Decomposing Carbon Leakage

-an Analysis of the Kyoto Protocol-

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Abstract

The focus of this paper is carbon leakage under the Kyoto protocol. The dynamic AGE model WorldScan is used to analyse the effects of both unilateral action and permit trading within Annex I . Two new IPCC-SRES scenarios, A1 and B1, are used as reference scenarios. The two scenarios turn out to generate similar leakage rates. Furthermore, leakage depends only to a limited extent on the policy applied. Typical values for the leakage rate turn out to be around 20 percent. Income is less affected than GDP. Important channels through which carbon leakage occurs, are the shift in energy-intensive production from Annex I towards non-Annex I and the shift within industries towards cheaper energy in non-Annex I. Crucial for these processes are trade elasticities and production substitution elasticities. A sensitivity analyses is done to assess the importance of these parameters.

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1. Introduction

By signing the Kyoto Protocol in December 1997, industrialized countries and countries in transition, the so-called Annex I countries, committed themselves to the reduction of their Greenhouse Gas emissions, with the ultimate goal to stabilize global emissions and to prevent undesirable climate changes. Although the agreement achieved in Kyoto is an important first step towards this ultimate goal, it is clear that also emissions outside the group of Annex I countries (Non-Annex-I) have to be taken into account to assess the contribution of this agreement to the stabilization of global emissions. First of all, the relative importance of Annex-I reductions depends on autonomous increases of emissions in Non-Annex-I. If Annex-I emissions are a smaller part of global emissions, the relative impact of Annex-I reductions on global emissions is automatically smaller. Secondly, the impact depends on induced changes in emissions in Non-Annex-I. An increase in Non-Annex-I emissions as a result of mitigation policies in Annex-I, makes these policies less effective in stabilizing global emissions.

This paper will focus on this induced, so-called leakage effect and especially on carbon leakage. To assess the order of magnitude of this leakage and to unravel the different causes of leakage we use WorldScan, a dynamic AGE model of the world economy, developed at CPB. Besides leakage of emissions to countries outside Annex I, leakage may also occur within the Annex I region. The latter might occur if Annex I countries have emission targets that exceed their expected emissions. This leaves room, often labelled “hot air”, in those countries to increase their emissions as a result of policies in other Annex I countries without violating the Kyoto protocol. This paper will also address the possible hot air, which is expected only to exist in Russia or the Former Soviet Union.

In the analysis we will split up leakage in three different ways. First, we use the well-known Kaya identity where a change in emissions is disentangled into a change into a change in production, a change in the energy intensity of production and a change in the carbon intensity of energy. Secondly, we decompose emissions into emissions that are ultimately used for domestic final demand and emissions that are use for net exports of goods and services. To that end we compute for all sectors the implicit carbon content, taking into account all intermediate deliveries and all imports. With this decomposition we can compute how mitigation policies change the carbon content of final demand in Annex-I and Non-Annex-I. Thirdly, in the sensitivity analysis we split changes in emissions into changes that result from shifts over sectors and changes that results from shifts in production technologies.[1]

[1]The distinction between changes in production technologies and shifts over sectors is a vague one. In every economic model sectoral output consist of heterogeneous products, which implies that production functions always describe, besides technological options, also the consequences of shifts over products. However, in sensitivity analysis the distinction between demand and production functions is a convenient one because both elements refer to specific model parameters.

There are at least three reasons for leakage. First, as a result of reduced energy demand in Annex-I the producer prices of energy in all regions will decline. Cheaper energy in countries that do not adopt mitigation policies will stimulate domestic energy demand. Secondly, energy taxes in Annex I countries may provoke relocation of energy-intensive production to countries that do not impose energy taxes. Thirdly, income effects in non-complying countries may change their domestic energy demand.[2]

Taking these transmissions into account we can conclude that the leakage rate will depend on a variety of assumptions. Of overriding importance are assumptions about developments in absence of mitigation policies, or the so-called business-as-usual (BaU) baseline. In general one can say that the larger countries without mitigation policies are, relative to countries that realize reductions of emissions, and the more they are integrated into the global economy, the larger will be the leakage rate. Large countries can easily absorb a significant amount of extra energy if energy prices decline. Countries that already have a substantial market share in foreign markets and that are open to imports can easily take over a considerable part of energy intensive production from Annex-I. Also the degree of integration of energy markets in the baseline is important. If trade in fossil fuels is difficult and energy markets are more or less regional markets, the energy prices in Non-Annex-I will hardly be effected. Finally, if the BaU baseline contains hot air within Annex-I, that will generate leakage within Annex-I and as a result the leakage to Non-Annex-I will be smaller.

In this paper we use two new scenarios developed by the IPCC in the Special report on Emissions Scenarios (IPCC, 2000). These scenarios are referred to as A1 and B1. Both scenarios assume high growth rates, especially in Non-Annex-I. The main difference is that in B1 very rapid autonomous improvement in energy efficiency is assumed. This makes the necessary reductions to comply with the Kyoto Protocol smaller and it generates a substantial amount of hot air in the Former Soviet Union, even in 2020. These two reference scenarios will be described in section 2. Because both scenarios are rather similar with respect to the openness of Non-Annex-I and the share of Non-Annex-I in the world economy, mitigation policies will have similar leakage rates. Because towards 2020 the share of Non-Annex-I in the world economy is steadily increasing, the leakage rate differs more in time than between the two scenarios, albeit that the existence of substantial hot air in the B1 scenario reduces leakage towards Non-Annex-I compared to the A1 scenario, where hot air disappears towards the end of the scenario period. Lejour (1999) uses WorldScan to analyse leakage against two other scenarios. These scenarios, developed for the OECD (1997) study, differ significantly with respect to Non-Annex-I. One scenario assumes rapid growth of Non-Annex-I regions and further globalization through the lowering of barriers in international markets for goods, services and financial capital, while the other scenario is much less optimistic about growth and openness of Non-Annex-I. That study shows a significantly larger leakage rate in the first scenario than in the second one.

As starting point of the scenarios we use the GTAP4 database. On the energy side of that database we added some extra information and some modifications. We confronted the value of output per region in GTAP4 with volume data of output provided by the IEA. We assumed that the resulting implicit price can be seen as a producer price which applies to all categories of demand. Only for oil we made a distinction between the price for domestic sales and exports, using IEA price data on exports and imports of oil. Also that method ensures that the model reproduces the IEA volume data of energy production per region. Then we calculated indirect taxes on

[2] See also e.g. Oliveira-Martins et.al. (1992).

domestic use, irrespective from the suppliers, so that market prices provided by IEA were reproduced. That procedure assumed that the value data of energy use in GTAP do not contain these indirect taxes. We therefore computed new value data including these revealed domestic taxes.

The leakage rate will not only depend on the reference scenario, but also on the instruments that are used to reach the targets that Non-Annex-I countries set themselves. In general one can say that the more efficient the instruments are, the lower the leakage rate will be. Efficient instruments will lead to smaller distortions and therefore to less relocation of energy-intensive production to Non-Annex-I. In section 3 we consider two policies: unilateral taxes (UNI) and free emission trade within Annex-I (FTR). The later will show a somewhat smaller leakage to Non-Annex-I, because it leads on average to smaller price distortions. Both UNI and FTR may induce leakage within Annex-I if hot air exists in the baseline. As far as there is still hot air after unilateral policies, this internal leakage will be larger in case of free emission trade.

In the implementation of the Kyoto agreement many other instruments may be used besides unilateral taxes or free trade of emission right within AN-I, but these instruments are beyond the scope of this paper. Some of these instruments we analysed in Bollen et.al. (1999), where we simulated trade within limited clubs, limits to imports or exports of emission right and projects under the clean development mechanism.

To determine the leakage rate, not only the instruments or the magnitude of variables in the baseline are important, but also the assumptions about production possibilities and behavioural relations. In model terms this mainly refers to price elasticities. First of all the price elasticity of energy supply is a key determinant. Inelastic supply, i.e. small price elasticities, will increase leakage. Suppliers of fossil fuels are then prepared to lower their prices drastically in order to maintain output levels as far as possible after the decline in demand from Non-Annex-I countries. Similarly the price elasticity of energy demand in Non-Annex-I is an important determinant of leakage. The higher these price elasticities the larger leakage will be, because the easier Non-Annex-I can increase energy demand as a result of lower prices. Changes in the price-elasticity of energy demand in Annex-I, on the other hand, has an opposite effect on the leakage rate. That would provoke larger shifts over sectors in the trade patterns. Finally, the price elasticities of trade flows of all goods and services are important. The higher these elasticities, the larger leakage. High price elasticities in energy markets imply integrated global energy markets. That means that suppliers of energy in Non-Annex-I are confronted with a decline in demand for their output as a result of mitigation policies in Annex-I and suppliers of energy in Annex-I can easily shift their sales to Non-Annex-I. High price elasticities in other markets facilitate shifts in trade patterns of energy intensive products. To explore the impact of some of these price elasticities we present in section 4 some sensitivity analyses with WorldScan.

Leakage can only occur as a result of trade, trade in energy carriers, or trade in other products. Therefore, to avoid leakage one could see compensating trade policies, like the taxation of energy intensive imports, as an option. Or one could exempt energy-intensive producers in exposed sectors in Annex-I from carbon taxes. Such counter veiling measures or beyond the scope of the current paper. In Tang et.al. (1998) such measures were discussed on the basis of WorldScan simulations.

WorldScan is a multiregion, multisector, applied general-equilibrium model which focuses on long-term growth and trade in the world economy (CPB, 2000). The model is especially adapted to quantify the effects of policies to mitigate CO_2 emissions. In this paper we aggregate the results into 4 regions: Western Europe, Eastern Europe + Former Soviet Union, Rest OECD and Rest of the World or Non-Annex-I.

2 The baselines

The effects of CO2 abatement policies depend on the baseline used. The emission targets set in the Kyoto agreement are expressed relative to the emission levels in 1990. The future growth of emissions, as projected in the baseline, is critical in determining the efforts required to meet the Kyoto commitments. There are an infinite number of possible alternative futures to explore. In this paper we follow two scenarios which have been constructed for the Special Report on Emissions Scenarios (SRES) of the IPPC (IPCC, 2000). These scenarios are described by the rather unimaginative names A1 and B1.

The A1 scenario describes a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are convergence, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The global economy expands at an average annual rate of about 3% to 2100.This is approximately the same as average global growth since 1850, although the conditions that lead to this global economic growth in productivity and per capita incomes in the scenario are unparalleled in history. Energy and mineral resources are abundant in this scenario because of rapid technical progress, which both reduce the resources needed to produce a given level of output and increases the economically recoverable reserves. Final energy intensity (energy use per unit of GDP) decreases at an average annual rate of 1.3%. The A1 scenario is based on a balanced mix of primary energy sources and has an intermediate level of CO2 emissions.

The B1 scenario describes a convergent world with rapid change in economic structures, and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity. Global income per capita is somewhat lower than in A1. A higher proportion of this income is spent on services rather than on material goods The B1 scenario sees a relatively smooth transition to alternative energy systems as conventional oil and gas resources decline. There is extensive use of conventional and unconventional gas as the cleanest fossil resource during the transition, but the major push is towards post-fossil technologies driven in large part by environmental concerns.

Basically, the SRES scenarios focus on the long run and certain aspects become manifest only in the far future. For example, the strong increase in the use of biofuels and non-thermal electricity in B1 takes shape only in the second half of the 21^{st} century. All the same, in the medium run there are important differences, especially concerning fossil energy use and CO2 emissions. In this paper our time horizon is 2020 and we think it useful to take both baselines A1 and B1 into consideration.

The stories behind these scenarios haven been implemented by different modelling groups (RIVM, 1999). This exercise resulted in more detailed trajectories, *e.g.* for GDP, population, emissions and fuel demand. To mimic the given trends in these scenarios in broad outline, we adjusted in WorldScan the upgrading of the labour force, convergence of consumption patterns and adjustments of interest rates. More attention has been paid to calibrate energy demand. We adjusted the cost parameters in the production function in such a way that WorldScan exactly follows the growth rates of demand for oil, coal, gas, biofuels and non-thermal energy given in A1 and B1.

Figure 2.1a Various indicators in A1 scenario (average five year percentage change)

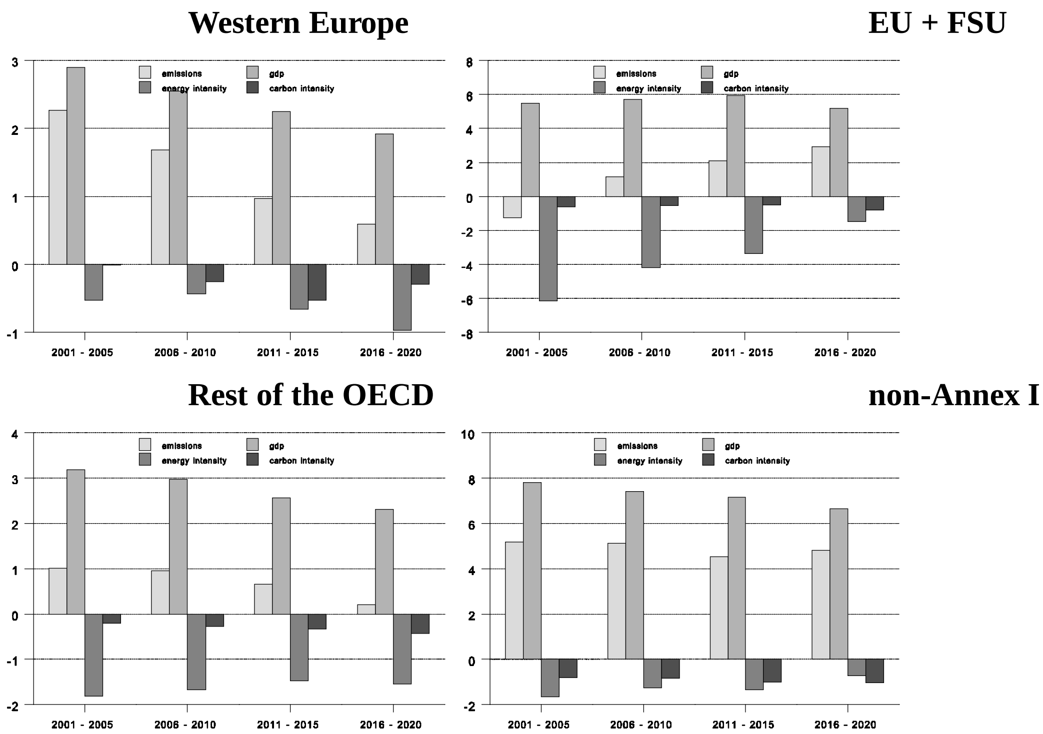


Figure 2.1b Various indicators in B1 scenario (average five year percentage change)

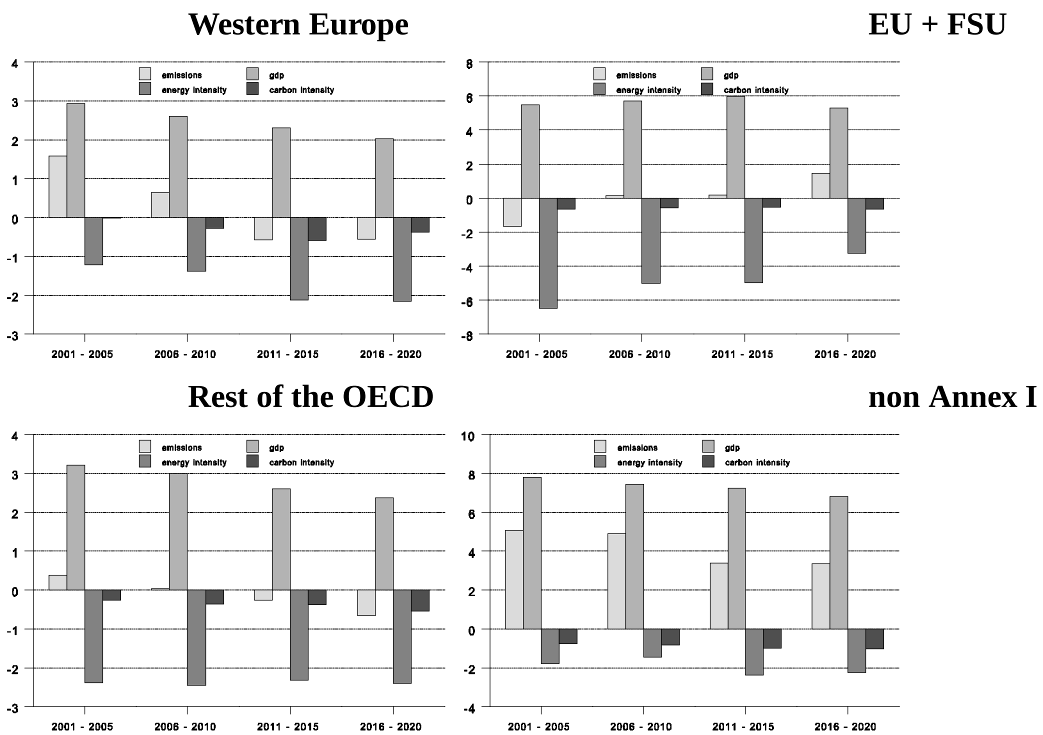


Figure 2.1 shows for the four aggregated regions the growth in GDP, emissions, energy intensity and carbon intensity. Both scenarios can be characterised as high growth scenarios. In the time period considered, there is hardly any difference in GDP growth between the A1 and B1 scenario. However, emissions in B1 are much lower than in A1, caused by a both a stronger decrease in energy intensity and a stronger decrease in carbon intensity.

3 Simulation results

3.1 Emission reductions and carbon taxes

In this section we will discuss two policy scenarios with IPCC's A1 scenario as starting point and the same two policy scenarios with IPCC's B1 scenario as starting point. Both policy scenarios impose the Kyoto targets on Annex-I emissions. We assume that the average Kyoto targets for the first budget period will be realized in 2010 and that from 2000 onwards the targets gradually converge from the baseline emissions to the target in 2010. The targets are kept constant from 2010 till 2020. In the first policy scenario the targets of individual regions are reached by unilateral carbon taxes. In the second policy scenario free trade of emission rights within Annex-I is allowed, which boils down to a uniform tax in Annex-I to reach the overall Annex-I target, combined with transfer payments as a result of trade in emission rights.

Figure 3.1a emissions and carbon taxes in A1 scenario

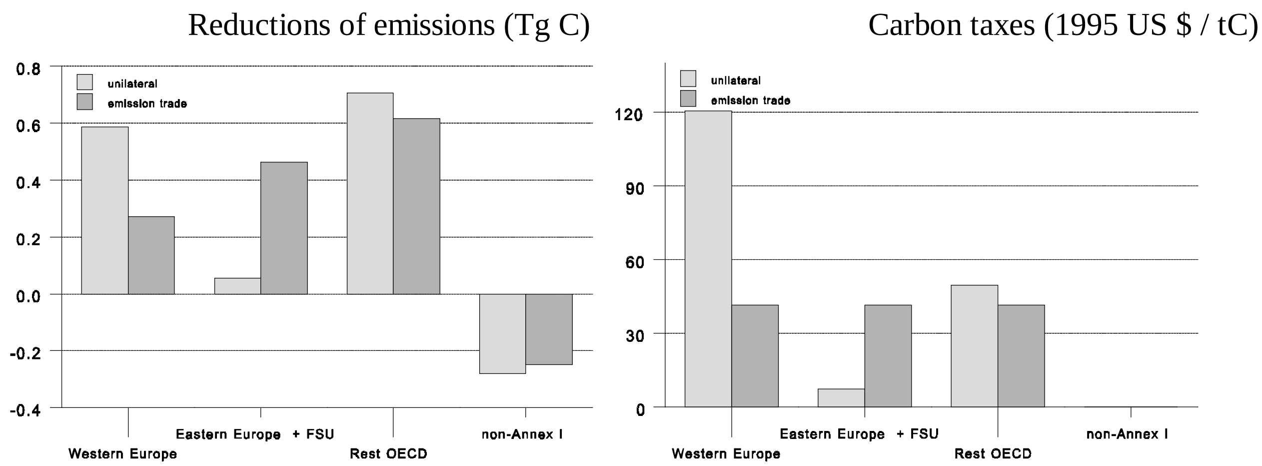


Figure 3.1b emissions and carbon taxes in B1 scenario

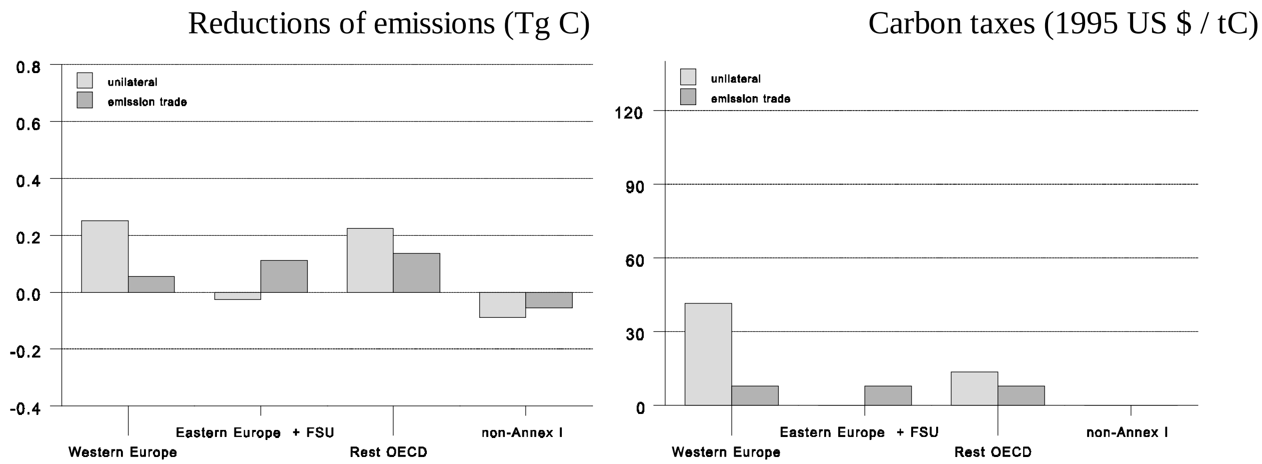


Figure 3.1 shows the resulting emission reductions and carbon prices in 2020. In the A1 scenario Western Europe has to reduce its emissions with .6 TgC, which is almost 40% of the emissions in the baseline. To realize that reduction with unilateral taxes Western Europe needs a carbon tax of 121$/tC[3]. Table 3.1 shows that that tax leads to large increases in the market prices of energy, especially of coal, because the carbon content of coal per US$ is relatively large. Eastern Europe and the Former Soviet Union only have to reduce .06 TgC, about 5% of their baseline emissions. Reductions in the Rest of the OECD are in absolute terms even larger than in Western Europe. But the reduction of .7 TgC is only 25% of their baseline. That means that their carbon tax can be lower than in Western Europe. Another reason for the relatively low carbon tax is the relatively low energy prices in the Rest of the OECD, especially because of low energy prices in the United States. The carbon tax of 50 $/tC leads to relatively large increases in energy prices in the Rest of the OECD.

Table 3.1 Real energy prices in 2020[4]

(cumulated % change)

A1 scenario

	unilateral				emission trade			
	WE	EF	RO	NA	WE	EF	RO	NA
market prices								
Coal	90,8	8,1	70,8	-2,3	-2,2	84,1	58,4	-2,2
Oil	29,6	5,7	15,5	-2,3	-2,4	79,4	12,5	-2,4
Natural Gas	22,3	3,8	16,8	-0,9	-0,9	35,5	13,9	-0,9
producer pr.								
Coal	0,0	-10,0	-10,9	-1,3	-1,2	-16,8	-9,2	-1,2
Oil	-2,8	-5,1	-2,0	-2,3	-2,2	-8,9	-2,0	-2,2
Natural Gas	0,3	-4,3	-2,8	-0,8	-0,7	-10,0	-2,4	-0,7

B1 scenario

	unilateral				emission trade			
	WE	EF	RO	NA	WE	EF	RO	NA
market prices								
Coal	35,3	-4,4	20,1	-1,1	-0,6	16,4	11,6	-0,6
Oil	11,3	-2,4	4,6	-0,8	-0,7	22,6	2,5	-0,7
Natural Gas	8,5	-1,3	4,7	-0,3	-0,2	7,1	2,7	-0,2
producer pr.								
Coal	-1,5	-4,4	-5,1	-0,6	-0,3	-4,8	-2,8	-0,3
Oil	-1,2	-1,4	-0,7	-0,8	-0,6	-2,8	-0,6	-0,6
Natural Gas	-0,1	-1,3	-1,4	-0,3	-0,2	-2,4	-0,8	-0,2

[3] $/tC stands for 1995-US dollars per ton carbon

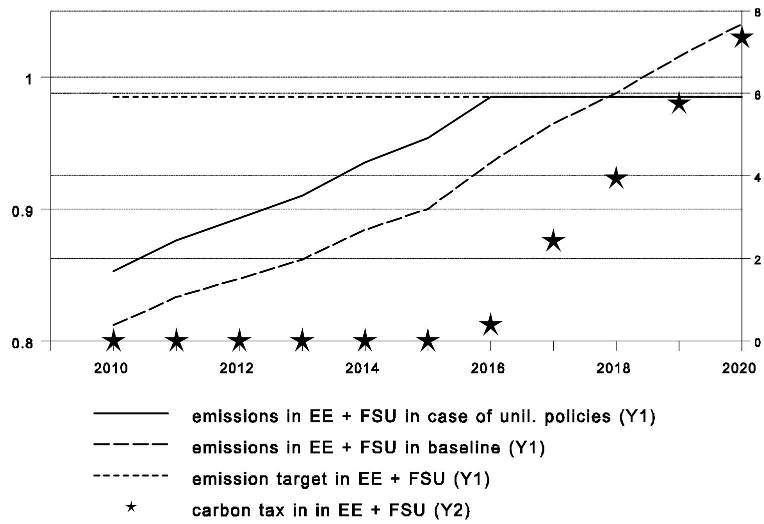
[4] energy prices deflated by consumer price index

In case of unilateral taxes the carbon leakage in Non-Annex-I is .28 TgC, which is 20% of the Annex-I reductions. As percentage of the baseline emissions the increase in Non-Annex-I is only 3%.

The picture changes radically in case trade in emission rights is allowed. Then the carbon tax is equal for all Non-Annex-I regions at a level of 42 1995-US$/tC. Because of differences in marginal abatement costs, related to differences in energy prices in the baseline, the impact of this tax on reductions differs across regions. Emissions in Western Europe are reduced by 18% of their baseline level (.27 TgC), in EE+FSU by 45% (.46TgC) and in the Rest of the OECD by 21% (.62 TgC). So, compared to the unilateral case it is mainly a shift of reductions from Western Europe to EE+FSU. The leakage in Non-Annex-I is somewhat smaller in case of emission trade because free trade implies a more efficient reduction of emissions and less improvement of Non-Annex-I competitiveness in energy-intensive goods.

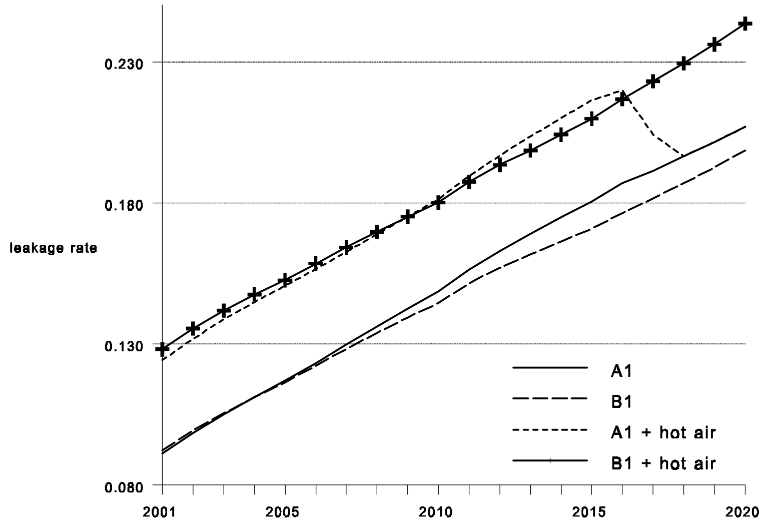
Taking IPCC's B1 scenario, with very rapid autonomous increase in energy efficiency, as baseline has two major consequences. First of all, for Western Europe and the Rest of the OECD are only about one third of the necessary reductions in the A1 scenario. That means that also the carbon tax in those regions in the unilateral case are about one third of the levels discussed above. Secondly, EE+FSU has in the B1 scenario in 2020 a significant amount of hot air, 22% of their baseline emissions or .18 TgC. That means that in the unilateral case there is leakage within Annex-I and EE+FSU will increase their emissions compared to the baseline. In case of emission trade the increase will be much larger and that will decrease the reductions of Annex-I as a whole. This means that emission trade will lead to more global emissions, even with smaller leakage to Non-Annex-I.

Figure 3.2 Hot air and unilateral policies in the A1 scenario



The A1 scenario does not contain hot air in 2020, but it does in the years before. Figure 3.2 shows the dynamics of the emissions in EE+FSU. The bold dashed line indicates the emissions in the A1 baseline without mitigation policies. Only in 2018 these emissions cross the target (the horizontal dashed line). That means that the baseline contains hot air till 2018. The solid line shows the emissions in the unilateral mitigation variant. In the first periods this line lies substantially above the baseline emissions as a result of leakage within Annex-I. Because of mitigation policies in other Non-Annex-I regions EE+FSU increase their emissions. As a result, they will reach their target earlier, already in 2016. From then on also EE+FSU has to introduce a unilateral tax to prevent their emissions from exceeding the target. The tax levels are indicated by stars in the figure. So, part of the hot air that existed in the baseline disappeared in the unilateral variant. Although the tax rate is positive, emissions still lie above the base-line level between 2016 and 2018.

Figure 3.3 Leakage rate



The existence of hot air complicates the analysis of leakage to Non-Annex-I. One is inclined to define the leakage rate as the increase of emissions in Non-Annex-I as share of the reductions in Annex-I. The two lower curves in Figure 3.3 show the leakage rate according to this conventional definition. Both lines refer to unilateral policies. The solid line describes the leakage rate in the A1 scenario and the dashed one the leakage rate in B1. However, in case of hot air and leakage within Annex-I, this definition of leakage is actually not appropriate. The increase of emissions in EE+FSU as a result of leakage within Annex-I is included in the denominator, lowering total Annex-I reductions, and is not part of the numerator describing leakage. The upper two curves in Figure 3.3 are based on an alternative definition. In that definition EE+FSU are part of Non-Annex-I in those periods in which their emissions are below their target. In other words, the alternative definition describes leakage of emissions from countries that apply mitigation policies towards countries that are not restricted in their emissions.

Figure 3.3 shows that the leakage rate hardly differs between the A1 and B1 scenarios. The only important difference occurs at the end of the scenario period when there is still a substantial amount of hot air in the B1 scenario. The similar leakage rate in both scenarios is a manifestation of a similar relative size of Non-Annex-I in both scenarios. That the relative size of Non-Annex-I is important becomes clear in the analysis of the leakage rate over time. The gradual increase in the leakage rate is the result of the gradual increase in the share of Non-Annex-I in the world economy. Also the larger leakage rates in the alternative definition are the result of this mechanism. In the alternative definition the group of not restricted countries is larger than Non-Annex-I and therefore that group is responsible for more leakage.

Before we investigate emission reductions and carbon leakage in further detail, first the impact of mitigation policies on production and income will be discussed in the next subsection.

Figure 3.4a Impact on production and income in A1 scenario
(cumulated % change in 2020)

Unilateral | Emission trade

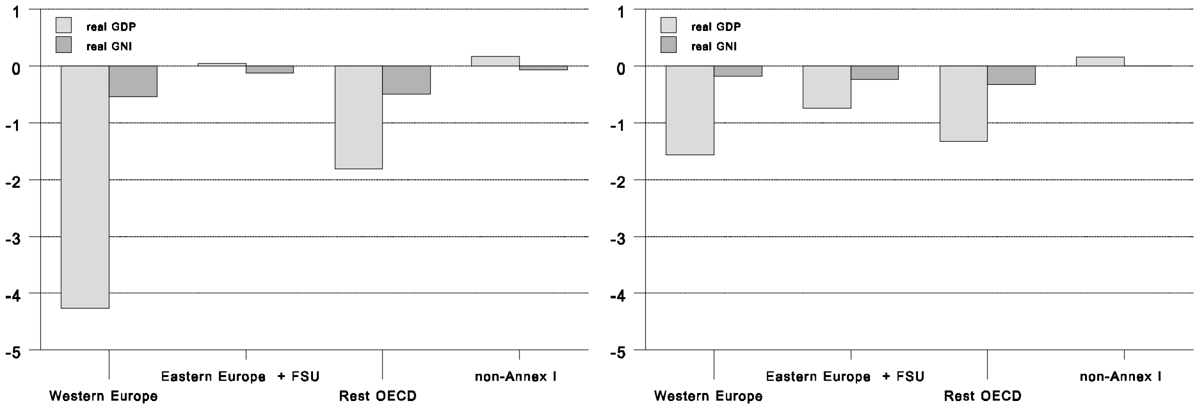
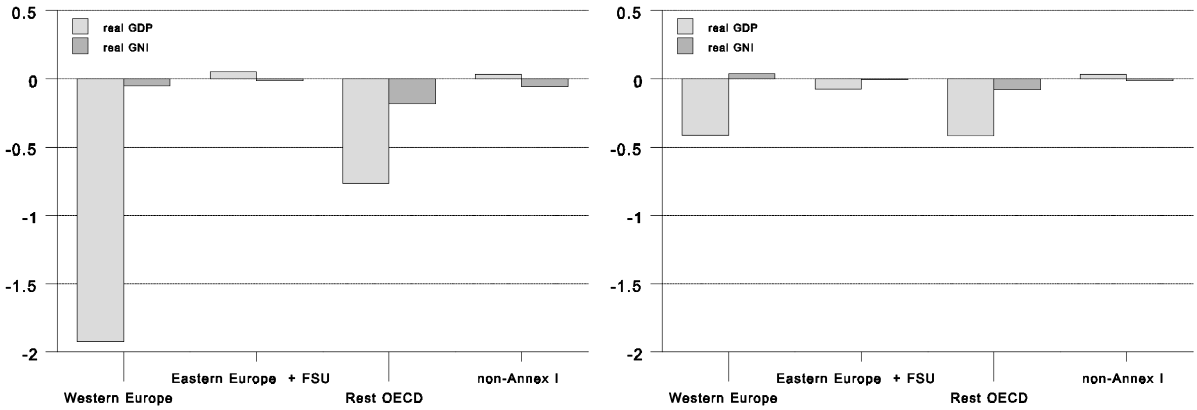


Figure 3.4b Impact on production and income in B1 scenario
(cumulated % change in 2020)



3.2 Impact on production and income

Figure 3.4 shows the impact on real gross domestic product (GDP) and real gross national income (GNI) in 2020 as percentage of the baseline. Unilateral policies in the A1 scenario lead to a decline in European GDP of more than 4%. The forced reduction of energy use can be seen as a negative supply shock, diminishing the production potential. However, the decline in real GNI is with about 0.5 % much less substantial. Change in terms of trade are responsible for 3% of this difference between the impact on real GDP and real GNP. As a result of domestic carbon taxes Western Europe can import cheaper energy while it profits from price increases of their exports. The remaining 0.5 % of the difference is the result of increased net interest income from abroad. That increase is the result of typical current account dynamics after a negative supply side shock. As a result of the (gradual) reduction in production potential the capital stock is adjusted downwards. This implies in the first years a sharp decline in investments. Lower investment demand manifests itself in a temporary improvement of the trade balance and consequently an improvement of the current account, which increases the stock of net wealth invested abroad. As a result, net interest income from abroad rises. Once the capital stock is adjusted downwards, investments return to the level needed for structural expansion and replacement of depreciated investments. Also the current account will return to its baseline level, but the composition of the current account will be permanently changed. The temporary increase in net savings leads to a permanent increase in net wealth invested abroad and to a permanent increase in net interest income from abroad. The trade balance not only returns to its baseline level, but ultimately even converges to a level below the baseline, financed by increased interest income. This mechanism distinguishes models with endogenous current accounts, like WorldScan and G-Cubed (McKibbin et.al., 1998), from models with a fixed current account like GREEN (Van der Mensbrugghe, 1998).

Also for the Rest of the OECD the figure shows a much smaller decline in GNI than in GDP, indicating also for that region an improvement of the terms of trade. The production effect in Non-Annex-I is slightly positive. There the increased energy use can be seen as a positive supply shock. Due to terms-of-trade losses the income effect is negative, but negligible. The EE+FSU are hardly affected in the unilateral case. In the case of emission trade their GDP is negatively affected because they will realize more Annex-I reductions within their borders. The direct impact of these reductions on their income is more than compensated by payments of other Annex-I countries for emission rights. However, free trade has still a slight negative overall impact on their income. The causes lie in their energy markets. Because they are not fully integrated within the world energy market, the decline in domestic energy demand is especially felt by domestic producers. That leads to a sharp decline in domestic energy production, lowering domestic rent income. It also leads to a sharp decline in domestic producer prices of energy, implying a worsening of the terms of trade.

3.3 A further breakdown of emission reductions and leakage

In this subsection we will give two breakdowns of the emission reductions and leakage in the A1 scenario. First we will give a decomposition according to the Kaya identity. Then we will present a measure for the carbon content of final demand. That measure enables us to split emissions into emissions used for own final demand and for implicit net exports of emissions.

Figure 3.6 Emission reduction split up according to Kaya-identity in A1 scenario

(cumulated % change in 2020)

Unilateral — Emission trade

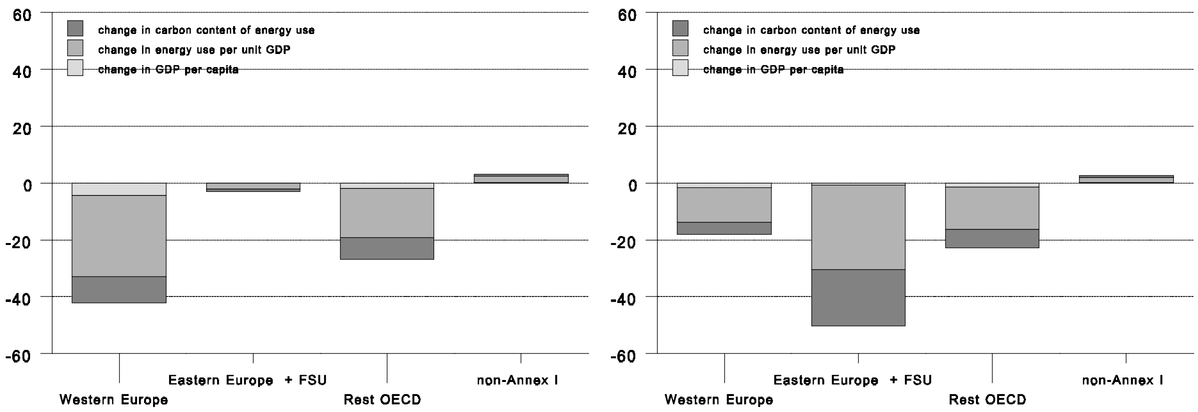


Figure 3.6 contains the decomposition of relative changes in emissions into a percentage change of GDP, a percentage change of the energy intensity of GDP and a percentage change of the

carbon intensity of energy use.[5] The figure shows that changes in overall production only to a limited extent count for changes in emissions. More substantial is the contribution of changes in the carbon content of energy. These changes reflect the substitution across energy carriers, from coal to oil and gas and from fossil fuels to bio fuels and non-thermal energy.

The most important cause of changes in emissions is the change in the energy use per unit GDP. This change in energy efficiency reflects shifts over sectors and substitution within production processes. It may also reflect some shifts across different producers of the same fossil fuel. Because of quality differences the energy content of one dollar of coal may differ among producers. As a result of a carbon tax users will shift towards higher quality coal leading to an overall reduction of the energy content of output.

Although the leakage rate is substantial, the percentage change of emissions in Non-Annex-I is very small. This demonstrates the huge relative size of Non-Annex-I at the end of the scenario period.

A second decomposition is based on the analysis of the final use of emissions. To that end we computed for all sectors the implicit carbon content, taking into account all intermediate deliveries and all imports. The results are shown in table 3.2. With the implicit emission coefficients in that table we can compute the implicit use of emissions for final demand in each region. By subtracting these implicit emissions from the emissions that were actually created in that region we get the implicit net exports of emissions. Of course implicit net exports of emissions add up to zero over the regions.

[5] Because the figure neglects second order effects, the three percentage changes only roughly add up to the percentage change of emissions.

Table 3.2 Carbon content of sectoral output in two scenarios
(in kg / thz US$)

	Western Europe			Eastern Europe and Former Soviet Union			Rest of the OECD			non_Annex I		
	1995	2020		1995	2020		1995	2020		1995	2020	
		A1	B1		A1	B1		A1	B1		A1	B1
Agriculture	11,1	8,6	6,6	59,5	17,7	14,0	12,5	8,0	6,6	16,9	10,6	9,0
Coal	234,9	199,5	156,3	184,8	43,8	38,9	192,1	107,7	104,6	271,8	126,5	117,1
Oil	51,8	34,9	26,4	109,5	32,3	27,5	7,8	4,1	3,5	84,9	45,7	41,4
Natural Gas	46,2	33,2	25,6	61,4	17,9	14,8	92,3	82,8	67,8	138,7	114,7	101,4
Other Minerals	21,0	15,7	12,2	143,1	37,0	27,9	19,2	11,5	9,5	53,5	32,1	26,6
Intermediate Goods	74,3	55,3	44,0	253,0	76,4	63,0	88,4	56,0	48,5	200,4	138,5	122,6
Consumption Goods	16,4	13,3	10,5	189,6	70,7	57,2	38,4	24,7	20,6	51,0	32,9	27,9
Capital Goods	15,4	12,5	9,9	79,0	25,4	20,1	21,8	14,9	12,5	54,0	36,3	31,4
Electricity	134,7	113,4	88,1	543,1	255,3	206,7	132,5	104,6	84,1	308,8	222,3	195,5
Services	10,4	8,2	6,3	70,9	23,0	18,3	13,9	9,0	7,4	36,5	25,5	21,9
Trade & Transport	7,4	5,9	4,4	62,8	19,0	14,6	8,8	6,2	4,9	28,2	18,6	15,8

Figure 3.7 shows that in the A1 scenario in 2020 the OECD economies are net implicit importers of carbon. For their final demand globally more carbon is emitted than they emit themselves. Or, in other words, the carbon content of OECD's imports exceeds the carbon content of OECD's exports. The reason is not primarily that the OECD countries are specialized in energy-extensive sectors, but that non-OECD countries are less energy-efficient in all sectors as is shown in table 3.2.

Figure 3.7 Implicit net exports of carbon in A1 scenario in 2020 (TgC)

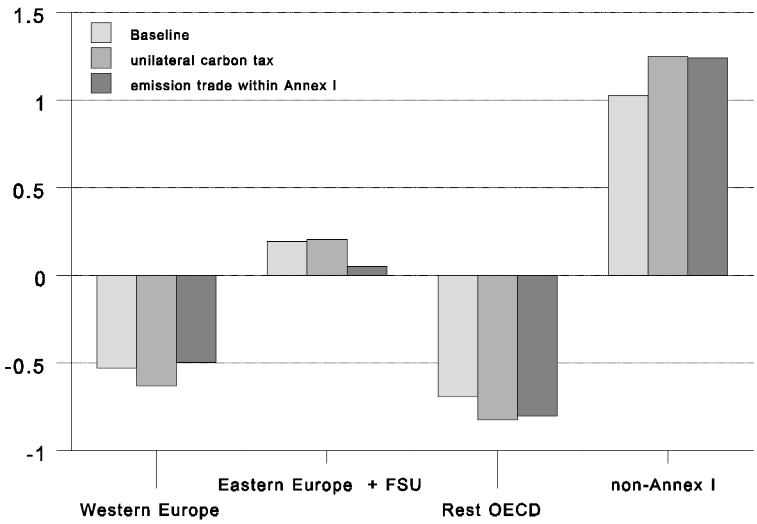


Figure 3.7 also contains the net exports in case of unilateral mitigation policies in the A1 scenario. The net exports of Non-Annex-I increase by .22 TgC. That is only .06 TgC less than the total leakage of .28 TgC. That means that most of the increase in emissions in Non-Annex-I is ultimately used for final demand in Annex-I countries. Annex-I's reductions in emissions is only partly a reduction in implicit final use of emissions. The increase in Non-Annex-I net implicit exports of emissions is the result of three factors. First, in every sector their own production becomes more energy-intensive, as table 3.3 shows. That makes also their exports more carbon intensive. Secondly, the gains in energy-efficiency in Annex-I lowers the carbon content of Annex-I's exports and Non-Annex-I's imports. Thirdly, Non-Annex-I takes over some of Annex-I's production in energy intensive sectors. For as far that production is ultimately again exported to Annex-I countries the mitigation in Annex-I merely is a shift of production across borders.

In case of trade in emission rights, the net implicit exports of emissions of EE+FSU decline significantly. So, while their exports of formal emission rights goes hand in hand with a reduction of implicit exports. Exports of EE+FSU become more energy-intensive, which lowers the implicit carbon content of their exports. The mirror image can be found in Western Europe where net implicit imports of emissions decline, because of the lower carbon content of imports from EE+FSU.

This analysis of implicit carbon use shows the importance of trade in relation to leakage. Trade is not only the ultimate cause of leakage (economies in autarky do not react to policies abroad), but it is also the channel through which leakage is partly exported back to the countries that set themselves targets.

Table 3.3a Carbon content of sectoral output in 2020 with two alternative policies in A1 scenario

	Western Europe		Eastern Europe and Former Soviet Union		Rest of the OECD		non-Annex I	
	unilateral	emission trade	unilateral	emission trade	unilateral	emission trade	unilateral	emission trade
Agriculture	6.6	7.3	17.2	11.1	6.8	6.9	11.0	10.8
Coal	88.0	134.6	44.8	26.9	61.8	66.8	133.0	131.3
Oil	28.7	33.3	32.9	23.1	3.4	3.4	48.1	47.6
Natural Gas	26.8	31.1	17.9	11.2	75.1	75.8	118.7	117.5
Other Minerals	12.6	13.7	36.2	23.4	9.0	9.3	33.2	32.8
Intermediate Goods	42.1	49.2	74.5	41.3	46.6	47.6	144.1	142.4
Consumption Goods	10.5	11.4	69.5	46.8	21.0	21.4	33.9	33.4
Capital Goods	10.5	11.2	24.9	16.0	13.1	13.2	37.7	37.1
Electricity	56.7	79.7	250.4	159.1	65.6	69.8	230.2	227.6
Services	6.4	7.2	22.6	14.3	7.7	7.8	26.5	26.1
Trade & Transport	4.6	5.1	18.5	11.7	5.1	5.2	19.2	18.9

Table 3.3b Carbon content of sectoral output in 2020 with two alternative policies in B1 scenario

	Western Europe		Eastern Europe and Former Soviet Union		Rest of the OECD		non-Annex I	
	unilateral	emission trade	unilateral	emission trade	unilateral	emission trade	unilateral	emission trade
Agriculture	5.8	6.3	14.4	12.3	6.2	6.3	9.2	9.1
Coal	103.9	141.8	42.4	33.4	88.2	94.3	120.2	118.5
Oil	24.1	26.2	28.6	25.4	3.2	3.3	42.4	42.0
Natural Gas	23.1	25.3	15.4	12.9	66.1	66.7	103.1	102.2
Other Minerals	10.8	11.8	28.9	24.5	8.6	8.9	27.1	26.8
Intermediate Goods	38.1	42.7	65.5	53.2	45.0	46.3	124.9	123.7
Consumption Goods	9.3	10.0	58.8	51.4	19.4	19.9	28.3	28.1
Capital Goods	9.0	9.6	20.7	17.7	11.9	12.1	31.9	31.5
Electricity	60.1	80.1	217.0	181.4	71.2	76.1	199.1	197.1
Services	5.6	6.1	18.9	16.0	7.0	7.1	22.3	22.0
Trade & Transport	3.9	4.3	15.1	12.8	4.6	4.7	16.1	15.9

4 Sensitivity analysis

Leakage may occur through migration of energy intensive industries away from Annex 1 regions and through substitution within industries in non-Annex 1 countries towards cheaper energy[6]. Armington elasticities rule the substitution between domestic and imported goods. Substitution possibilities within sectors depend on the substitution parameters of the production function. This section explores how sensitive WorldScan results are to these two sets of key parameters: Armington elasticities and substitution elasticities. We run a number of variants with different parameter settings and compare the effects of the policy simulations with the reference case.

Changing the Armington elasticities

[6] Income effects are negligible small, so leakage through this channel is not taken into consideration.

WorldScan contains rather high long-run price elasticities in demand for foreign goods. Elasticities vary between 5 and 16 (in absolute values). In the case of positive carbon prices, sectors with a high carbon content, *e.g.* intermediates, will 'suffer' more. High trade elasticities will induce a strong shift in demand from expensive domestic sectors towards inexpensive foreign sectors. To assess the role of these trade elasticities we halve the long-run Armington elasticities. We calibrate both the A1 and B1 scenario with these lower elasticities, to ensure that the baseline with new parameter values contains the same energy use as the original baseline, and run the unilateral and free trade cases.

Changing substitution parameters

Substitution possibilities depend on structure and parameters of the production function. WorldScan assumes a nested CES structure, which is more or less identical over regions and sectors. Output is a CES-aggregate of value-added and intermediates. Intermediates, for its part, is a CES-aggregate of energy and other intermediates. Next, the energy nest is a CES aggregate of all fossil inputs, electricity, biofuels and non-thermal electricity[7]. Crucial in the simulations we are considering, is how energy demand reacts to price changes (at a given output). The magnitude of this price elasticity of energy demand depends on substitution possibilities within the energy nest and the substitution between the energy nest and other nests in the production function. To assess the sensitivity of these substitution possibilities, we calibrate a model version with lower substitution parameters. The substitution parameter between energy and other intermediaries is halved from 0.8 to 0.4, the intra energy substitution is reduced from 2.0 to 0.8. Again, we calibrate both the A1 and B1 scenarios to target the same energy use and analyse the free trade and unilateral cases.

Some results

Table 4.1 presents the leakage rates under alternative specifications, Table 4.2 presents the corresponding carbon prices.

Table 4.1 Leakage rate[1] under alternative specifications

	Reference	Low Armington	Low substitution
Unilateral case		%	
A1	20	16	22
B1	20	16	17
Annex 1 trading			
A1	19	15	19
B1	17	16	17

[1] Leakage rate defined as the change in emissions in Non-Annex I as a percentage of the reduction in Annex I.

According to the entries in column 2 of Table 4.1, lower trade elasticities lead to lower leakage rates, in both scenarios and in both policy cases. Although, the effects are modest. Carbon prices are slightly lower. However, one has to realise that the general price level in the Armington variant is lower. Given the stronger home bias in demand, fast growing economies have to lower

[7] In the electricity sector, electricity is not included in the energy nest.

their prices to create enough export possibilities. Their terms of trade deteriorate. For OECD countries there is a terms of trade gain.

Table 4.2 Carbon prices in Annex 1 under alternative specifications

	Reference	Low Armington	Low substitution
Unilateral case		*1995 US$ / tC*	
A1			
Western Europe	120	118	220
EE + FSU	50	48	93
Rest OECD	7	7	12
B1			
Western Europe	41	39	75
EE + FSU	14	13	24
Rest OECD	0	0	0
Annex 1 trading			
A1	42	40	77
B1	8	7	14

Lowering substitution parameters in the production function gives more ambiguous results. In the unilateral case there is an increased leakage the A1 scenario, but a decrease in the B1 world. In the case of free trade, changing substitution within sectors does not seem to alter the leakage rate. However, carbon prices in all situations rise.

A decomposition

If trade elasticities or production elasticities change, substitution over sectors *and* substitutions within sectors may change. Both effects may have an opposite impact on the leakage rate. For example, lowering the substitution parameters, both the intra energy substitution and the substitution between energy and other intermediaries, hampers the shift towards cheaper energy. This gives a downward pressure on leakage. The price elasticity of demand decreases as a consequence of the lower substitution between the different energy carriers. Hence, a higher price increase is needed to realize a given decrease in the energy demand. Lowering the substitution possibilities between energy and other intermediaries leads to a further rise in abatement costs. The higher carbon prices induce a larger shift in energy-intensive production from Annex I to non-Annex I, *i.e.* a larger shift over sectors. This gives an upward pressure on leakage.

A decomposition of the leakage rate can shed some light on this issue. We compute the carbon content of fossil energy in all sectors in the base line. Next, we compute the effect of the change is sector structure on emissions using the baseline direct carbon contents[8]. This indicates

[8]This measure of carbon content differs from the one discussed in the previous section. Here only the direct emissions used in the production process are taken into account, not the implicit emission related to the intermediary use of other products.

the effect of substitution over sectors. The complement denotes the effect of changes within sectors. As an illustration, for the unilateral case in the A1 scenario a decomposition has been made. Table 4.3 presents some results.

Table 4.3 Decomposition of leakage rate[1] in A1, unilateral case

	Reference	Low Armington	Low substitution
		%	
Total	20	16	22
over sectors	9	3	16
within sectors	11	13	6

[1] Leakage rate defined as the change in emissions in Non-Annex I as a percentage of the reduction in Annex I.

Lowering the Armington elasticities in this variant lowers the effect of shifts over sectors from 9% to 3%. There is a small effect on shifts within sectors. Energy prices in non-Annex I are a bit lower. The lower energy prices will induce substitution within sectors towards fossil fuels and an upward pressure on leakage. Due to substitution within sectors, leakage rises from 11% to 13%.

Lowering the substitution parameters leads to a higher carbon price. The higher carbon prices induce a larger shift in energy-intensive production from Annex 1 to non-Annex 1, *i.e.* a larger shift over sectors (from 9% to 16%). Compared to the reference case, in non-Annex 1 there is less substitution towards cheaper energy, the carbon content. is lower. Due to substitution within sectors, leakage decreases from 11% to 6%.

5 Conclusions

The focus of this paper is carbon leakage under the Kyoto protocol. The dynamic AGE model WorldScan is used to analyse the effects of both unilateral action and permit trading within Annex I . Two new IPCC scenarios, A1 and B1, are used as ‘Business-As-Usual’ scenarios. Both scenarios assume high growth rates, especially in Non-Annex-I. The main difference is that in B1 very rapid autonomous improvement in energy efficiency is assumed. That makes the necessary reductions to comply with the Kyoto Protocol smaller and it generates a substantial amount of hot air in the Former Soviet Union, even in 2020. The two scenarios turn out to generate similar leakage rates to non-Annex I regions. However there is a large difference in leakage within the Annex I region. In 2020 reduction in restricted Annex I countries are still partly offset by induced increases of emissions in the Former Soviet Union. Typical values for the leakage rate to non-Annex I turn out to be around 20 percent. Leakage in case of free emission trade is slightly lower compared to the case with unilateral mitigation policies.

In the analysis we split up leakage in three different ways. First, we use the well-known Kaya identity where a change in emissions is disentangled into a change into a change in production, a change in the energy intensity of production and a change in the carbon intensity of energy. Changes in energy intensity of production are more important than changes in carbon intensity of energy. The latter is more important in countries that reduce their emissions than in countries that increase their emissions. Changes in the level of total production are negligible as cause of leakage.

Secondly, we decomposed emissions into emissions that are ultimately used for domestic final demand and emissions that are use for net exports of goods and services. To that end we computed for all sectors the implicit carbon content, taking into account all intermediate deliveries and all imports. With this decomposition we could compute how mitigation policies change the carbon content of final demand in Annex-I and Non-Annex-I. It turned out that most of the leakage to is implicitly used for final demand in Annex I regions. The implicit net imports of carbon through trade in goods and services increase along with leakage of emissions to non-Annex I.

Thirdly, in sensitivity analyses we split changes in emissions into changes that result from shifts over sectors and changes that results from shifts in production technologies.[9] Crucial for these processes are trade elasticities and production substitution elasticities. In the sensitivity analyses we assessed the importance of these parameters. In these exercises we tried as far as possible to prevent changes in the baseline having an influence on the outcomes. Higher trade elasticities tend to lead to higher leakage as a result of shifts over sectors, but to slightly smaller leakages through changes in input structures of production. Lower substitution elasticities in the production process tend to decrease leakages through changes in the input structures, but a also increases significantly leakage as a result of shifts over sectors.

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[9] The distinction between changes in production technologies and shifts over sectors is a vague one. In every economic model sectoral output consist of heterogeneous products, which implies that production functions always describe, besides technological options, also the consequences of shifts over products. However, in sensitivity analysis the distinction between demand and production functions is a convenient one because both elements refer to specific model parameters.