

Carbon Leakage from the Clean Development Mechanism

Knut Einar Rosendahl^a and Jon Strand^{bc}

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. 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 also account for potential reverse or negative leakage effects in Non-Annex B from higher emissions cap in Annex B. Our conclusion is that net leakage typically is positive and sizeable, thus leading to an overall increase in global GHG emissions when CDM projects are undertaken. Leakage is greater when the different fossil fuel markets are more segregated.

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^a Corresponding author. Research Department, Statistics Norway. P.O. 8131 Dep., N-0033 Oslo, Norway. E-mail: ker@ssb.no. Phone: (+47) 21094954. Fax: (+47) 21094963

^b DECRG, Environment and Energy Team, World Bank. E-mail: jstrand1@worldbank.org

^c Department of Economics, University of Oslo

1. Introduction

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

It is important to emphasize that the CDM is an offset mechanism, and that its objective is not 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, this reduction is credited to the Annex B party. In other words, for every GHG emissions reduction achieved through a CDM project in Non-Annex B, the total cap on GHG emissions in Annex B is lifted accordingly.²

In this paper we argue that energy-related CDM projects typically tend to increase global GHG emissions. Several problematic issues have been discussed in relation to the CDM.³ Our

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.

³ These issues include defining the appropriate baseline, avoiding perverse incentives to inflate emissions, and providing disincentives to introduce environmental policies in Non-Annex B countries. The issues have been widely discussed in previous literature, including Fischer (2005), Wara (2008), Strand (2011), and Rosendahl

focus is on leakage, which has been less studied in relation to the CDM. If 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 CDM projects are required to account for leakage, market leakage is generally neglected (cf. Vöhringer et al., 2006).⁴ Hence, global GHG emissions may increase as a consequence of these projects.

The story above is only half-way told, however. A CDM project increases the effective cap on Annex B emissions. Thus, given a binding cap, Annex B consumers will buy more fossil fuels than without the CDM project. This also affects fossil fuel markets: It may lead to higher fuel prices and thus, possibly, *negative* spillover effects in Non-Annex B. Any net leakage must occur in Non-Annex B, as total emissions in Annex B are given by the (increased) cap. The effect on global GHG emissions of a CDM project (or several projects) depends on the sum of the two types of leakage. If global emissions increase (decrease) as a result of the CDM project *combined with* the higher Annex B cap, we will call this positive (negative) leakage.

Our paper studies analytically how carbon leakage from energy-related CDM projects depends on different characteristics of the fossil fuel markets. We provide numerical examples to illustrate possible magnitudes of 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

and Strand (2009a) (the latter study also includes a previous version of the analysis in the present paper). This literature concludes that there is a significant risk of overestimating emission reductions from CDM projects.

⁴ Direct leakage effects, e.g., associated with constructing a wind mill, are sometimes accounted for.

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 is highly dependent 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.⁵

The traditional understanding of leakage is related to unilateral environmental policy, with a substantial literature on this issue. Considering analytical work, Copeland and Taylor (2005) analyze leakage effects through trade in “dirty” goods, whereas 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 Maria 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 take this literature in new directions, by explicitly distinguishing between regional fuel markets, and between two types of fossil fuels. In particular, in the “standard” model with only one global fossil fuel market with a unified price, we show that there is no leakage. Thus, this “standard” model is not useful for studying the leakage issue. Our extended model, with some fuels not being fully global, enables us to identify a variety of sources of leakage.

Empirical studies have largely focused on leakage resulting from climate policies being pursued only in Annex B (or OECD) countries (cf., e.g. Babiker (2005) and Houser et al

⁵ This paper models leakage effects in fossil fuel markets only. Leakage may however also occur through product markets, notably for energy-intensive goods, if a CDM project leads to lower output of these products.

(2008)).⁶ The assessed magnitude of carbon leakage from unilateral climate policies varies substantially across studies. Interestingly, leakage from unilateral Annex B policies tends to be highest if fossil fuel markets are global, because demand outside of the Annex B is then more affected by demand reductions within Annex B. As noted above, we show that leakage from CDM projects is higher when fossil fuel markets are more segregated. The reason is that with unilateral Annex B policy, 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 must take place in Non-Annex B only (where there is no cap on emissions).

Few empirical studies on leakage related to the CDM, or to offset mechanisms in general, currently exist. A study by Böhringer et al (2003), of CDM projects in the electricity sector in India, indicates that leakage amounts to 50-60% of the direct emissions reduction.⁷ The study does not consider the effects of an increased cap in Annex B, however. Bollen et al. (1999) and Kallbekken (2007) use global CGE models to analyze leakage from the 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 driven by reduced output in the CDM host country. None of these papers provides an analytical study of leakage from CDM projects such as in the current paper. Murray et al. (2004) estimate leakage from carbon sequestration projects, using an intertemporal simulation model for agricultural and forestry sectors, and find that leakage through inter alia the timber

⁶ 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 export rebates; see e.g. Böhringer et al. (2010).

⁷ A related study by Glomsrød and Taoyuan (2007) finds that investing in coal cleaning in China may lead to increased overall carbon emissions despite negative direct effects on emissions, due to rebound effects.

market ranges from less than 10% to more than 90%.⁸ There is also a growing literature on the indirect effects of biofuels policies on land use and corresponding greenhouse gas emissions (see, e.g., Keeney and Hertel, 2009; Searchinger et al., 2008; Fargione et al., 2008).

Initially, most emission reductions from CDM projects have come from non-CO₂ gases like HFCs. However, the share of energy-related CDM projects has gradually grown, and accounted for 82 per cent of volumes contracted in 2008 (Capoor and Ambrosi, 2009). Contracted volumes of energy-related CDM projects totalled 323 MtCO₂ in 2008, which is comparable to annual CO₂-emissions in e.g. Poland.⁹ Even more importantly, a future scale-up of the CDM will inevitably involve fossil energy to a substantial extent. Although our discussion relates to the CDM, our findings are relevant for energy-related 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. 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 CDM projects due to international trade in fossil fuels

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

⁸ They also present and discuss an analytical model somewhat similar to the special case presented in equation (10) below, but with differing carbon sequestration reduction rates per harvested unit..

⁹ Realized emission reductions have so far been lower, due to a time lag between contract and project realization.

instance, import prices of coal differ significantly across countries (IEA, 2008), and most trade in coal occurs between countries in the same region.¹⁰ This is partly due to relatively high transport costs for coal,¹¹ and partly 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 (Aune et al., 2009).

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.¹² The respective substitution elasticities are often referred to as Armington elasticities (Armington, 1969).

¹⁰ 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).

¹¹ 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.

¹² 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 Böhringer et al. (2010), Keeney and Hertel (2009), Banse et al. (2008), Babiker (2005) and Böhringer and Lange (2005).

We consider trade in fossil fuels between the two aggregate regions Annex B (A) and Non-Annex B (N). In this section we consider only one (aggregate) fossil fuel. In Section 3 we analyze the effects of having two fossil fuels with different characteristics. Following the discussion above, we assume that fuels produced in different regions are imperfect substitutes. The size of the substitution elasticity and 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 by one unit of carbon, and simultaneously increases the cap on Annex B emissions by one unit. Our purpose is to examine the effects on global emissions, through changes in the fossil fuel market.¹³ 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 fixed cap on emissions in Annex B is implemented through a uniform, endogenous price of carbon (τ_A).

Changes in carbon emissions in Non-Annex B (dE_N) due to the CDM project are given by:

$$(1) \quad dE_N = \sum_{j=A,N} dC_{N,j} - 1,$$

where $dC_{N,j}$ denotes changes in consumption *outside the CDM project* of the fossil fuel produced in region j . That is, net changes in emissions in Non-Annex B consist of the

¹³ Although a single CDM project will have only marginal effects on international fuel prices, even marginal price effects can have non-negligible consumption effects *relative to* the direct consumption reduction due to the CDM project. Moreover, as annually contracted energy-related CDM projects in 2007-2008 amounted to 8-9 per cent of annual EU emissions, the combined effects of all CDM projects in coming years are not at all negligible.

emission reductions due to the CDM project ($= -1$), plus potential consumption (i.e., emission) changes elsewhere in Non-Annex B.

In Annex B we have correspondingly:

$$(2) \quad dE_A = \sum_{j=A,N} dC_{A,j} = 1.$$

We notice that net changes in emissions in Annex B are given by the increased cap due to the CDM project, which is set equal to one.

Supply and demand of the fossil fuels produced in the respective regions must balance, and so we have:

$$(3) \quad dS_N = dC_{A,N} + dC_{N,N} - \theta_N$$

$$(4) \quad dS_A = dC_{A,A} + dC_{N,A} - (1 - \theta_N),$$

where S_i denotes supply in region i and θ_i denotes the initial market value shares of the domestically-produced fuel in region i . That is, the change in supply of fossil fuels produced in a region must equal the total change of consumption of fuels produced in this region, including the direct consumption reduction due to the CDM project (i.e., the last term in (3) and (4)).¹⁴

Changes in demand and supply depend on changes in fossil fuel prices as well as the carbon price (other goods are not included in this partial equilibrium model). Instead of expressing these relationships also on change form, it is more instructive to express these on level form.

¹⁴ Here we implicitly assume that the CDM project's reduction of domestically-produced fuels versus imported fuels is the same as in the Non-Annex B region as a whole. If the reduction of fuel use through the CDM project goes substantially more in the direction of imported fuels, some of the results below may no longer hold.

In order to simplify the expressions, and without loss of generality, we normalize all initial prices to one.

Supply of fossil fuels in region i is an increasing function of its price (P_i):

$$(5) \quad S_i = S_i^0 (P_i)^{\gamma_i} \quad i = A, N,$$

where $\gamma_i \geq 0$ is the supply elasticity and superscript 0 denotes baseline levels of the endogenous variables, i.e., before the CDM project is implemented.

Consumption of fossil fuels is described by the following equations:

$$(6) \quad C_{i,j} = C_{i,j}^0 \frac{TC_i}{TC_i^0} \left[\frac{PR_i(1+\tau_i^0)}{P_j + \tau_i} \right]^{\sigma_i} \quad i, j = A, N$$

$$(7) \quad \left[\theta_i \left(\frac{P_i + \tau_i}{1 + \tau_i^0} \right)^{1-\sigma_i} + (1-\theta_i) \left(\frac{P_j + \tau_i}{1 + \tau_i^0} \right)^{1-\sigma_i} \right]^{\frac{1}{1-\sigma_i}} = PR_i \quad i = A, N; j = A, N; i \neq j$$

$$(8) \quad TC_i = TC_i^0 (PR_i)^{\delta_i} \quad i = A, N.$$

Equation (6) 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 ($P_j + \tau_i$), i.e., relative to the regional consumer price in region i (PR_i). The (Armington) substitution elasticity $\sigma_i \geq 0$ between fuels produced in Annex B and Non-Annex B influences on the effects of relative price changes. Note that the carbon price is part of the consumer price of fossil fuels in region A, but is zero in region N (i.e., $\tau_N = 0$).

Equation (7) expresses the regional consumer price as a CES aggregate of the consumer prices of fuels produced in the two regions. Finally, equation (8) is the demand function in

region i , where total consumption is a decreasing function of the regional consumer price, $\delta_i \leq 0$ being the demand elasticity.

Except for the inclusion of the CDM project, the model above is a standard trade model.

When we differentiate equations (5) – (8) and combine with equations (1) – (3) we get 15 equations in 15 endogenous variables (dS_i , $dC_{i,j}$, dE_i , dTC_i , dP_i , dPR_i , $d\tau_A$).

We will now evaluate the effects on global emissions (dE) of carrying out the CDM project.

As mentioned before, the intention of the CDM is that global emissions remain unchanged. A positive (negative) value of dE is therefore equivalent to a positive (negative) net leakage effect of the CDM project. Due to the normalization of the CDM project, dE represents the net leakage as a share of direct emission reductions in the project, and we will refer to this as the “CDM leakage rate”.¹⁵ We further normalize total consumption in Annex B to one so that TC_N denotes total consumption in Non-Annex B relative to total consumption in Annex B. Annex B countries (excl. the U.S.) currently account for about 30 per cent of global energy-related CO₂ emissions, so that the value of TC_N in this respect is slightly above two. Finally, we assume that average import shares are below 50%, i.e., $\theta_A + \theta_N > 1$. Although import shares for individual countries may well exceed 50%, both Annex B as a group (i.e., including Russia) and Non-Annex B as a group have import shares below 50% for each of the three fossil fuels oil, coal and natural gas (BP, 2009).

¹⁵ The term “leakage rate” is usually used with regards to unilateral climate policies in a region R , as the ratio between increased emissions outside region R and emission reductions within region R . In our paper the “CDM leakage rate” refers to the ratio between the change in global emissions and the emission reduction in the CDM project.

In Appendix A we show that the CDM project unambiguously increases the price of fossil fuels produced in Annex B, and reduces the price of fossil fuels produced in Non-Annex B. Fossil fuels output then increases in Annex B, and falls in Non-Annex B. The explanation is the following: Consumption in Annex B increases when the carbon price falls due to a higher emissions cap, and demand for fuels produced in Annex B increases more than demand for fuels produced in Non-Annex B. For the net reduction of consumption in Non-Annex B (i.e., including the CDM project), the situation is the opposite. Hence, the price of fuels produced in Annex B must increase, whereas the price of fuels produced in Non-Annex B must fall.

The change in global emissions, i.e., the CDM leakage rate, can then be calculated as follows (see Appendix A):

$$(9) dE = -\frac{1}{\Delta} \delta_N TC_N (\theta_A + \theta_N - 1) \left[(\theta_A + \theta_N - 1) \gamma_N + \theta_A \theta_N (\gamma_A - \gamma_N) + \theta_N TC_N (1 - \theta_N) (\gamma_A - \gamma_N) \right],$$

where $\Delta > 0$ except in very special cases (when $\Delta = 0$). The sign of this expression is in general ambiguous, and depends on the sign of the square parenthesis. The other factors are jointly positive. The sign of this 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 in Non-Annex B ($\gamma_A \geq \gamma_N$), dE is strictly positive. On the other hand, if the supply elasticity in Non-Annex B is high compared to in Annex B, and import shares ($1 - \theta_i$) are not too small, leakage may 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 strictly positive carbon leakage (i.e., higher global

*emissions) if the supply elasticity in Annex B is at least as high as that in Non-Annex B ($\gamma_A \geq \gamma_N$). Carbon leakage **can** be strictly negative if $\gamma_A < \gamma_N$ and import shares are sufficiently large.*

It is of interest to consider a few special cases. First, consider a hypothetical case with no trade in fossil fuels between Annex B and Non-Annex B (i.e., $\theta_i = 1$). In this case there cannot be any leakage effects from the higher emissions cap in Annex B, simply because any net leakage must take place in Non-Annex B, and leakage from Annex B to Non-Annex B is impossible when the fossil fuel markets are separated. As shown in Appendix B, the CDM leakage rate then reduces to the following simple expression:

$$(10) \quad dE = \frac{-\delta_N}{\gamma_N - \delta_N}.$$

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 CDM leakage rate is $\frac{1}{2}$. If demand is less (more) elastic than supply, the CDM leakage rate is lower (higher) than $\frac{1}{2}$, as consumers to a lesser extent will increase their consumption when fuel prices fall. We also notice from equation (9) that if only $\theta_N = 1$ (and $\theta_A \leq 1$), then leakage is strictly positive irrespective of the supply elasticities as the last term becomes zero. The same does not hold if only $\theta_A = 1$ (and $\theta_N \leq 1$).

Next, consider the hypothetical case with average import shares approximating 50%, i.e., $(\theta_A + \theta_N) \rightarrow 1$. Carbon leakage then tends towards zero (cf. (9)). 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 (from relaxing 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, and global emissions are unchanged as intended.

As the substitution elasticities tend towards infinity ($\sigma_i \rightarrow \infty$), the carbon leakage rate again tends towards zero (cf. Appendix B). This would be the case with a single unified fuels market for Annex B and Non-Annex B, with a single global fuel price. The explanation is similar to the above situation: Fuel prices must remain unchanged, as reduced consumption due to the CDM project is exactly matched by increased consumption in Annex B.

Although the special cases discussed above are not in themselves very realistic, they are useful as benchmark cases. We can 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 ($\sigma_i \rightarrow \infty$), or the average import shares tend towards 50% ($\theta_A + \theta_N \rightarrow 1$), there is no carbon leakage from a CDM project in the limit. Global emissions are then unchanged.*
- b) *If there is no trade in fossil fuels between Annex B and Non-Annex B ($\theta_i = 1$), the CDM leakage rate only depends on elasticities in Non-Annex B, and equals $-\delta_N/(\gamma_N - \delta_N) > 0$. Global emissions increase accordingly.*

Equation (9) shows that the *size* of the leakage rate depends on supply, demand and substitution elasticities as well as import shares and the relative size of Non-Annex B. Thus, in order to assess the leakage rate quantitatively, these parameters have to be quantified. However, econometric studies of price elasticities vary a lot, and empirical studies of substitution elasticities are few. Thus, it is difficult to conclude unambiguously e.g. whether demand or supply elasticities are greater in absolute values, and whether elasticities in Annex

B are higher or lower than those in Non-Annex B. A first step may be to investigate in which direction the different parameters affect the leakage rate:

Proposition 2:

In a fossil fuel market with only one fuel, and imperfect substitution between fuels produced in Annex B and Non-Annex B, the carbon leakage of a CDM project

a) is independent of the demand elasticity in Annex B, and increases in absolute value with the demand elasticity in Non-Annex B;

b) increases with the supply elasticity in Annex B and decreases with the supply elasticity in Non-Annex B;

c) decreases in absolute value with the substitution elasticities if $\sigma_i = \sigma$; and

d) increases with the market shares of domestic suppliers if $\theta_i = \theta$ and $\gamma_i = \gamma$.

Proof: See Appendix C.

We notice that the demand elasticity in Annex B does not affect leakage at all. The reason is that total emissions in Annex B are exogenously determined by the cap, and so the elasticity only affects the carbon price in Annex B (τ_A) needed to comply with the emissions cap.

Consistent with equation (10), a higher demand elasticity in Non-Annex B tends to increase leakage as consumers respond more strongly to lower fuel prices. We further see that 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.

We also notice that the leakage rate is lower the more integrated fossil fuel markets in Annex B and Non-Annex B are. By highly integrated markets we mean either high substitutability

(high σ) and consequently highly integrated prices, or extensive trade between the two regions (θ close to $\frac{1}{2}$). On the other hand, if the fossil fuel market is more segregated, price reductions in Non-Annex B will not automatically lead to similar price reductions in Annex B, e.g., because of transport costs. Thus, fuel consumers in Non-Annex B will consume more domestically produced fuel, resulting in higher carbon leakage.

Note that this result is opposite to the outcome of unilateral climate policy in Annex B, 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). Further examination of equation (9) shows that if the initial carbon price in Annex B is low, then the substitution elasticity in Annex B (σ_A) has little influence on the leakage rate. In this case, what matters is the substitution elasticity in Non-Annex B.

In global CGE models based on GTAP (cf. footnote 12), a standard value of the substitution elasticity between imported and domestically produced natural resources (including coal) is 2.8, while standard values of substitution elasticities between imports from different countries are twice that level (i.e., 5.6). Hertel et al. (2007) find a similar estimate of the latter elasticity for coal (6.1, with standard deviation 2.4). Given such elasticities, a reasonable estimate for the substitution elasticity between Annex B and Non-Annex B may be in the range 3-5.5.¹⁶

¹⁶ 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 11), favouring regional producers.

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 all price elasticities are equal to 0.8 in absolute value, and set $\theta = 0.95$, $\sigma = 4.5$ and $TC_N = 2.2$ (see discussion of TC_N above), then the CDM leakage rate is 20%. Other assumptions about the elasticities would imply different estimates of the leakage rate – we return to this in Section 3.¹⁷

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 energy in electric power production. As shown in our working paper, Rosendahl and Strand (2009b), this will tend to reduce the CDM leakage rate somewhat, as the increased renewable power production will keep power prices from rising and therefore reduce the incentives to increase fossil-based power production. The intuition 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 falls, 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-fired power plants, leading to increased supply and reduced prices of electricity (as a second order effect).

Numerical simulations suggest that the CDM leakage rate now depends significantly on the supply elasticity of fossil fuel and the demand elasticity of fossil fuel from consumers outside of the electricity market (given that its share of fossil fuels is significant), see Rosendahl and Strand (2009b). The elasticities in the electricity market are less important, which seems

¹⁷ The estimated elasticities of substitution between imports from different countries in Hertel et al. (2007) are respectively 6.1, 10.4 and 34.4 for coal, natural gas and oil. If we double or quadruple the substitution elasticity in our calculations, the CDM leakage rate is reduced from 20% to respectively 13% and 8%.

intuitive as the electricity price is not directly affected (a new renewable power plant replaces the old fossil-based plant). The share of fossil fuels going to the power market is important for the CDM 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.

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 fuel is traded freely in a global market ($j=G$), with one common price. Moreover, we disregard substitution possibilities between the two fossil fuels.¹⁸ The purpose here is to investigate the effects of reducing emissions, through a CDM project, of either a regionally traded fuel or a globally traded fuel. As before, we normalize the emission reduction from the CDM project to one unit, and examine the effects on global emissions of undertaking an additional project, assuming that the CDM project increases the cap on Annex B emissions equivalently.

The revised model setup is elaborated in Appendix D. There we also show that if the CDM project reduces consumption of the regional fossil fuel in Non-Annex B, the price of this fuel decreases whereas the price of the globally traded fuel increases due to increased consumption in Annex B. In this case, the CDM leakage rate is given by (see Appendix D):

¹⁸ Substitution possibilities are important for coal versus gas (mainly in electricity production), but less so for oil versus gas or coal (since oil is mainly a transportation fuel which gas and coal are not). Significant substitution possibilities tend to wipe out the distinction between the globally traded and the regionally traded fuel.

$$(11) \quad dE = \frac{-\delta_N^R}{(\gamma_N^R - \delta_N^R)} + \frac{C^G}{\Omega} \alpha_A (1 - \alpha_A) \delta_A^G \delta_N^G (\gamma_A^R - \delta_A^R) \quad (\text{regional fuel}),$$

where α_A denotes Annex B's market share of demand in the global market, and $\Omega < 0$ (see Appendix D). If the CDM project reduces the use of the globally traded fossil fuel, the price of this fuel decreases (the price of the regional fuel in Non-Annex B is unchanged). The effects on global emissions, i.e., the CDM leakage rate, are now given by (see Appendix D):

$$(12) \quad dE = -\frac{1}{\Omega} C_A^R (1 - \alpha_A) \gamma_A^R \delta_A^R \delta_N^G \quad (\text{global fuel}).$$

From (12), we see directly that a CDM project that reduces consumption of the global fossil fuel unambiguously increases global emissions. In (11), however, the two terms have opposite signs, and we cannot immediately say which term is larger. Thus, a CDM project that reduces the consumption of the regional fossil fuel has an ambiguous impact on emissions.

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 ($\theta_i = 1$), and zero with one global fuel ($\sigma_i \rightarrow \infty$). In order to explain our new result, consider first a CDM project that reduces consumption of the global fossil fuel. The cap in Annex B is then raised, and the first-order effect is to increase consumption of *both* fossil fuels. Consumption of the global fossil fuel in Annex B must increase by less than the decrease in fuel consumption due to the CDM project. Thus, the global fossil fuel price falls. This leads to increased consumption of this fuel in the rest of Non-Annex B. As the regional market in Non-Annex B is unaffected in this case, leakage must be strictly positive.

As shown analytically in Rosendahl and Strand (2009b), and confirmed by the numerical examples in Table 1 below, a CDM project that reduces the consumption of the regional fossil fuel will also tend to cause positive leakage. The intuition is the following: Since the CDM

project reduces consumption of the regional fuel, we can distinguish between the effects in this regional fuel market and the effects elsewhere (as the regional market in Non-Annex B by assumption is disconnected from other markets), corresponding to the two terms in equation (11). In the regional Non-Annex B market we get positive leakage effects along the lines discussed above (similar to equation (10)). 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 in equilibrium 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 leakage for this particular consumption were, e.g., 50% of the original CDM project, negative leakage would amount to merely 25%, i.e., significantly less than the positive leakage in the regional fuel market in Non-Annex B.

Although positive leakage tends to be more likely than negative leakage, one cannot rule out the latter possibility. This follows from the arguments in the previous paragraph: If positive leakage in the regional market is 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.

Table 1 shows leakage rates for CDM projects reducing the use of either the regionally or the globally traded fossil fuel under different assumptions. In the base case, all demand and supply elasticities have the same absolute values (only relative elasticities matter here), and market sizes and market shares are equal. That is, demand in the global market equals combined demand in the two regional markets, and the two regional markets are equal in size.

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

	<i>Regional fuel</i>	<i>Global fuel</i>
Base case	30%	10%
Supply elasticities two times as big as demand elasticities	22%	7%
Annex B elasticities two times as big as Non-Annex B elasticities	36%	7%
Elasticities in regional markets two times as big as in global market	36%	14%
Global market size two times as big as sum of regional market sizes	25%	6%
Non-Annex B consumption two times as big as Annex B consumption	25%	13%
“Oil and coal” ^a	27%	12%
“Fossil and non-fossil” ^b	-20%	10%

^a Oil is the global fuel and coal the regional fuel. Market shares are 40/60 and 20/80 for respectively oil and coal demand in Annex B vs. Non-Annex B (incl. the U.S.). Coal elasticities two times bigger than oil elasticities.

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

Above we concluded that the CDM leakage rate could be negative only if the CDM project reduces consumption of the regional fuel. Nevertheless, we notice from Table 1 that the CDM leakage rate is highest by a clear margin when the regional fuel consumption is reduced in all scenarios listed except the last one. For instance, in the base case the CDM leakage rate is 30% when the CDM project reduces consumption of the regional fuel, and 10% when it reduces consumption of the global fuel. 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).

The table further shows that the CDM leakage rate depends significantly on assumptions about elasticities and market shares/sizes. For instance, it could be the case that fuel demand

is less price responsive than fuel supply. If so, the leakage rate is smaller as shown by the table. On the other hand, if we think of oil as the global fuel, one could argue that (supply and demand) elasticities on average are higher for the regional fuel than the global fuel, as both oil demand and oil supply are supposedly less price responsive than e.g. coal demand and coal supply (fewer substitution possibilities in oil demand, and higher capital costs and market power in oil supply). We get the same conclusion if we assume that supply and demand in Annex B are more price responsive than in Non-Annex B, e.g., because of more widespread use of market mechanisms. Finally, if we take into account that fuel consumption in Non-Annex B is higher than in Annex B, leakage also falls. The same conclusion holds if the global market is larger than the regional market.

In the second-to-last row of Table 1 we assume that oil is the global fuel and coal the regional fuel. Here we have used approximate market shares/sizes from 2007,¹⁹ and also assumed higher elasticities for coal than for oil. A CDM project that reduces consumption of the regional fuel, coal, then has a CDM leakage rate of 27%.²⁰

In the last row we have assumed that regional demand in Non-Annex B is completely unresponsive to demand ($\delta_N^R = 0$). This could illustrate the effects of assuming global fossil fuel markets combined with mitigation of other greenhouse gases such as HFC (which

¹⁹ There is of course some coal trade between Annex B and Non-Annex B countries, but one cannot speak of one global coal market in the same way as for oil (see discussion above). Still, this scenario should be considered as illustrative. Note that the U.S., not having ratified the Kyoto Protocol, is included in Non-Annex B here.

²⁰ If the reduction in coal use is due to replacement of coal power by renewable power production (cf. discussion at the end of Section 2), and assuming that about 50% of coal use in Non-Annex B goes to the power sector and about 20% of power production is non-fossil based, then the CDM leakage rate becomes 21% instead of 27%.

constituted a majority of CDM volumes in the beginning). Then, other emissions in Non-Annex B are unaffected by this project. However, reduced mitigation in Annex B has negative leakage effects in Non-Annex B, explaining the negative sign in the last row.

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, leakage depends on the relative elasticities in the two markets. For instance, if the two markets are equal, there is no leakage (as with only one market). As shown in Rosendahl and Strand (2009b), 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 *I* is to reduce both global consumption and the price in market *I*, and to increase both global consumption and the price in market *II* (because the increased cap in Annex B is ‘divided’ between the two markets). If supply in market *I* is much *less* elastic than Non-Annex B demand, then leakage in this market is significant and positive. Thus, reduced demand in the CDM project will be accompanied by a notable increase in demand elsewhere in Non-Annex B. If supply in market *II* is much *more* elastic than Non-Annex B demand, then there will be little negative leakage in this market. 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. Global carbon emissions will then 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 analytical model we have used to derive the main results is

somewhat restrictive, however, and it would be useful to investigate this issue further in an appropriate numerical model (we return to this issue below).

The analysis shows that important questions are 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 the CDM, is global in principle, but transport costs are higher than for oil. Thus, trade is more regional for coal than for oil, and coal prices vary more than oil prices across regions (also because of larger 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, leakage when crediting 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 one particular case 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 treated in our models above, should enable more precise assessments of leakage effects for individual CDM projects, and thus the degree to which they should be credited. The most uncertain parameters in our view are the substitution elasticities. In other words, how integrated are international fossil fuel markets, in particular the coal market? For instance, it would be useful to know to what degree a coal price shock in one country disperses through the international coal market. Are price changes in countries far away comparable with price changes in neighbouring countries? This could be tested either through empirical work, or by simulations on an appropriate global coal market model.

Other well-known problems with the effectiveness of the 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 the 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. In this way, the price of CDM credits will to a larger extent reflect the correct price per unit reduction of GHG emissions, hopefully increasing the cost-efficiency of international climate policy instruments.

An important practical question is whether such lack of effectiveness of the 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 and with increasingly precise estimates of parameters entering into our formulas, should form the basis for quota allocations. Some of these parameters, including market shares of different fuels in different markets and their carbon emissions, are relatively easy to pin down. Others, such as demand and supply elasticities and, in particular, elasticities of substitution between fuels from different regions, can be harder to assess precisely. Determining such parameters with maximum precision will then be helpful for future assessment of the CDM and its impact on global GHG emissions. Using more disaggregated models, with detailed description of the international energy markets that take into account imperfect substitution between fuels from different regions, either directly or by modelling transport costs and bilateral trade, could also be useful. Simulations on such models could tell whether the numerical results we have found above are reasonable or not.

We finally 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 the U.S., one international offset would transfer into 0.8 allowances from 2018 (House of Representatives, 2009, pp. 740-743). That is, awarded emission quotas from CDM projects would be reduced by 20%. Note, however, that this bill has not passed the U.S. Senate.

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Appendix

A. Derivation of equation (9)

Differentiating (5) – (8), and adding (1) – (4), we derive the following price effects (the carbon price also changes, affecting dP_i , but we do not need to know $d\tau_A$ to calculate dE):

$$(A1) \quad dP_A = \frac{1}{\Delta} (\theta_A + \theta_N - 1) (\gamma_N (1 - \theta_A) + \theta_N TC_N (\gamma_N - \delta_N))$$

$$(A2) \quad dP_N = -\frac{1}{\Delta} (\theta_A + \theta_N - 1) (\gamma_A \theta_A + (1 - \theta_N) TC_N (\gamma_A - \delta_N))$$

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

where:²²

$$\Phi = \gamma_A \gamma_N (\theta_A - \theta_A^2) + \sigma \gamma_A \tau_A (\theta_A^2 - \theta_A^3) + \sigma \gamma_N \tau_A (\theta_A^3 - 2\theta_A^2 + \theta_A)$$

$$\begin{aligned} \Gamma = & \gamma_A \gamma_N (1 - \theta_A - \theta_N + 2\theta_A \theta_N) + \gamma_N \delta_N (\theta_A - 1 + 2\theta_N - \theta_N^2 - 2\theta_A \theta_N + \theta_A \theta_N^2) + \gamma_A \delta_N (-\theta_A \theta_N^2) \\ & + \sigma \gamma_N (\theta_N - \theta_N^2 - \theta_A \theta_N + \theta_A \theta_N^2 + \tau_A \theta_A \theta_N - \tau_A \theta_A^2 \theta_N) + \sigma \delta_N (\tau_A \theta_A^2 - \tau_A \theta_A) \\ & + \sigma \gamma_A (\theta_A \theta_N - \theta_A \theta_N^2 + \tau_A \theta_A - \tau_A \theta_A^2 - \tau_A \theta_A \theta_N + \tau_A \theta_A^2 \theta_N) \end{aligned}$$

$$\begin{aligned} \Psi = & \gamma_A \gamma_N (\theta_N - \theta_N^2) + \gamma_A \delta_N (\theta_N^3 - \theta_N^2) + \gamma_N \delta_N (2\theta_N^2 - \theta_N^3 - \theta_N) \\ & + \sigma \gamma_A (\theta_N^3 - 2\theta_N^2 + \theta_N) + \sigma \gamma_N (\theta_N^2 - \theta_N^3) + \sigma \delta_N (\theta_N^2 - \theta_N) \end{aligned}$$

We see that all the terms in Φ , Γ and Ψ are non-negative. Moreover, unless $\theta_A = \theta_N = 1$ and either $\gamma_A = 0$ or $\gamma_N = \delta_N = 0$, or unless $\gamma_A = \gamma_N = \delta_N = 0$, some of these terms are strictly positive. Thus, we conclude that Δ is non-negative, and strictly positive except in very special cases, and hence $dP_A > 0$ and $dP_N < 0$.

²² In order to simplify the expressions somewhat we have set $\sigma_i = \sigma$. The conclusions about the sign of the different terms also hold with different substitution elasticities, i.e., $\sigma_A \neq \sigma_N$. On the other hand, we cannot see any arguments in favour of either higher or lower substitutability in Annex B vs. Non-Annex B.

The CDM leakage rate is given by $dE = \sum_i dS_i$, which further depends on dP_i ($i=A,N$). Thus:

$$(A3) \quad dE = \gamma_A S_A^0 dP_A + \gamma_N S_N^0 dP_N = -\frac{1}{\Delta} \delta_N TC_N (\theta_A + \theta_N - 1) \left[(\theta_A + \theta_N - 1) \gamma_N + \theta_A \theta_N (\gamma_A - \gamma_N) + \theta_N TC_N (1 - \theta_N) (\gamma_A - \gamma_N) \right].$$

B. Proof of Corollary 1

When $\theta_A = \theta_N = 1$, Δ reduces to $\Delta = (\gamma_A \gamma_N - \gamma_A \delta_N) TC_N$. Equation (10) can then be found by

inserting for Δ in (9):

$$(B1) \quad dE = -\frac{1}{(\gamma_A \gamma_N - \gamma_A \delta_N) TC_N} \delta_N TC_N [\gamma_N + (\gamma_A - \gamma_N)] = \frac{-\delta_N}{\gamma_N - \delta_N}.$$

When $\sigma \rightarrow \infty$, it is straightforward to see that several terms in Δ tend to infinity. Thus, we must have $\Delta \rightarrow \infty$ and hence $dE \rightarrow 0$.

C. Proof of Proposition 2

a) We first notice that δ_A does not enter into equation (9), and hence does not affect dE . Next, differentiate dE with respect to δ_N . Other parameters are then constant, and dE can be expressed as (see (9) and the expression for Δ in Appendix A):

$$(C1) \quad dE = -\frac{\delta_N K_1}{K_2 - K_3 \delta_N},$$

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 dE .

Then we find that:

$$(C2) \quad \frac{d(dE)}{d\delta_N} = -\frac{K_1 (K_2 - K_3 \delta_N) - K_1 \delta_N}{(K_2 - K_3 \delta_N)^2} = -K_1 \frac{K_2 - \delta_N (K_3 + 1)}{(K_2 - K_3 \delta_N)^2},$$

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

b) We next differentiate with respect to γ_A . dE can then be expressed as:

$$(C3) \quad dE = -\frac{L_1 - L_2\gamma_A}{L_3 + L_4\gamma_A},$$

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

Further, we differentiate with respect to γ_N . dE can then be expressed as:

$$(C4) \quad dE = -\frac{M_1\gamma_N - M_2}{M_3 + M_4\gamma_N} = -\frac{M_1 - (M_2/\gamma_N)}{(M_3/\gamma_N) + M_4},$$

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

c) We now differentiate with respect to σ , assuming $\sigma_i = \sigma$. dE can then be expressed as:

$$(C5) \quad dE = -\frac{O_1}{O_2 + O_3\sigma},$$

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 dE .

Again, it is straightforward to see that the absolute value of dE strictly decreases when σ increases, i.e., $d|dE|/d\sigma < 0$.

d) Finally, we differentiate with respect to θ , assuming $\theta_i = \theta$ and $\gamma_i = \gamma$. The expression for dE then simplifies to:

$$(C6) \quad dE = -\frac{1}{\Delta} \delta_N TC_N (2\theta - 1)^2 \gamma,$$

where the terms in Δ simplify to:

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

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

$$\Psi = \gamma^2 (\theta - \theta^2) + \gamma\delta_N (\theta^2 - \theta) + \sigma\gamma(\theta - \theta^2) + \sigma\delta_N (\theta^2 - \theta).$$

Then we have:

$$(C7) \quad \begin{aligned} \frac{d(dE)}{d\theta} &= -\delta_N \gamma TC_N \frac{1}{\Delta^2} \left[4(2\theta-1)\Delta - (2\theta-1)^2 \frac{d\Delta}{d\theta} \right] \\ &= \delta_N \gamma TC_N \frac{1}{\Delta^2} (1-2\theta) \left[4\Delta + (1-2\theta) \frac{d\Delta}{d\theta} \right] \end{aligned}$$

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

$$(C8) \quad \begin{aligned} \frac{d\Delta}{d\theta} &= \gamma^2 (1-2\theta) (1-TC_N)^2 + \sigma \gamma (1-2\theta) (\tau_A + (1+\tau_A)TC_N + (TC_N)^2) \\ &\quad - \sigma \delta_N TC_N (1-2\theta) (\tau_A + TC_N) - \gamma \delta_N TC_N (1-2\theta) (TC_N - 3) \end{aligned}$$

All terms in (C8) except the last are non-positive, and at least two of them are strictly negative. When multiplied by $(1-2\theta)$ in (C7), they become strictly positive. We know from before that all terms in Δ are non-negative. Thus, let us single out the terms inside the square parenthesis of (C7) that include $\gamma \delta_N$, including the last one in (C8), knowing that the sum of the remaining terms (denoted Λ) must be strictly positive. Equation (C7) then becomes:

$$(C9) \quad \begin{aligned} \frac{d(dE)}{d\theta} &= \delta_N \gamma TC_N \frac{1}{\Delta^2} (1-2\theta) \\ &\left[\Lambda + \gamma \delta_N \left(4(TC_N(-1+3\theta-3\theta^2) + (TC_N)^2(\theta^2-\theta)) - (1-2\theta)TC_N(1-2\theta)(TC_N-3) \right) \right], \\ &= \delta_N \gamma TC_N \frac{1}{\Delta^2} (1-2\theta) \left[\Lambda + \gamma \delta_N (-TC_N - (TC_N)^2) \right] \end{aligned}$$

which is strictly positive.

D. Model setup in Section 3 and derivation of equations (11) and (12)

Following the model setup represented by equations (1) – (8), we assume that $\theta_i^R = 1$ and $\sigma_i^G \rightarrow \infty$. Equations (1) – (4) are then replaced by (both fossil fuels are measured in carbon units):

$$(D1) \quad dE_N = dC_N^R + dC_N^G - 1$$

$$(D2) \quad dE_A = dC_A^R + dC_A^G = 1$$

$$(D3) \quad \sum_{i=A,N} dS_i^G = \sum_{i=A,N} dC_i^G + CDM^G$$

$$(D4) \quad dS_N^R = dC_N^R + (1 - CDM^G)$$

$$(D5) \quad dS_A^R = dC_A^R,$$

where $CDM^G = 1$ if the CDM project reduces globally traded fuel use, and $CDM^G = 0$ if it reduces regionally traded fuel use. Equation (5) carries over, with S_i , P_i and γ_i being replaced by S_i^j , P_i^j and γ_i^j . Equations (6) – (8) are replaced by:

$$(D6) \quad C_i^j = C_i^{j,0} \left(\frac{P_i^j + \tau_i}{P_i^{j,0} + \tau_i^0} \right)^{\delta_i^j} \quad i = A, N; \quad j = R, G.$$

By differentiating these equations we obtain (with initial prices still normalized to one):²³

$$(D7) \quad dP_N^R = -\frac{1}{(\gamma_N^R - \delta_N^R)C_N^{R,0}} < 0 \quad (\text{regional fuel})$$

$$(D8) \quad dP^G = \frac{1}{\Omega} [\alpha_A \delta_A^G (\gamma_A^R - \delta_A^R)] > 0 \quad (\text{regional fuel})$$

$$(D9) \quad dP^G = -\frac{1}{\Omega} \frac{C_A^R}{C^G} [\gamma_A^R \delta_A^R] < 0 \quad (\text{global fuel}),$$

where

$$\Omega = \left[C_A^R \delta_A^R \gamma_A^R (\beta_A \gamma_A^G + (1 - \beta_A) \gamma_N^G - \alpha_A \delta_A^G - (1 - \alpha_A) \delta_N^G) + C^G \alpha_A \delta_A^G (\beta_A \gamma_A^G \gamma_A^R + (1 - \beta_A) \gamma_A^R \gamma_N^G - (1 - \alpha_A) \gamma_A^R \delta_N^G - \beta_A \delta_A^R \gamma_A^G - (1 - \beta_A) \delta_A^R \gamma_N^G + (1 - \alpha_A) \delta_A^R \delta_N^G) \right] < 0$$

and α_A and β_A denote Annex B's market shares of demand and supply, respectively, in the global market. Note that P^G is unchanged when the CDM project reduces use of the globally traded fuel. The CDM leakage rate is $dE = (\sum_j dC_N^j)$, where dC_N^j depends on dP_N^P and dP^G .

Thus, equations (11) and (12) can be derived by using (D6) – (D9).

²³ In order to simplify the expressions somewhat, we assume from now on that the initial carbon price in Annex B is small compared to the prices of fossil fuels. The main conclusions still hold if we relax this assumption.