The first-order effect of a CDM project in market *G1* is to reduce both global consumption and the price in market *G1*, and to increase both global consumption and the price in market *G2* (because the increased cap in Annex B is 'divided' between the two markets). If supply in market *G1* is much *less* elastic than Non-Annex B demand, then leakage in this market is significant positive. The first-order effect of reduced demand will mainly be accompanied by increased demand elsewhere in Non-Annex B. If supply in market *G2* is much *more* elastic than Non-Annex B demand, then there will be little negative leakage in this market. The first order effect of increased demand in Annex B is then accompanied by increased supply and only small demand reduction in Non-Annex B. Thus, overall leakage is positive.

4. Conclusions

The analysis above suggests that the CDM is likely to be accompanied by carbon leakage in Non-Annex B countries. As a result, global carbon emissions are likely to increase, given that the emissions quota for Annex B is raised by an amount equal to the primary emissions reduction resulting from CDM projects.

The analysis shows that an important question is to what degree fossil fuel markets are global, and to what degree price signals disperse in the market. This varies by fuel, depending not least on their transport costs. One extreme here is the oil market, which is basically global with a more or less uniform price across countries. Gas markets are by contrast much more divided, due to significant transport costs and reliance on existing infrastructure, and to the greater need for long-term contracts in setting prices. The coal market, highly relevant with respect to CDM, is global in principle, but

[20] If the CDM project takes place for the other fossil fuel (*G2*), this inequality is turned around. Note that since total Annex B demand is capped, demand elasticities in Annex B affect the *size* of the leakage, but not its sign.

transport costs are higher than in the oil market. Thus, trade is more regional than in the oil market, and coal prices vary more across regions than in the oil market (this is also due to more quality differences). Consequently, market price effects due to reduced coal use resulting from a CDM project are typically strongest in the geographical proximity of the project site, and thus leakage effects will also tend to be strongest there.

Moreover, in practice end-users do not trade directly in the global fuel markets, and the difference between the end-user price and the world market price may vary, and respond to changes in domestic demand and supply, at least in the short to medium term. Thus, a given reduction in domestic consumption will likely reduce the market price by more in the domestic retail market than in the international market (in the short- to medium term). A disproportionate share of the leakage will then occur domestically.

What if anything can be done to affect, and correct for, the degree of leakage when awarding credits for emissions reductions from CDM projects? One basic difficulty is that the leakage effect of a specific project is empirically elusive. It cannot readily be observed as it is scattered among many economic agents, each of whom increases its emissions due to market equilibrium effects, in regional and/or global markets, and for both energy and final goods. A further complicating factor is that any particular incidence of leakage typically cannot be attributed to any one particular CDM project; leakage is an overall market phenomenon. A correct assessment of leakage effects requires a complete understanding of the structure of fossil fuels markets, which is almost by definition controversial. Better empirical work, in particular to pin down key parameters, should enable a more precise assessment of leakage effects for individual CDM projects, and thus the degree to which they should be credited.

Other well-known problems with the effectiveness of CDM to deliver global GHG emissions reductions, such as lack of additionality, and baseline manipulation, can in principle be eliminated or at least reduced through appropriate strategies or policies directed at individual CDM projects or CDM as a mechanism. For leakage, this is more difficult. Leakage rather needs to be identified and quantified through model calculations (we will argue, through procedures discussed in this paper). Emissions reduction credits can then be awarded in accordance with the (model based) calculated net emissions effects.

An important practical question is whether such lack of effectiveness of CDM should be assigned on a general basis (say, with a 20% reduction in awarded emissions quotas, relative to the "statutory" emissions reductions),[21] or rather calculated on an individual or sectoral basis (cf. Vöhringer et al., 2006). In either case, we will argue, analyses such as that undertaken here, with follow-ups, should form the basis for quota allocations. In addition to such analytical work, it is then crucial that key parameters that enter our formulas be identified and estimated. While some of these parameters, including market shares of different fuels in different markets and their carbon emissions, are relatively easy to find, others, such as demand and supply elasticities and elasticities of substitution between different fuels, are much harder to assess precisely. Identifying such parameters with maximum precision will then be helpful for future assessment of the CDM and its impact on global GHG emissions.

We finally need to stress that much of the basic modelling of leakage from CDM projects still remains. In particular, we have not studied leakage in the form of relocation of industrial activity through product market effects. This, and the topics mentioned above, should all be highly prioritized research topics to which we intend to contribute.

[21] Interestingly, in The American Clean Energy and Security Act, passed by the U.S. House of Representatives June 2009, and including inter alia a cap-and-trade system for U.S., one international offset will be transferred into 0.8 allowances from 2018 (House of Representatives, 2009, pp. 740-743). That is, awarded emission quotas from CDM projects will be reduced by 20%.

References

Armington, P. (1969), A Theory of Demand for Products Distinguished by Place of Production, *International Monetary Fund Staff Papers* **16**, 159-78.

Aune, F.R., K.E. Rosendahl and E. Sagen (2009), Globalisation of natural gas markets – effects on prices and trade patterns, *The Energy Journal* 30 (Special Issue "World Natural Gas Markets and Trade: A Multi-Modeling Perspective"), 39-54.

Babiker, M.H. (2001), Subglobal climate-change actions and carbon leakage: the implication of international capital flows, *Energy Economics* 23, 121-139.

Babiker, M.H. (2005), Climate change policy, market structure, and carbon leakage, *Journal of International Economics* 65, 421–445.

Banse, M., H. van Meijl, A. Tabeau and G. Woltjer (2008), Will EU Biofuel Policies affect Global Agricultural Markets? *European Review of Agricultural Economics* 35, 117-141.

Bohm, P. (1994), On the Feasibility of Joint Implementation of Carbon Emissions Reductions, in A. Amano, B. Fisher, M. Kuroda, and T. Nishioka (eds.): *Climate Change: Policy Instruments and Their Implications*. Proceedings of the Tsukuba Workshop of IPCC Working Group III, pp. 181-198.

Bollen, J., A. Gielen and H. Timmer (1999), Clubs, ceilings and CDM: Macroeconomics of compliance with the Kyoto Protocol, *The Energy Journal* 20 (Special Issue: The Costs of the Kyoto Protocol: A Multi-Model Evaluation), 177–206.

Böhringer, C., K. Konrad and A. Löschel (2003), Carbon Taxes and Joint Implementation. An Applied General Equilibrium Analysis for Germany and India, *Environmental and Resource Economics* 24, 49-76.

Böhringer, C. and A. Lange (2005): Economic Implications of Alternative Allocation Schemes for Emission Allowances, *Scandinavian Journal of Economics* 107, 563–581.

CERC (2006), Explanation for escalation rates for escalable components in imported coal and captive coal mine based thermal power projects, Consultant's report for the Central Electricity Regulatory Commission, New Delhi, September 2006.
http://www.cercind.gov.in/29092006/Consultant_s_Report.pdf

Copeland, B.R. and M.S. Taylor (2005), Free trade and global warming: a trade theory view of the Kyoto Protocol, *Journal of Environmental Economics and Management* 49, 205–234.

Demailly, D. and P. Quirion (2006), CO_2 Abatement, Competitiveness and Leakage in the European Cement Industry Under the EU ETS: Grandfathering Versus Output-Based Allocation, *Climate Policy* 6, 93-113.

Demailly, D. and P. Quirion (2008), European Emission Trading Scheme and Competitiveness: A Case Study on the Iron and Steel Industry, *Energy Economics* 30, 2009-2034.

Di Mario, C. and E. van der Werf (2008), Carbon leakage revisited: unilateral climate policy with directed technical change, *Environmental and Resource Economics* 39, 55–74.

Eichner, T. and R. Pethig (2009), Carbon Leakage, the Green Paradox and Perfect Future Markets, CESifo Working Paper No. 2542.

EIA (Energy Information Administration) (2009), *International Energy Outlook 2009*, DOE/EIA-0484(2009), May 2009. Washington, DC: EIA.
http://www.eia.doe.gov/oiaf/ieo/index.html

Fischer, C. (2005), Project-based Mechanisms for Emissions Reductions: Balancing Trade-offs with Baselines, *Energy Policy* 33, 1807-1823.

Fischer, C. and A.K. Fox (2009), Comparing Policies to Combat Emissions Leakage, Resources for the Future Discussion Paper, 09-02.

Fudenberg, D. and J. Tirole (1992), *Game Theory*, Cambridge, MA: MIT Press.

Gerlagh, R. and O. Kuik (2007), Carbon Leakage with International Technology Spillovers, Nota Di Lavoro 33.2007, Fondazione Eni Enrico Mattei (FEEM).

Glomsrød, S. and W. Taoyuan (2005): Coal cleaning: a viable strategy for reduced carbon emissions and improved environment in China? *Energy Policy* **33**, 525–542.

Golombek, R. and M. Hoel (2004), Unilateral emission reductions and cross-country technology spillovers, *Advances in Economic Analysis and Policy* 4(2), article 3.

Grubb, M. and K. Neuhoff (2006), Allocation and Competitiveness in the EU Emkissions Trading Scheme: Policy Overview, *Climate Policy* 6, 137-160.

Hagem, C. (1996), Joint Implementation Under Asymmetric Information and Strategic Behavior, *Environmental and Resource Economics* 8, 431-447.

Hertel, T.W. (ed.) (1997), *Global Trade Analysis: Modeling and Applications*, Port Chester, NY: Cambridge University Press.

Hertel, T.W., D. Hummels, M. Ivanic and R. Keeney (2004), How Confident Can We Be in CGE-Based Assessments of Free Trade Agreements? GTAP Working Paper No. 26, Revised Version March 2004.

Hertel, T.W., A.A. Golub, A.D. Jones, M. O'Hare, R.J. Plevin and D.M. Kammen (2009): Global Land Use and Greenhouse Gas Emissions Impacts of U.S. Maize Ethanol: The Role of Market-Mediated Responses, GTAP Working Paper No. 55.

Hoel, M. (1991), Global environmental problems: the effects of unilateral actions taken by one country, *Journal of Environmental Economics and Management* 20, 55–70.

Hoel, M. (1996), Should a carbon tax be differentiated across sectors? *Journal of Public Economics* 59, 17-32.

House of Representatives (2009), The American Clean Energy and Security Act (H.R. 2454), Bill Text as Passed by House of Representatives.
http://energycommerce.house.gov/Press_111/20090701/hr2454_house.pdf

Houser, T., R. Bradley, B. Childes, J. Werksman and R. Heilmayr (2008), *Lelveling the Carbon Playing Field: International Competition and US Climate Policy Design,* Washington DC: Peterson Institute.

IEA (International Energy Agency) (2008), *Coal Information 2008*. Paris: OECD/IEA.

Ismer, R. and K. Neuhoff (2004), Border Tax Adjustments: A Feasible Way to Address Non-participation in Emissions Trading, CMI Working Paper no 36, University of Cambridge.

Kallbekken, S. (2007), Why the CDM will reduce carbon leakage, *Climate Policy* 7, 197–211.

Pauwelyn, J. (2007), US Federal Climate Policy and Competitiveness Concerns: The Limits and Options of International Trade Law, Working Paper 07-02, Nicholas Institute for Environmental Policy Solutions, Duke University.

Reinaud, J. (2005), Industrial Competitiveness Under the European Union Emissions Trading Scheme, IEA Information paper. Paris: International Energy Agency.

Rosendahl, K.E. and J. Strand (2009), Simple Model Frameworks for Explaining Inefficiency of the Clean Development Mechanism, Policy Research Working Paper WPS 4931, The World Bank.

Vöhringer, F., T. Kuosmanen and R. Dellink (2006), How to attribute market leakage to CDM projects, *Climate Policy* 5, 503–516.

Wara, M.W. (2008), Measuring the Clean Development Mechanism's Performance and Potential, *UCLA Law Review* 55, 1759-1803.

Wirl, F., C. Huber and I.O. Walker (1998), Joint Implementation: Strategic Reactions and Possible Remedies, *Environmental and Resource Economics* 12, 203-224.

Appendix

A. Expression for Δ in equations (6) – (8)

The expression for Δ is given by:

(A1) $$\Delta = \Phi + \Gamma TC_B + \Psi (TC_B)^2$$

where

$$\Phi = \gamma_A \gamma_B \left(\theta_A - \theta_A^2\right) + \sigma \gamma_A \tau_A \left(\theta_A^2 - \theta_A^3\right) + \sigma \gamma_B \tau_A \left(\theta_A^3 - 2\theta_A^2 + \theta_A\right)$$

$$\begin{aligned}\Gamma = {} & \gamma_A \gamma_B \left(1 - \theta_A - \theta_B + 2\theta_A \theta_B\right) + \gamma_B \delta_B \left(\theta_A - 1 + 2\theta_B - \theta_B^2 - 2\theta_A \theta_B + \theta_A \theta_B^2\right) + \gamma_A \delta_B \left(-\theta_A \theta_B^2\right) \\ & + \sigma \gamma_B \left(\theta_B - \theta_B^2 - \theta_A \theta_B + \theta_A \theta_B^2 + \tau_A \theta_A \theta_B - \tau_A \theta_A^2 \theta_B\right) + \sigma \delta_B \left(\tau_A \theta_A^2 - \tau_A \theta_A\right) \\ & + \sigma \gamma_A \left(\theta_A \theta_B - \theta_A \theta_B^2 + \tau_A \theta_A - \tau_A \theta_A^2 - \tau_A \theta_A \theta_B + \tau_A \theta_A^2 \theta_B\right)\end{aligned}$$

$$\begin{aligned}\Psi = {} & \gamma_A \gamma_B \left(\theta_B - \theta_B^2\right) + \gamma_A \delta_B \left(\theta_B^3 - \theta_B^2\right) + \gamma_B \delta_B \left(2\theta_B^2 - \theta_B^3 - \theta_B\right) \\ & + \sigma \gamma_A \left(\theta_B^3 - 2\theta_B^2 + \theta_B\right) + \sigma \gamma_B \left(\theta_B^2 - \theta_B^3\right) + \sigma \delta_B \left(\theta_B^2 - \theta_B\right)\end{aligned}$$

We see that all the terms in Φ, Γ and Ψ are non-negative. Moreover, unless $\theta_A = \theta_B = 1$ *and* either $\gamma_A = 0$ or $\gamma_B = \delta_B = 0$, or unless $\gamma_A = \gamma_B = \delta_B = 0$, some of the terms are strictly positive. Thus, we conclude that Δ is non-negative, and strictly positive except in very special cases.

B. Proof of Corollary 1

When $\theta_A = \theta_B = 1$, Δ reduces to $\Delta = \left(\gamma_A \gamma_B - \gamma_A \delta_B\right) TC_B$. Equation (9) can then be found by inserting for Δ in (8) (using also $\alpha_B = 1$):

(A2) $$L = -\frac{1}{\left(\gamma_A \gamma_B - \gamma_A \delta_B\right) TC_B} \delta_B TC_B \left[\gamma_B + \left(\gamma_A - \gamma_B\right)\right] = \frac{-\delta_B}{\gamma_B - \delta_B}$$

When $\sigma \to \infty$, it is straightforward to see that several terms in (A1) become infinitely large. Thus, we must have $\Delta \to \infty$.

C. Proof of Proposition 2

First, let us differentiate with respect to δ_B. L can then be expressed as (see (8) and (A1)):

$$\text{(A3)} \qquad L = -\frac{\delta_B K_1}{K_2 - K_3 \delta_B}$$

where K_2, $K_3 > 0$ (except in special cases where K_2, $K_3 \geq 0$) and K_1 has the same sign as L. Then we find that:

$$\text{(A4)} \qquad \frac{dL}{d\delta_B} = -\frac{K_1 \left(K_2 - K_3 \delta_B\right) - K_1 \delta_B}{\left(K_2 - K_3 \delta_B\right)^2} = -K_1 \frac{K_2 - \delta_B \left(K_3 + 1\right)}{\left(K_2 - K_3 \delta_B\right)^2},$$

which has the opposite sign of K_1 and thus of L. Hence, $d|L|/d|\delta_B| > 0$, except when $L = 0$ initially.

Second, let us differentiate with respect to γ_A. L can then be expressed as:

$$\text{(A5)} \qquad L = -\frac{L_1 - L_2 \gamma_A}{L_3 + L_4 \gamma_A}$$

where $L_i > 0$ (except in special cases where $L_i \geq 0$). Then it is straightforward to see that L strictly increases when γ_A increases. Hence, $dL/d\,\gamma_A > 0$.

Third, let us differentiate with respect to γ_B. L can then be expressed as:

$$\text{(A6)} \qquad L = -\frac{M_1 \gamma_B - M_2}{M_3 + M_4 \gamma_B} = -\frac{M_1 - \left(M_2 / \gamma_B\right)}{\left(M_3 / \gamma_B\right) + M_4}$$

where $M_i > 0$ (except in special cases where $M_i \geq 0$). Again, it is straightforward to see that L strictly decreases when γ_B increases. Hence, $dL/d\,\gamma_B < 0$.

Fourth, let us multiply all supply and demand elasticities by a factor k. Then we can write:

(A7) $$L = -\frac{k^2 N_1}{k^2 N_2 + kN_3} = -\frac{N_1}{N_2 + \left(N_3 / k\right)}$$

where N_2, $N_3 > 0$ (except in special cases where N_2, $N_3 \geq 0$) and N_1 has the same sign as L. We see that by increasing k, L strictly increases in absolute value. Thus, multiplying supply and demand elasticities by a factor $k > 1$ strictly increases the absolute value of L.

Fifth, let us differentiate with respect to σ. L can then be expressed as:

(A8) $$L = -\frac{O_1}{O_2 + O_3\sigma}$$

where O_2, $O_3 > 0$ (except in special cases where O_2, $O_3 \geq 0$) and O_1 has the same sign as L. Again, it is straightforward to see that the absolute value of L strictly decreases when σ increases, i.e., $d|L|/d\sigma < 0$.

Finally, let us differentiate with respect to θ, when we assume $\theta_d = \alpha_B = \theta$ and $\gamma_s = \gamma$. The expression for L then simplifies to:

(A9) $$L = -\frac{1}{\Delta}\delta_B TC_B \left(2\theta - 1\right)^2 \gamma$$

with

$$\Delta = \Phi + \Gamma TC_B + \Psi (TC_B)^2$$

$$\Phi = \gamma^2\left(\theta - \theta^2\right) + \sigma\gamma\tau_A\left(\theta - \theta^2\right)$$

$$\Gamma = \gamma^2\left(1 - 2\theta + 2\theta^2\right) + \gamma\delta_B\left(-1 + 3\theta - 3\theta^2\right) + \sigma\gamma\left(1 + \tau_A\right)\left(\theta - \theta^2\right) + \sigma\delta_B\tau_A\left(\theta^2 - \theta\right)$$

$$\Psi = \gamma^2\left(\theta - \theta^2\right) + \gamma\delta_B\left(\theta^2 - \theta\right) + \sigma\gamma\left(\theta - \theta^2\right) + \sigma\delta_B\left(\theta^2 - \theta\right)$$

Then we have:

(A10)
$$\frac{dL}{d\theta} = -\delta_B \gamma TC_B \frac{1}{\Delta^2}\left[4(2\theta-1)\Delta - (2\theta-1)^2 \frac{d\Delta}{d\theta}\right]$$
$$= \delta_B \gamma TC_B \frac{1}{\Delta^2}(1-2\theta)\left[4\Delta + (1-2\theta)\frac{d\Delta}{d\theta}\right]$$

$\frac{d\Delta}{d\theta}$ can be expressed as:

(A11)
$$\frac{d\Delta}{d\theta} = \gamma^2(1-2\theta)(1-TC_B)^2 + \sigma\gamma(1-2\theta)\left(\tau_A + (1+\tau_A)TC_B + (TC_B)^2\right)$$
$$-\sigma\delta_B TC_B(1-2\theta)(\tau_A + TC_B) - \gamma\delta_B TC_B(1-2\theta)(TC_B - 3)$$

All terms in (A11) except the last one are negative, and the sum of these three terms is strictly negative unless $\theta = ½$. We know from before that all terms in Δ are non-negative. Thus, let us focus on the terms inside the square parenthesis of (A10) that include $\gamma\delta_B$, knowing that the sum of the remaining terms (denoted Λ) must be strictly positive (unless $\theta = ½$). Equation (A10) then becomes:

(A12)

$$\frac{dL}{d\theta} = \delta_B \gamma TC_B \frac{1}{\Delta^2}(1-2\theta)$$
$$\left[\Lambda + \gamma\delta_B\left(4\left(TC_B\left(-1+3\theta-3\theta^2\right) + (TC_B)^2\left(\theta^2-\theta\right)\right) - (1-2\theta)TC_B(1-2\theta)(TC_B-3)\right)\right]$$
$$= \delta_B \gamma TC_B \frac{1}{\Delta^2}(1-2\theta)\left[\Lambda + \gamma\delta_B\left(-TC_B - (TC_B)^2\right)\right]$$

which is strictly positive for $\theta > ½$. We know from before that $L = 0$ for $\theta = ½$, and $L > 0$ for $\theta > ½$. Hence, we have shown that L is strictly increasing in θ (given the assumptions above).

D. Leakage from replacing fossil fuels with renewables

Here we consider a CDM project that replaces coal with renewable resources as inputs into electric power production, and examine how this may affect the leakage rate. To simplify we assume $\theta = 1$, so that the fossil fuel markets in Annex B and Non-Annex B are completely separated. Although this is unrealistic, such an analysis will indicate how the leakage rate is affected by replacing fossil fuels by an otherwise unprofitable substitute.

Consider an electricity market in Non-Annex B with both fossil and renewable plants. Equilibrium in the electricity market before implementing the CDM project can then be expressed as:

$$\text{(A13)} \qquad S_B^E \equiv S_B^{FE,0}\left(\frac{P_B^E}{P_B^{E,0}}\right)^{\gamma^{FE}}\left(\frac{P_B^{F,0}}{P_B^F}\right)^{\delta^{FE}} + cdm_B + S_B^{RE,0}\left(\frac{P_B^E}{P_B^{E,0}}\right)^{\gamma^{RE}} = C_B^{E,0}\left(\frac{P_B^E}{P_B^{E,0}}\right)^{\delta^E} \equiv C_B^E$$

where S^{FE} denotes fossil-based electricity production, S^{RE} renewable electricity production, and C^E total electricity consumption. P^F and P^E denote prices of fossil fuel and electricity, respectively (there is no need to distinguish between consumer and producer prices here). cdm_B denotes (as before) production from a specific fossil based power plant which can be replaced by a renewable plant through a CDM project.

Equilibrium in the fossil fuel market can be expressed as:[22]

$$\text{(A14)} \qquad S_B^F \equiv S_B^{F,0}\left(\frac{P_B^F}{P_B^{F,0}}\right)^{\gamma^F} = S_B^{FE,0}\left(\frac{P_B^E}{P_B^{E,0}}\right)^{\gamma^{FE}}\left(\frac{P_B^F}{P_B^{F,0}}\right)^{\delta^{FE}} + cdm_B + C_B^{F,0}\left(\frac{P_B^F}{P_B^{F,0}}\right)^{\delta^F} \equiv TC_B^F$$

S^F denotes fossil fuel production, whereas C^F denotes consumption of fossil fuels outside the electricity market.

When the CDM project is implemented, cdm_B will be reduced in equation (A14) but not in equation (A13) as it is replaced by a corresponding renewable plant. Still, the price of fossil fuel will change, and this will also affect the electricity market indirectly.

Normalizing cdm_B to one, the leakage rate now equals $L = 1 + dS_B^F$ (remember that the cap on emissions in Annex B is lifted by one unit, so if emissions in Non-Annex B (S_B^F) are reduced by less than one unit, leakage is positive). Differentiating equations (A13) and (A14), we obtain:

[22] We normalize units so that conversion rates between fossil fuel and electricity can be ignored. Conversion rates are assumed to be equal across plants.

(A15)

$$L = \frac{\left(\delta^{E} - (1-\alpha)\gamma^{RE}\right)\left(\frac{\alpha}{\alpha+\beta}\delta^{FE} + \frac{\beta}{\alpha+\beta}\delta^{F}\right) - \alpha\frac{\beta}{\alpha+\beta}\gamma^{FE}\delta^{F}}{\left(\delta^{E} - (1-\alpha)\gamma^{RE}\right)\left(\frac{\alpha}{\alpha+\beta}\delta^{FE} + \frac{\beta}{\alpha+\beta}\delta^{F}\right) - \alpha\frac{\beta}{\alpha+\beta}\gamma^{FE}\delta^{F} + \gamma^{F}\left(\alpha\gamma^{FE} + (1-\alpha)\gamma^{RE} - \delta^{E}\right)},$$

where α^{FE} and β^{FE} denote fossil-based electricity production's share in the power and fossil fuel markets, respectively.

It is easy to show that the leakage rate in equation (A15) is between 0 (if $\delta^{FE} = \delta^{F} = 0$) and 1 (if $\gamma^{F} = 0$),[23] but it is difficult to read more out of this equation without making further assumptions. If for instance all elasticities have the same absolute magnitude, it can easily be shown that the carbon leakage rate is between 33% and 50% (depending on market shares). It is also straightforward to show that if the closed fossil-based plant is *not* replaced by a renewable plant, the leakage rate is between 50% and 75% (if all elasticities have the same absolute magnitude).

Figure A1 illustrates the effects on the leakage rate of the different elasticities. As a benchmark we assume that all elasticities are equal to 0.5 in absolute value, and that the market shares are $\alpha^{FE} = 0.9$ and $\beta^{FE} = 0.5$. The leakage rate is then 0.44. In the figure, one elasticity is changed at a time (assuming that $|\delta^{FE}| = \gamma^{FE}$). The figure indicates that the two most important elasticities are the supply elasticity of fossil fuel (γ^{F}) and the demand elasticity of fossil fuel from consumers outside the electricity market (δ^{F}) (given that its share of fossil fuels is significant). The elasticities in the electricity market are of lesser importance.

The leakage rate decreases with the share of fossil based power in the electricity market (α^{FE}), and with the share of fossil going to the electricity market (β^{FE}). Simulations indicate that the size of α^{FE} is of less importance than the size of β^{FE}.

[23] All terms are non-negative, and the numerator is less than the denominator.

Figure A1. Leakage rates for different values of elasticities