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Non-CO_2 Greenhouse gases
All gases count

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Abstract in English

Under the Kyoto Protocol, a group of countries commit themselves to reduce the emissions of greenhouse gases to some 5% below the 1990 level. Countries can decide to spread their reduction commitment over several gases to lower compliance costs. Employing a multi-gas strategy can offer considerable efficiency gains because of the widely diverging marginal abatement cost for the different emission sources. In this Discussion Paper, the analysis of climate policy for the most important greenhouse gas, carbon dioxide, is extended with two other important greenhouse gases, methane and nitrous oxide. The multi-region and multi-sector Applied General Equilibrium model WorldScan has been used as an instrument for addressing this issue. The approach presented is consistent with the bottom-up information on reduction possibilities for those non-CO_2 greenhouse gases while it allows for general equilibrium effects and intergas interactions. Including non-CO_2 greenhouse gases into the analysis has important sectoral impacts while the regional effects are limited. A considerable part of the burden on gas, coal and oil products will be shifted to the agricultural sectors. Reductions of non-CO_2 gases could be especially important for countries like China and India.

Key words: Climate policy, non-CO_2 gases, Applied General Equilibrium Model

Abstract in Dutch

Een groep landen heeft zich in het Kyoto-protocol verplicht de emissies van broeikasgassen te reduceren tot ongeveer 5% onder het niveau van 1990. Landen kunnen hun reductie-inspanning spreiden over diverse gassen om de bijbehorende kosten te verlagen. Het toepassen van een multi-gas-strategie biedt een aanzienlijke efficiëntiewinst door de grote verschillen in marginale reductiekosten van de diverse emissiebronnen. In dit Discussion Paper wordt de analyse van klimaatbeleid voor alleen het belangrijkste broeikasgas, kooldioxide, uitgebreid met twee andere belangrijke broeikasgassen, methaan en distikstofoxide (lachgas). Het multi-regio- en multi-sector toegepast algemeen evenwichtsmodel (WorldScan) is hierbij als onderzoeksinstrument gebruikt. De gepresenteerde benadering is consistent met bottom-up informatie over deze niet-CO_2-broeikasgassen, terwijl het algemeen evenwichtseffecten en interacties tussen gassen toestaat. Het opnemen van niet-CO_2-broeikasgassen in de analyse heeft belangrijke sectorale gevolgen, terwijl de regionale effecten beperkt blijven. Een aanzienlijk deel van de lastendruk op gas, kolen en olie wordt verschoven naar de landbouwsectoren. Reductie van niet-CO_2-gassen zou vooral belangrijk kunnen zijn voor landen als China en India.

Steekwoorden: klimaatbeleid, niet-CO_2-gassen, Toegepast Algemeen Evenwichtsmodel

Een uitgebreide Nederlandse samenvatting is beschikbaar via www.cpb.nl.

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Summary

The Kyoto Protocol (1997) commits a group of industrialised countries to reduce their emissions of greenhouse gases in 2008-2012 to approximately 5% below their 1990 levels. Countries can decide to spread their reduction commitment over several gases to lower the compliance costs. Spreading the reductions over multiple gases may have a considerable impact on the economic costs of compliance, even though the non-CO_2 gases are only responsible for a relatively small share of total emissions. Most importantly, the widely diverging marginal abatement costs of the gases offer the potential for realising considerable efficiency gains. This Discussion Paper presents the results of incorporating methane and nitrous oxide in a multi-region and multi-sector applied general equilibrium model (WorldScan). The approach presented is consistent with bottom-up information on reduction possibilities for those non-CO_2 greenhouse gases, while it allows for general equilibrium effects and inter-gas interactions. Most applied general equilibrium models for climate policies only use a rule of thumb for emission reductions of non-CO_2 gases.

The results show that non-CO_2 abatement can lower costs substantially for all regions, although the magnitude of this cost reduction varies over regions. For the members of EU-15, the USA and other OECD countries, the share of non-CO_2 gases in total reduction is modest and declines rapidly at higher prices, so that there is a smaller role for non-CO_2 gases at higher emission prices. However, the sectoral effects of employing a multi-gas strategy are considerable at low prices. Part of the burden on gas, coal and oil products has now been shifted to the agricultural sectors. Reductions of non-CO_2 gases could be especially important for countries like China and India if they would participate in international climate policy.

1 Introduction[1]

The Kyoto Protocol (1997) commits a group of industrialised countries—the Annex-B countries[2]— to reduce their emissions of greenhouse gases in 2008-2012 to approximately 5% below their 1990 levels. Compared to a reference scenario without climate policy, the reduction is much larger than this 5%, however. Emissions have grown in most countries since 1990, and will continue to do so without additional policy measures. This sizeable reduction has raised concern about the associated economic costs. Fortunately, the Protocol contains a number of flexibility mechanisms to lower the costs of compliance. One of these is the 'what-flexibility'[3]— the possibility of spreading the reduction commitments over multiple gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and a group of fluorinated gases.

Most economic analyses deal only with CO_2 emission reductions, but interest in non-CO_2 greenhouse gases is growing. Even though non-CO_2 greenhouse gases are responsible for only 28% of the Kyoto gas emissions measured in CO_2-equivalents,[4] their inclusion in the calculations may have a considerable impact on the economic costs of compliance: the widely diverging marginal abatement costs of the gases offer the potential for realising considerable efficiency gains. Previous studies have estimated the cost savings of a multi-gas strategy compared to a CO_2- only policy to be more than proportional to the emission contributions of the non-CO_2 greenhouse gases (Hayhoe *et al.*, 1999; Manne and Richels, 2001; Reilly *et al.*, 1999; Reilly *et al.,* 2003, Hyman *et al.*, 2002). In most of these studies, the non-CO_2 greenhouse gases are incorporated in the model through exogenous marginal abatement cost (MAC) curves, derived from bottom-up analyses.[5] The MAC-curves show the cost of abating the next incremental ton of greenhouse gas for each level of overall abatement. A MAC-curve is derived by ordering abatement opportunities by cost from low to high, and plotting the total abatement volume of each option.

An important disadvantage of using exogenous MAC-curves is their inability to capture inter-gas interactions. For instance, several methane sources are linked to energy use, so that a tax on fossil fuels will also bring down methane emissions. Moreover, employing exogenous MAC-curves also neglects general equilibrium effects, such as the impact on import and export

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[2] The Annex I or Annex B group consists of Western and Eastern Europe, the USA, Canada, Japan, Australia, New Zealand and the former Soviet Union (the USA and Australia have decided not to ratify the Protocol, however). The Annex B group can thus roughly be identified with the industrialised countries and the countries in transition; the non-Annex B group consists of the developing countries.

[3] The other flexibility mechanisms are when-flexibility and where-flexibility. When-flexibility relates to the timing of reductions (in the 2008-2012 period). Where-flexibility means that countries can accomplish part of their reduction abroad, through emission trading or setting up reduction projects in other countries (via Joint Implementation or the Clean Development Mechanism).

[4] For an explanation of the unit for measuring emission volumes, see the Box on page 10.

[5] Notable exceptions are Manne and Richels (2001) and Hyman *et al.* (2002).

prices, effects on terms of trade and on the investment in and depletion of fossil fuel resources. Finally, welfare analysis is not possible in a partial equilibrium approach. The economic costs measured as the area under a partial equilibrium MAC-curve are not consistent with equivalent variation, the welfare measure that is commonly used in assessing policy costs.

Measuring greenhouse gas emissions

The Kyoto Protocol covers six different greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and three F-gases (HFC, PFC and SF_6). The emission targets in the Kyoto protocol apply to the aggregate of these six gases. These gases differ in their Global Warming Potential (GWP), i.e. their effect on radiative forcing. The GWP of a greenhouse gas is defined as the ratio of the cumulative radiative forcing that would result from the emissions of one kilogram of that gas to that from emission of one kilogram of carbon dioxide over a period of time (usually 100 years). The table below (derived from Jensen et al., 2001) presents the GWPs of the different gases.

Emission volumes are thus commonly expressed in carbon dioxide equivalents (CO_2-equivalents): the metric volume times the GWP. For instance, the emission of 1 ton of methane has the same impact on radiative forcing as 21 ton of CO_2. Carbon dioxide equivalents can easily be converted to carbon equivalents (Ceq) by multiplying the carbon dioxide equivalents by 12/44 (the ratio of the molecular weight of carbon to carbon dioxide).

Table: Kyoto greenhouse gases, Global Warming Potential and main emission sources

Greenhouse gas	GWP	Emission sources
CO_2	1	Combustion of fossil fuels (coal, oil and gas)
CH_4	21	Cattle and manure, rice, natural gas, waste and fuel losses/leakage
N_2O	310	Agricultural soils, fertilizer and industrial production (adipic and nitric acid)
HFCs[a]	140-11700	Air conditioning and foam blowing
PFCs[a]	6200-9200	Aluminium and semiconductors
SF_6	23900	Magnesium, semiconductors and electrical switchgear

[a] Differences across regions exist due to the composition of the F-gases.

For these reasons, we have incorporated the abatement of methane and nitrous oxide as an endogenous component in the multi-region and multi-sector Applied General Equilibrium (AGE) model WorldScan (CPB, 1999).[6] In this paper, we investigate the impact of including these gases in the analysis in addition to CO_2-emissions from fossil fuel combustion. The key feature of our approach is that abatement of non-CO_2 greenhouse gases implies a loss of productivity: resources have to be diverted to abatement (*cf.* Hyman *et al.*, 2002; Copeland and Taylor, 2003). The association of a productivity loss with abatement makes that the MAC-curves are endogenously generated in our model. The difference between our approach and models in which MAC-curves are exogenous, is that in our approach, the full general equilibrium effects are taken into account, as the abatement costs are part of the firm's optimisation problem. A firm can choose to abate emissions to avoid paying a tax on these emissions, but this comes at the cost of reduced productivity, as resources have to be diverted to

[6] The so-called F-gases are not incorporated as their volume is negligibly small.

abatement. Alternatively, the firm can choose not to abate at all, paying the full emission tax. In general, there will be an interior optimum. The bottom-up MAC-curve of the non-CO_2 greenhouse gases implicitly determines this optimum. Hence, our approach is consistent with bottom-up information, while it allows for general equilibrium effects and inter-gas interactions.

In the analysis, we focus on the general equilibrium marginal abatement cost curves, as these indicate the cost-saving potential of including non-CO_2 greenhouse gases in climate policy. With this focus in mind, we perform two types of analyses. First, we decompose the change in the MAC-curves in different general equilibrium effects. Subsequently, we compare the costs of a multi-gas strategy to the costs of a CO_2-only approach.

This paper is organised as follows. In Section 2, we will first discuss the emissions in the baseline scenario, focusing on the importance of non-CO_2 gases in different regions and for different sectors. This gives a first indication of the effects of extending climate policy to non-CO_2 gases. In Section 3, we discuss the modelling of non-CO_2 gases in WorldScan, with special emphasis on the effect of abatement on productivity. The results are presented in Section 4. Section 5 concludes.

2 Emissions

2.1 Baseline scenario

In the reference or baseline scenario it is assumed that no climate policy measures are applied other than the current measures; it is a so-called Business-as-Usual (BaU) scenario. The impact of climate policy such as the effect on GDP and sectoral structure can then be determined by comparing the results from the baseline scenario to the results of a scenario in which new measures are initiated. The baseline scenario is thus used as a benchmark.

The choice of baseline scenario is not neutral, as its characteristics have an important effect on the estimated costs of climate policy. Firstly, the baseline emissions set the reduction volume, which is defined relative to 1990 emissions. Moreover, in a baseline scenario with high (low) economic growth, costs will be higher (lower). Also the sectoral composition, technological change and demographic developments will have an effect on the costs of climate policy.

Our baseline scenario is built up from several partial scenarios, each providing complementary information. The economic developments and the CO_2-emission projections are taken from a version of the 'Strong Europe' scenario (CPB, 2003). In addition, projections for the regional emission factors of the non-CO_2 gases to predict future emission intensities are taken from the A1B scenario of the IMAGE SRES scenarios (RIVM, 2001). The A1B scenario is consistent with the 'Strong Europe' scenario of CPB (2003).[7] This A1B scenario describes a world with increasing globalisation, rapid technological progress, and high economic growth. Finally, the projections of non-CO_2 greenhouse gases for the individual EU-countries stem from the Sectoral Objectives Study (Capros, Kouvaritakis and Mantzos, 2001; Hendriks *et al.*, 2001).

Table 2.1 and 2.2show the composition of non-CO_2 emissions in several regions. The non-CO_2 greenhouse gases account for a considerable share in total emissions, ranging from roughly 15% in the USA, the Rest of OECD and the EU-15 countries to even 40% in Latin America. The sectoral composition of the emissions varies greatly over regions. Firstly, emissions from rice cultivation are only important in the WorldScan region Rest of World. Also the share of emissions from the production of nitric and adipic acid varies strongly over regions. Despite its modest contribution to total emissions, the production of nitric and adipic acid is an important emission source, because of its large reduction potential at low costs, as will be discussed below. Thirdly, the share of emissions from leakages in energy production differs considerably among regions. Also for this source, there are substantial reduction possibilities at fairly low costs. We will come back to the possible implications of the sectoral composition of emissions in Section 2.3.

[7] Bollen et al. (2004) also used the 'Strong Europe' scenario, but they derived the energy and climate developments from the B1 scenario of IMAGE SRES.

Table 2.1 Regional and sectoral composition of non-CO_2 emissions (%) in WorldScan, 1997[a]

	USA	EU-15	Former Soviet Union	Eastern Europe	Rest OECD	Middle East	Latin America	Rest of World	World
Livestock	30	42	22	30	53	33	82	43	43
Paddy rice	1	0	1	0	5	3	2	24	11
Leakages coal	25	7	6	37	6	0	1	11	11
Leakages oil	3	1	4	1	2	12	4	1	3
Leakages gas	23	7	62	11	17	41	3	3	15
Fertilizer use	13	27	5	11	12	8	7	17	14
Adipic and nitric acid	6	16	1	11	6	1	1	1	3
Non-CO_2 gases	14	14	25	20	13	22	41	31	23

[a] The share of the different sources is calculated relative to the total non-CO_2 emissions of non-CO_2 sources (weighted by their GWP) included in the model; the share of non-CO_2 gases is defined relative to the sum of the non-CO_2 and CO_2 emissions.
Source: WorldScan based on RIVM (2001).

Table 2.2 Regional and sectoral composition of non-CO_2 emissions (%) for several European countries in WorldScan, 1997[a]

	Germany	France	Great Britain	Spain	Italy	Netherlands	Belgium[b]	Rest EU
Livestock	38	40	29	44	43	39	54	61
Paddy rice	0	0	0	0	0	0	1	1
Leakages coal	13	2	12	12	6	6	4	1
Leakages oil	1	0	1	1	0	1	0	0
Leakages gas	11	2	11	11	5	6	3	1
Fertilizer use	20	37	24	27	31	16	17	33
Adipic and nitric acid	17	19	22	5	14	32	21	3
Non-CO_2 gases	11	24	14	17	11	15	9	15

[a] The share of the different sources is calculated relative to the total non-CO_2 emissions of non-CO_2 sources (weighted by their GWP) included in the model; the share of non-CO_2 gases is defined relative to the sum of the non-CO_2 and CO_2 emissions.
[b] Including Luxembourg.
Source: Capros et al. (2001) and Hendriks et al. (2001).

2.2 Emissions: activity and emission intensity

The volume of greenhouse gas emissions depends on two distinct components: the production level and the emission intensity, i.e. the emissions per unit of output. Emissions are thus, by definition, the product of the activity level of the emission source and the emission factor:

$$E_{s,r,t} = E^{F}_{s,r,t} \cdot Q_{s,r,t} \tag{2.1}$$

with E the emission volume, E^F the emission coefficient or emission factor and Q the activity level of the emission source. The subscripts *s, r* and *t* refer to the emission source, region and time, respectively. Emission factors differ among regions, as regions differ in their production technologies and their input mix. Similarly, within a region, emission factors can change over time, as technologies develop and different inputs are used. These remarks hold both for CO_2 and for the non-CO_2 gases alike. However, for CO_2, the change in emission factor is modelled by explicitly modelling the input of different fuels, each with their own emission intensity. For non-CO_2, the emission intensity is influenced by a myriad of factors. For instance, emissions from paddy rice are influenced by nutrients, cultivar type and irrigation method (see e.g. Burniaux, 2000). It is not possible to model all these factors in WorldScan, also because of data problems. Therefore, we use the emission factor as a 'catchall' variable.

The emission factor may change in the baseline scenario without newly imposed climate policy measures This change in emission factor in the baseline is called Autonomous Emission Efficiency Improvement; this mechanism will be discussed in Section 2.2.1. If the emission factor changes as a result of climate policy, it is called Induced Technological Change. This mechanism is discussed in Section 2.2.2.

2.2.1 Baseline: Autonomous Emission Efficiency Improvement

In the baseline, the emission coefficient may vary over time as a result of technological developments or a change in input mix. For instance, farmers may decide to increase the share of sheep in their herd at the expense of cows, thus affecting the emission coefficient of livestock-related sources. These changes are not prompted by some desire to decrease emissions but stem from other considerations, such as technological developments, cost reduction and changes in lifestyle. When the emission coefficient decreases as a result of such 'autonomous' changes, this is called Autonomous Emission Efficiency Improvement (AEEI).

The change in emission factor in the baseline scenario has been derived from the emission volume and the corresponding activity levels from the IMAGE SRES scenarios (RIVM, 2001).[8] Table 2.3 presents the change in emission factor in the period 1997 - 2010 for several emission sources.

[8] There are small differences in the definition of WorldScan and IMAGE 2.2 emissions sources, causing some error in the estimates of WorldScan emission factors, but these errors are likely to be small. For the European countries, there is an additional source of error. As the Sectoral Objectives Studies do not include information on activity levels, we have used the data for the aggregated European Union from the IMAGE SRES scenarios as a proxy for the economic developments in the individual European countries. This introduces two types of error. First of all, it is of course not justified to use 'toto pro pars': the economic developments in the individual countries will differ from the overall average. Furthermore, the scenarios employed in the Sectoral Objectives Study are not the same as the scenarios underlying the IMAGE emission projections. However, the emission factors calculated on the basis of these data look quite reasonable.

Table 2.3 Emission factor in 2010 (1997 = 100; world average)

	Baseline emission factor
Livestock	74.2
Paddy rice	85.5
Leakage coal	81.6
Leakage gas	87.5
Leakage oil	97.9
Fertilizer use	100.5
Adipic and nitric acid	44.2

Source: WorldScan calculations on the basis of RIVM (2001).

Generally, the emission factors fall steadily over time. It should be noted that the global averages in Table 2.3 hide some important regional differences. For instance, the emission factor from the adipic and nitric acid production falls to 27 in the USA in 2010, whereas it stays relatively high at 96 for Latin America. This reflects differences in production technologies, abatement options, environmental policies and many other factors.

Table 2.4 shows the combined effect of the change in emission factor and in activity level on the emission volume for the various sources. This decomposition shows the importance of the variable emission factor in determining the emission volume. The change in emission factor can either compensate for or reinforce the change in activity level. Often, the emission intensity as measured by the emission factor falls, while sector output expands. The net effect on emissions depends on the relative magnitude of those effects. Generally, the emission volume rises in the baseline. This is in particular the case for emissions from fertilizer use, paddy rice, oil leakage and gas leakage.

Table 2.4 Decomposition of the global changes in emission volume in % per year for the baseline scenario (1997-2010)

	Emission factor	Activity level	Emission volume
Methane sources			
Livestock	– 2.3	2.8	0.5
Paddy rice	– 1.2	2.8	1.6
Leakage coal	– 1.5	0.0	– 1,5
Leakage oil	– 0.2	1.6	1.5
Leakage gas	– 1.0	2.5	1.5
Nitrous oxide sources			
Fertilizer use (N_2O)	0.0	4.5	4.5
Adipic and nitric acid (N_2O)	– 6.1	4.6	– 1.5

Source: WorldScan calculations on the basis of RIVM (2001).

2.2.2 Climate policy: Induced Technological Change

The emission factor may also fall as a result of climate policy. In that case, a tax on emissions induces firms to alter their production technology such that the emissions per unit of output fall. Of course, these reductions generally do not come for free. For instance, rice producers have to invest in new irrigation systems (intermittent irrigation) to lower methane emissions per unit of output. The information on abatement options and their costs is summarised in so-called Marginal Abatement Cost (MAC) curves. An important parameter for describing the MAC-curves is the reduction potential, i.e. the technical limit to the share of the emissions that can be abated. This variable is presented in Table 2.5 for several sources and regions. The MAC-curves themselves are presented in Appendix A and explained in detail in 3.1.1. The reduction potential in the livestock sector is set to zero, even though there are indications that there is a positive reduction potential (see e.g. Burniaux, 2000). However, the data are not very accurate. Furthermore, the reduction potential in the livestock sector is only positive for emissions from manure, which only make up 7% of total livestock emissions.

For all sources, except for leakages from gas production and distribution, the MAC-curves show that the reduction potential is already reached at fairly low emission taxes. This implies that reductions up to the reduction potential are generally cheap for non-CO_2 gases. The reduction potentials are often substantial. Especially for N_2O-emissions from adipic and nitric acid, the reduction potential is large: almost all emissions can be eliminated at virtually no costs. Also for emissions from losses and leakages from coal mining, oil production and gas production and distribution, the reduction potential is large.

Table 2.5 Regional reduction potential relative to 1997 emission factor

	USA	EU-15	Former Soviet Union	Eastern Europe	Rest OECD	Middle East	Latin America	Global average
Livestock[a]	0	0	0	0	0	0	0	0
Paddy rice	57	57	57	57	57	57	57	57
Leakages coal	88	52	61	73	76	86	100	80
Leakages oil	21	100	38	100	29	43	35	32
Leakages gas	56	49	43	100	55	60	59	53
Adipic and nitric acid	92	92	100	92	92	100	100	93

[a] The positive reduction potential for manure is ignored, as its emissions only constitute a minor fraction of total livestock emissions.

Source: EPA (2003), Brown et al. (1999)

2.3 Scope for non-CO_2 greenhouse gases

In most economic analyses of climate policy, only CO_2-emissions are considered. In that case, it is implicitly assumed that non-CO_2 greenhouse gases are reduced by the same relative amount as CO_2 , although no costs are attached to the reduction of non-CO_2 gases. By contrast, this paper focuses on the gains from what-flexibility, i.e. the difference in abatement costs when the emissions of all greenhouse gases are taxed and when only CO_2-emissions are taxed for a given emission target. Since non-CO_2 gases offer additional reduction options that are sometimes less expensive than the options involving the reduction of CO_2, the costs of a multi-gas strategy will be equal to or lower than a strategy in which only CO_2-emissions are abated.

However, the reduction potential and the reduction costs differ per emission source, so that the composition of the total emission volume is an important determinant of the abatement costs in a region. Hence, the effect of a multi-gas strategy is expected to vary by region, as the composition of the emission volume depends on the fundamental structure of the economy. Section 2.1 and 2.2 give a first indication of the importance of non-CO_2 greenhouse gases in different regions. Table 2.1, 2.2 and 2.5 suggest that all regions can gain by employing a multi-gas strategy, though to differing degrees. For the non-Annex B regions, the share of non-CO_2 emissions is generally high, while for the industrialised countries the share of emission sources with low abatement costs is fairly high.

For all regions, the scope for reduction by abating emissions from leakages in gas production and distribution is considerable. For instance, in the former Soviet Union where emissions from leakages in gas production and distribution account for 56% of total non-CO_2 emissions, almost 35% of the emission volume from this source can be abated at 100 dollar per ton carbon equivalent. For all regions, both the reduction potential and the share in total emissions are considerable for this source.

While reducing emissions from gas leakage and production is important for all regions, there are also emission sources that are especially important for a selection of regions. Emissions from adipic and nitric acid production are particularly important for European countries, because of their huge reduction potential at almost zero cost and their substantial share in emissions in these countries.

3 Non-CO_2 greenhouse gases in WorldScan

3.1 WorldScan

To determine the economic impact of including non-CO_2 greenhouse gases in climate policy, the non-CO_2 emission sources have been incorporated in the applied general equilibrium (AGE) model WorldScan. More information on this model can be found in the box below and in CPB (1999).

WorldScan in a nutshell

WorldScan (CPB, 1999) is a multi-sector, multi-region Applied General Equilibrium (AGE) model. The model is developed to study long-term global issues, such as globalisation and climate change policy. The model builds upon neoclassical theory, has strong micro-foundations and solves for the equilibrium that maximises welfare across the entire economy, subject to technological constraints, greenhouse gas limitations, etc. The model is calibrated on input-output tables and trade data from the GTAP5 database (Dimaranan and McDougall, 2002). The base year for the model is 1997. Production sectors use capital, labour, natural resources and intermediate inputs (including energy) to produce output. Production technologies are described by nested constant elasticity of substitution (CES) functions.

The version used in this study distinguishes 15 sectors and 16 regions. These are listed in the table below. The model thus contains considerable detail at the European level. Also the energy sectors are modelled in considerable detail. The sectoral and regional classification is the same as in CPB (2003), except that the agricultural sector is split in three separate sub sectors (livestock, paddy rice, other agriculture), while the sector ‘energy intensive products’ is split in two (chemical, rubber and plastic products and other energy intensive sectors) to host several non-CO_2 emission sources.

Sectors and regions in WorldScan

Sectors	Regions
Livestock	Germany
Paddy rice	France
Agriculture nec[a]	United Kingdom
Coal	The Netherlands
Oil	Belgium and Luxembourg
Natural gas and gas distribution	Italy
Minerals nec[a]	Spain
Chemical, rubber and plastic products	Rest of European Union
Petroleum and coal products	Eastern Europe
Other energy intensive sectors	Former Soviet Union
Consumer good sector	Turkey
Capital goods and durables	United states
Electricity	Rest OECD
Other services	Latin America and Mexico
Transport	Middle East and Northern Africa
	Rest of world

[a] Nec: not elsewhere classified.

In the WorldScan model, emissions are coupled to production and consumption levels. For CO_2, the emissions follow from the energy input into production and consumption. Carbon dioxide emissions are coupled proportionally to the burning of fossil fuels.[9] As in the case of CO_2, emissions from non-CO_2 gases stem from inputs in the production process. However, because the emission intensity of non-CO_2 emission sources depends on many factors, the dependence of emissions on inputs is not modelled explicitly. Instead, the non-CO_2 emissions are modelled by employing a variable emission factor (per source), linking emissions to output volume[10] The activities to which the non-CO_2 emission sources are linked in WorldScan are given in Table 3.1.

Table 3.1 Non-CO_2 emission sources and corresponding WorldScan sectors

Emission source	WorldScan sector/activity
Paddy rice	Rice cultivation
Manure, enteric fermentation and animal waste	Livestock
Losses in coal production and transport	Coal production
Losses/leakage in oil production and transport	Oil production
Losses/leakage in gas production and distribution	Gas production and distribution
Fertilizer use	Inputs of chemicals in agricultural sectors
Production of adipic and nitric acid	Production of chemicals

In this study, we have allowed for abatement through ITC for the following sources:[11]

- Paddy rice
- Losses and leakages coal mining
- Losses and leakages oil recovery
- Losses and leakages gas recovery
- Production of adipic and nitric acid
- Fertilizer use

The bottom-up MAC-curves used in this study are presented in Appendix A.

[8] For more information on the modeling of CO_2 emissions in WorldScan, see Bollen *et al*. (2002).

[10] There is one exception to this way of modeling emissions of non-CO_2 greenhouse gases. Emissions from fertilizer use are treated similar to CO_2 emissions, i.e. emissions are in fixed proportion to fertilizer input in agricultural sectors, and are not linked to any output level.

[11] The emissions per unit of output cannot be reduced for all emission sources. Moreover, for some sources, there are no reliable data available. For these sources, abatement is accomplished solely by demand shifts. For instance, while it is possible to reduce emissions from enteric fermentation, the estimates widely vary (Burniaux (2000) reports reduction potentials ranging from 5 to 60%). For that reason, abatement options for enteric fermentation are not considered. Moreover, abatement options for manure are ignored, as the data are inaccurate and manure emissions only make up 7% of the global livestock emissions.

3.2 Climate policy

Both for CO_2 and for the non-CO_2 greenhouse gases, emission reductions are attained by imposing an emission price or emission tax on polluting activities. This has an effect on both the activity level of production (output) and on the emission intensity (emission factor). The imposition of an emission tax results in higher user prices. In the production process, inputs with low emission intensity will be substituted for inputs with high emission intensity. In addition, the demand for emission-intensive products will fall.

There are several ways to endogenise pollution control for non-CO2 greenhouse gases, which are summarised in the box below. In our model, actors can choose between paying an emission tax and abating the emissions. Emission abatement comes at some cost, however, as resources have to be diverted to abatement. The optimal mix is thus determined by the particular MAC-curve.

How to model non-CO_2 abatement?

Non-CO_2 abatement can be modelled in several ways. One option is to include an abatement sector in the model. The abatement sector employs capital, labour and intermediate inputs to reduce emissions. This approach allows for flexibility in the factor shares of various abatement activities. A disadvantage of this approach, however, is that many abatement sectors would need to be modelled, as there are multiple abatement technologies for the different gases. Moreover, this method requires detailed data on the abatement technologies, which is currently not available in the form suitable for an AGE-model such as WorldScan.

An alternative approach would be to allow for an alternative production process for e.g. rice that is less emission intensive than the original technology but comes at a higher cost, as resources have to be spent on pollution control. Again, the limitation of this approach is that there are many alternative production activities, each with its own emission intensity. This implies that a large number of production functions need to be introduced to represent the changes in production costs and emission intensity.

A third approach is to model emissions as an input to the production, as in Hyman *et al*., 2002. While this approach is quite common in the analytical general equilibrium models (see e.g. Copeland and Taylor, 2002), there are some numerical problems when this approach is pursued in AGE modelling.[a]

Here, we follow a more direct, though similar approach. Emissions are modelled in the traditional way, as an undesirable output of production. Similar to Hyman *et al*., however, the fall in productivity associated with abatement is taken into account. Firms can thus choose between investing in pollution control (accepting a lower productivity) or paying higher emission taxes, as with CO_2. Generally, it will be optimal to abate part of the emissions, paying the emission tax over the remainder.

[a] The emission price function exhibits a discontinuity at $P^E = 0$.

The marginal abatement costs from bottom-up MAC-curves are partial equilibrium prices. These MAC-curves can be used to calculate the general equilibrium marginal abatement costs in an AGE-model such as WorldScan. The partial equilibrium MAC-curves describe the scope for Induced Technological Change (ITC) in reducing greenhouse gas emissions.

Abatement is achieved by lowering the emission intensity (emissions per unit of activity) of production. The emission factor thus declines with the imposition of an emission price. By definition it holds that

$$E^F\left(r(P_E)\right) = \overline{E}^F \cdot \left(1 - r(P_E)\right) \qquad , with\ \ r(P_E) = r_A + r_{ITC}(P_E), \tag{3.1}$$

with $\overline{E}^F$ the emission factor in the base year, and *r* the reduction as a function of the emission price P_E. The reduction *r* is the sum of the reduction as a result of climate policy (r_{ITC}) and the autonomous reduction in the baseline (r_A).

However, emission reductions through ITC do not come for free. Total Factor Productivity (TFP) of sectors producing non-CO_2 greenhouse gases will be lowered as a result of diverting part of the production of e.g. the livestock sector to emission abatement. The firm thus needs to decide which share of its resources to use for abatement. The optimum abatement level follows from profit maximisation.[12] Assuming that emissions are taxed at production, the profit of the firm becomes:

$$\Pi = p \cdot A \cdot Q - c \cdot Q - P_E \cdot \overline{E}^F \cdot (1 - r) \cdot Q, \tag{3.2}$$

where *p* is the producer price, *A* denotes the productivity with $A = 1$ for $r_{ITC} = 0$, *Q* is the activity level, *c* is the marginal cost at this activity level, and P_E is the emission price. We assume that productivity is a decreasing and concave function of the emission reduction r_{ITC} : the more resources are diverted to abatement, the less output is available for sale. The first order condition for the optimal reduction level reads:

$$\frac{\partial \Pi}{\partial r_{ITC}} = p \cdot A' Q + P_E \cdot \overline{E}^F \cdot Q = 0 \tag{3.3}$$

The firm chooses the optimal abatement level, maximising its profits. We assume free entry of firms and thus zero profits. Together with a postulated form for $P_E(r_{ITC})$, Equations (3.2) and (3.3) yield a differential equation for the productivity *A* as a function of r_{ITC}. A particular simple parameterisation for $r_{ITC}(P_E)$ is:

$$r_{ITC}(P_E) = \frac{P_E(\varepsilon - r_A)}{\delta + P_E} \qquad , for P_E \geq 0 \tag{3.4a}$$

with the inverse function:

[12] More details on the derivation can be found in Appendix B.

$$P_E(r_{ITC}) = \frac{\delta \cdot (r_{ITC})}{(\varepsilon - r_A) - r_{ITC}} \qquad \text{,for } 0 \le r_{ITC} < \varepsilon - r_A \tag{3.4b}$$

with ε denoting the technical limit to the possible emission reduction, δ the speed of convergence , and r_A the reduction through autonomous emission efficiency improvement. Hence, Equation (3.4) describes the partial equilibrium MAC-curve. With this parameterisation of the MAC-curve, we get the following expression for the total factor productivity:

$$A(r_{ITC}) = \eta \cdot \left(-\phi(r_{ITC})^{1/2} + \lambda \cdot r_{ITC} + (\varepsilon - r_A) \cdot c\right)^2 \cdot \left(\frac{\sigma + 2 \cdot \phi \cdot r_{ITC} - \lambda}{\sigma - 2 \cdot \phi \cdot r_{ITC} + \lambda}\right)^{-\frac{\lambda}{2\sigma}} \tag{3.5}$$

with

$$\phi = \delta \cdot E^F; \qquad \lambda = \phi \cdot (1 - r_A) - c; \qquad \sigma = \left(4 \cdot \phi \cdot c \cdot (\varepsilon - r_A) + \lambda^2\right)^{1/2};$$

and η a constant of integration following from the constraint $A(0) = 1$. Considering the relation between the parameters ε and the δ and the TFP-level gives some more insight in the implications of Equation (3.5). For a fixed emission price, the emission reduction will be larger for a larger ε or a smaller δ (see Equation (3.4)). Larger emission reductions will be associated with higher costs and thus a lower level of TFP.

Figure 3.1 shows the fit of a particular bottom-up MAC-curve[13] (leakages from coal mining in the USA) based on Equation (3.4). Figure 3.2 shows the corresponding productivity function *A*. The MAC-curve and the productivity curves are thus convex and concave functions of the relative reduction *r*, respectively. The emission factor declines as a function of the emission price and approaches the minimum dictated by the MAC-curve for an emission price going to infinity. The two figures show that considerable emission reductions are already reached at fairly low prices, while TFP has only decreased by 3% at the reduction potential.

[13] All bottom-up MAC-curves are taken from the EPA (2003) (using the base energy price scenario, assuming a 5% discount rate and a zero tax rate), except for the MAC-curves for paddy rice and fertilizer use, which are taken from Brown *et al.* (1999).

Figure 3.1 Fit of bottom-up MAC-curve

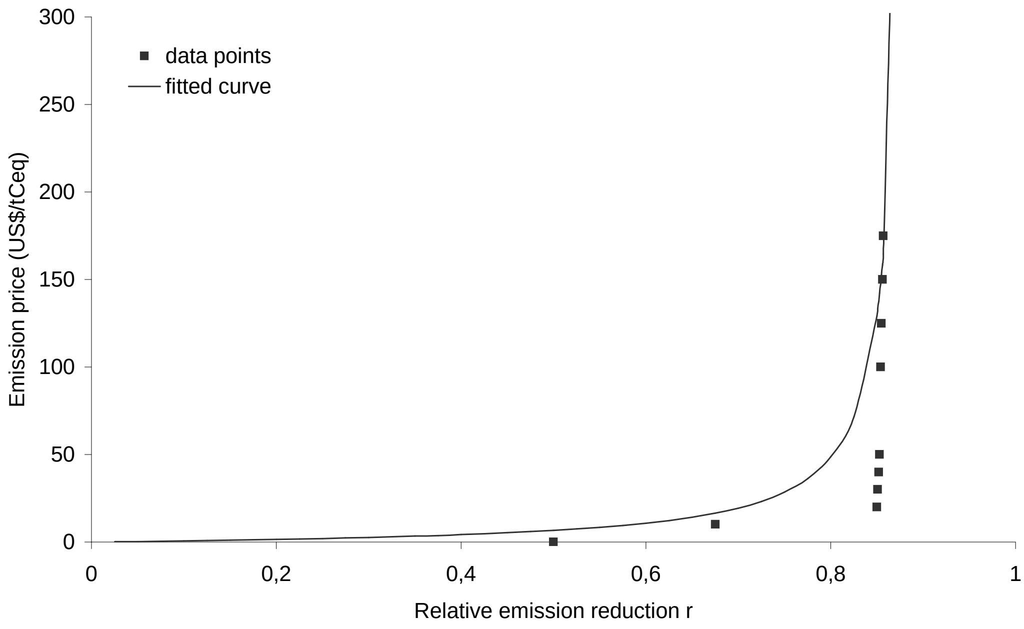
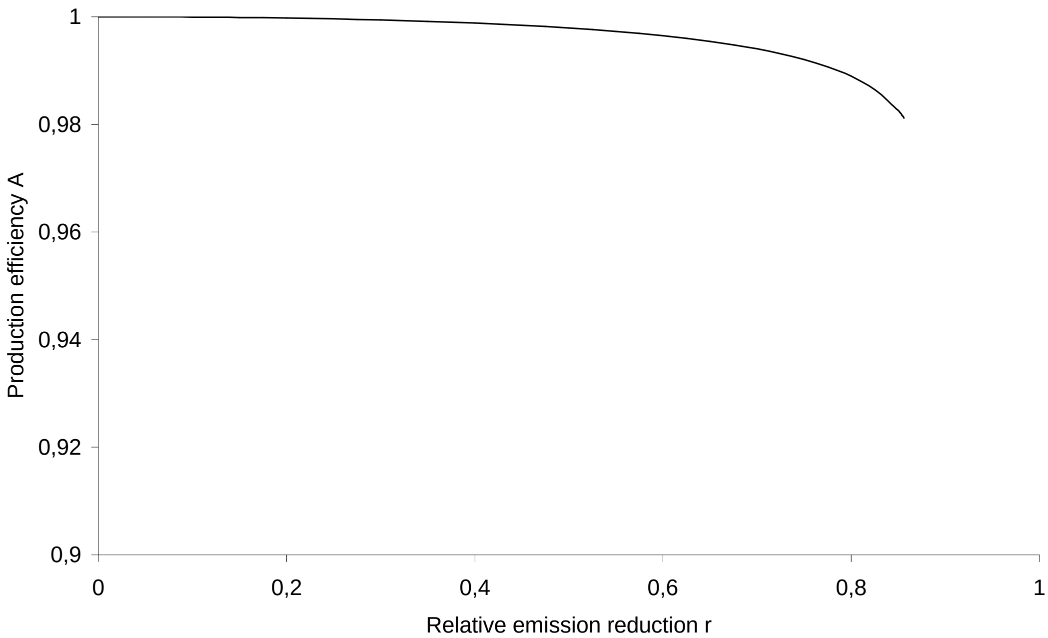


Figure 3.2 Productivity of a sector as a function of the relative reduction



Using the parameterisation of the MAC-curves, the model calculates the general equilibrium marginal abatement cost curves. These curves contain both effects of the imposition of an emission tax: (1) the decline of the emissions per unit of output and (2) the shift of demand to other products or to imports from countries with lower or no emission taxes. The fall in productivity leads to an increase in production costs. Firms can thus choose between paying the emission tax and investing in pollution control, accepting a lower productivity. In general, it will be optimal to abate part of the emissions, paying the emission tax over the remainder. The optimum is derived from the partial equilibrium MAC-curves. This approach thus integrates the bottom-up information from bottom-up MAC-curves with a general equilibrium approach.

Our approach is similar to both that of Burniaux (2000) and Brown *et al.* (1999) in the use of an emission response function (Equation (3.4)). However, our model differs from their approaches in one important respect. Both Burniaux (2000) and Brown *et al.* (1999) attach no costs to this induced technological change. In our model, productivity falls if the reduction effort increases. This reflects deployment of resources for abatement. In this respect, our approach is similar to that of Hyman *et al.* (2002) and to that of Copeland and Taylor (2003), who model emissions as an input to production. In their formulation this leads to a difference between potential output and true output, i.e. productivity falls.

Several points can be noted about the parameterisation of the MAC-curve. Firstly, the reductions from autonomous emission efficiency improvement (AEEI) have to be subtracted from the MAC-curves, as these options are no longer available. The specification (3.4) thus forces the MAC-curve to intersect the *x*-axis ($P^E=0$) at the point $r = r_A$. As the reduction share through AEEI generally changes over time, the corresponding MAC-curve will also shift.

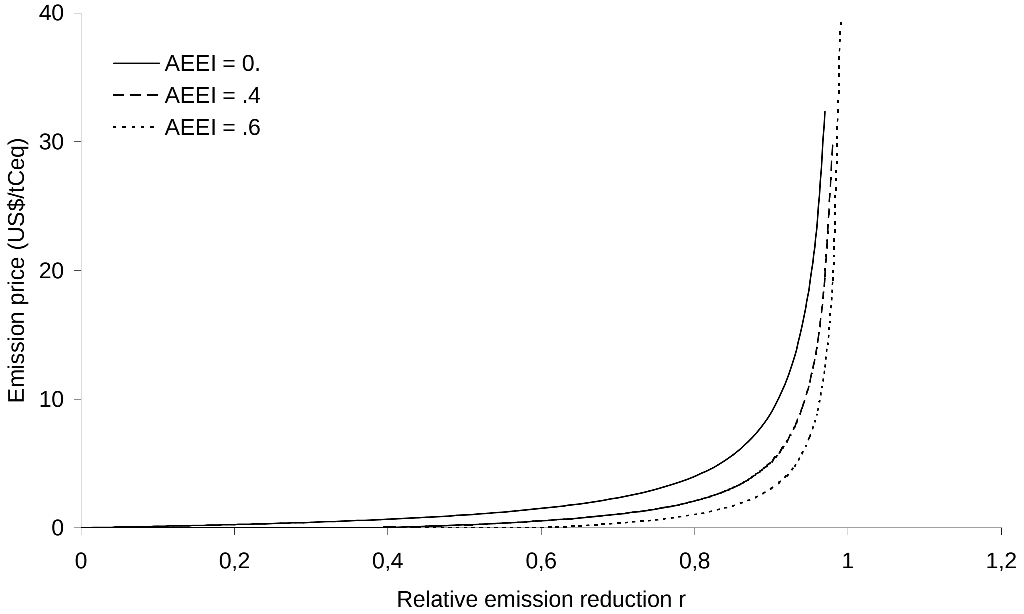
Table 3.2 gives an indication of the importance of AEEI. For example, for the EU-15 only 30% of the abatement options are left after subtracting the reduction volume accomplished by AEEI for the three major emission sources (leakages from coal and gas production and production of adipic and nitric acid).

Table 3.2 Percentage of the reduction options *left* after AEEI correction in 2010

	USA	EU-15	Former Soviet Union	Eastern Europe	Rest OECD	Middle East	Latin America	Rest of World
Paddy rice	64	65	88	78	101	88	66	74
Leakages coal	94	33	71	102	57	42	113	65
Leakages oil	173	49	88	88	145	58	129	89
Leakages gas	98	28	93	56	94	66	87	114
Adipic and nitric acid	21	36	56	62	24	70	96	84

This reduces the scope for reductions through Induced Technological Change in the long run. This is shown in Figure 3.3 for emissions from the production of nitric and adipic acid in the former Soviet Union. The figure shows how the MAC-curve shifts over time, as more and more options are exhausted under AEEI. Taking 1997 as a reference point, autonomous emission reductions increase from 0 to 0.384 in 2010 and 0.595 in 2020.

Figure 3.3 Shift of MAC-curve of emissions from the production of nitric and adipic acid in the former Soviet Union for different portions of AEEI



Secondly, several partial MAC-curves include negative cost abatement options.[14] Part of these reductions or even all can be consumed in the baseline, depending on the magnitude of the autonomous emission efficiency improvement. We assume positive costs for the no-regret options that are left after subtraction of the autonomous reductions. This reflects the view that the non-adoption of these techniques in the baseline indicates that the costs are positive in practice. An important reason is that transaction costs may not have been fully accounted for, so that abatement options with negative costs actually present net positive costs. Also, some actors may not be aware of the existence of negative cost options, as the returns are likely to be small in the baseline. Acquiring this information also represents a form of costs, which are in general not included in MAC-curves.

A third issue is the emission reduction in the limit of an infinite emission price. There are two possible views. Our parameterisation assumes that even in the limit of infinite costs, only a fraction of the emissions can be abated. However, one could also argue that the introduction of

[14] Negative cost options denote that emission reductions go hand in hand with overall efficiency improvement, leading to negative net costs. A well-known example is the capture and sale of methane in natural gas production (EPA, 2001). It is commonly assumed that these 'no regret' options are not implemented in the absence of climate policy because of factors such as transaction costs and information problems.

climate policy will stimulate the development of new abatement options, as in Hyman *et al* (2002).[15] At high enough emission prices, this will lead to more reduction options in the longer run. However, the course of the MAC-curve is then hard to predict, as also the curvature of the MAC-curves for lower emission prices is likely to change. Therefore, we have adopted the conservative approach, assuming a fixed reduction potential. For the short run, this seems to be a reasonable approach.

Fourthly, an important parameter is the price elasticity of reduction through ITC, which is governed by the parameter δ.[16] For all sources, except for leakages from gas production and distribution, the reduction potential is already reached at fairly low emission taxes (a low value of δ). This implies that reductions up to the reduction potential are generally cheap for non-CO_2 gases. Equation (3.4) and Figure 3.3 show that with an increase in the autonomous emission efficiency index (r_A), the abatement curve will fall below the curve of the base year. This reflects the intuition that abatement options generally will become cheaper over time.

A final point is that, in our general equilibrium framework, there will be spillover effects between the different gases. For instance, when reducing CO_2 in the coal sector, also methane emissions from coal production are reduced. The importance of these so-called co-benefits will be assessed in the next section.

[15] The bottom-up MAC-curves only use currently existing abatement technologies or technologies which are incremental improvements on current technologies.

[16] To be precise, the price elasticity of the ITC reduction is equal to $\delta / (\delta + P^E)$.

4 Results

The focus of this study is twofold. Firstly, we want to assess the impact of general equilibrium effects on marginal abatement costs. Secondly, this study examines the scope of what-flexibility for cost reductions. For both purposes, the general equilibrium MAC-curves provide useful insights. In Section 4.1, the impact of general equilibrium effects on marginal abatement costs is explored. In Section 4.2, we look at the effect of employing a multi-gas strategy instead of a policy directed at CO_2 only.

4.1 Decomposition of the general equilibrium effects

The previous section provides the building blocks for the decomposition of the general equilibrium effects. General equilibrium MAC-curves can be constructed by imposing different emission price levels for all regions and then determining the emission reductions.[17] We consider the year 2010, when the Kyoto Protocol is in full effect. We do not allow for emission trading, as we want to focus on the effect of what-flexibility in different regions separately.

For the decomposition of the MAC-curves, we performed several simulations with the WorldScan model. The partial relation between the emission price and non-CO_2 reduction is imposed a priori by Equation (3.4). In a first simulation we constructed a general equilibrium MAC-curve for CO_2 by imposing an emission tax on CO_2-emissions only. Also non-CO_2 emissions are reduced in that case, as a tax on CO_2 may reduce output from sectors that also emit non-CO_2 gases. These are the so-called co-benefits. In a second simulation, an emission price was imposed on non-CO_2 gases only. This simulation gives us information about the general equilibrium MAC-curve of non-CO_2 and the accompanying CO_2 co-benefits. As a final experiment the emission tax was imposed on all greenhouse gases, leading to the full general equilibrium MAC-curve.

Figure 4.1 and 4.2 present the cumulative MAC-curves for two different regions based on the simulations described above. Figure 4.1 shows the cumulative MAC-curves for the former Soviet Union, while Figure 4.2 presents these for the EU-15. The reason to focus on these two regions is that they represent the two extreme cases. For the former Soviet Union, general equilibrium effects are considerable, while these effects are only modest for the EU-15. General equilibrium effects in other regions are less pronounced than in the former Soviet Union, but stronger than for the EU-15.

The general equilibrium MAC-curve for all greenhouse gases can be decomposed into a part due to non-CO_2 greenhouse gases (the area left from the non-CO_2 general equilibrium curve) and a part due to CO_2 (the area right from the non-CO_2 general equilibrium curve). This general equilibrium MAC-curve for non-CO_2 greenhouse gases can be further decomposed into

[17] We have considered the imposition of an emission price in all regions simultaneously. Alternatively, we could have imposed an emission price in a single country at the time. This will not change our results qualitatively.

three components: co-benefits from CO_2, a partial equilibrium effect and a general equilibrium effect. The first curve on the left represents these non-CO_2 co-benefits resulting from an emission tax on CO_2 only. The second line from the left shows the cumulative effect of these co-benefits and the partial non-CO_2 MAC-curve. The area between the second and third MAC-curve gives the general equilibrium effect, i.e. the emission reduction resulting from demand shifts due to higher producer prices. Thirdly, the general equilibrium MAC-curve for CO_2 can be decomposed into CO_2 co-benefits from an emission tax on non-CO_2 and CO_2 reductions resulting from general equilibrium effects of an emission tax on CO_2.

Figure 4.1 shows, that for the former Soviet Union the different components of the full general equilibrium MAC-curve all constitute a substantial share. For the former Soviet Union, the most important source of non-CO_2 emissions is leakage from gas production and distribution, representing 62% of total non-CO_2 greenhouse gas emissions (Table 2.1). The reduction potential for this source is high: after correction for autonomous emission efficiency improvement the reduction potential is still 40% in 2010 (Table 3.2). In addition, even at higher emission prices, induced technological change offers several abatement options. Finally, the gas sector is also an important source of CO_2-emissions, explaining the sizeable co-benefits.

Figure 4.1 Decomposition of the non-CO_2 contribution to emission reductions in the former Soviet Union

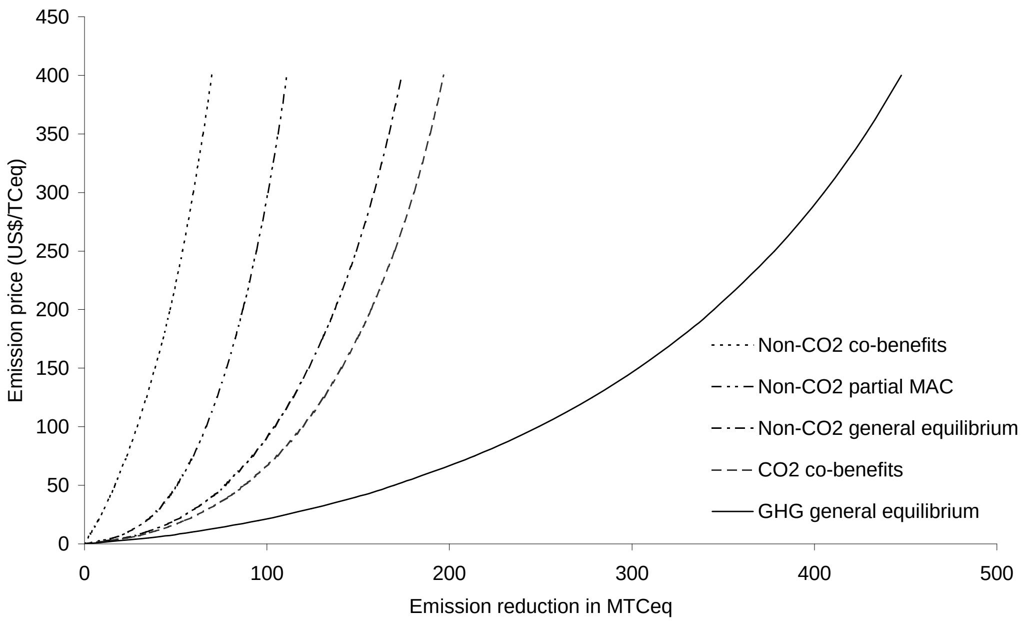


Figure 4.2 shows the cumulative MAC-curve for the 15 EU-countries. In contrast with the former Soviet Union, the contribution of non-CO_2 gases is negligible for the EU-15. There is only a modest demand shift for the non-CO_2 greenhouse gases. Again, these results can be explained on the basis of the relative importance of non-CO_2 gases and their marginal abatement costs. Table 2.1 shows that only 31% of the non-CO_2 greenhouse gases in the EU-15 are produced in sectors with a considerable reduction potential for induced technological

change. For the remainder (emissions from livestock and fertilizer use), reductions have to come solely from demand shifts. Moreover, in the agricultural sectors the co-benefits obviously will be modest. Furthermore, Table 3.2 shows that after correction for AEEI in the baseline only one third of the ITC reduction potential is left. Therefore, the net reduction potential from induced technological change is modest, and it is completely depleted at low emission prices.

Figure 4.2 Decomposition of the non-CO_2 contribution to emission reductions in the EU-15

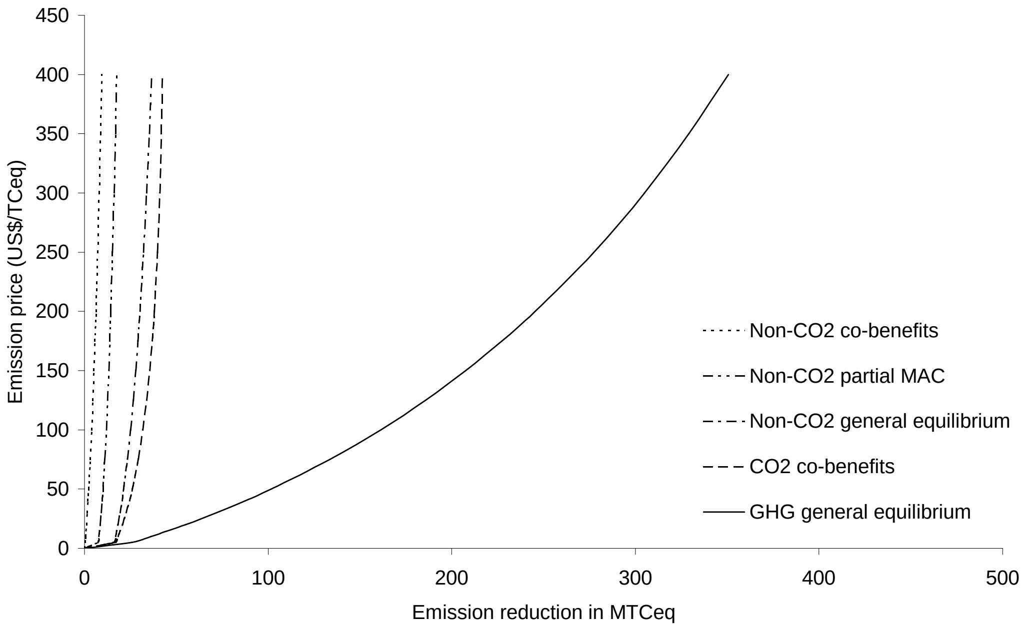
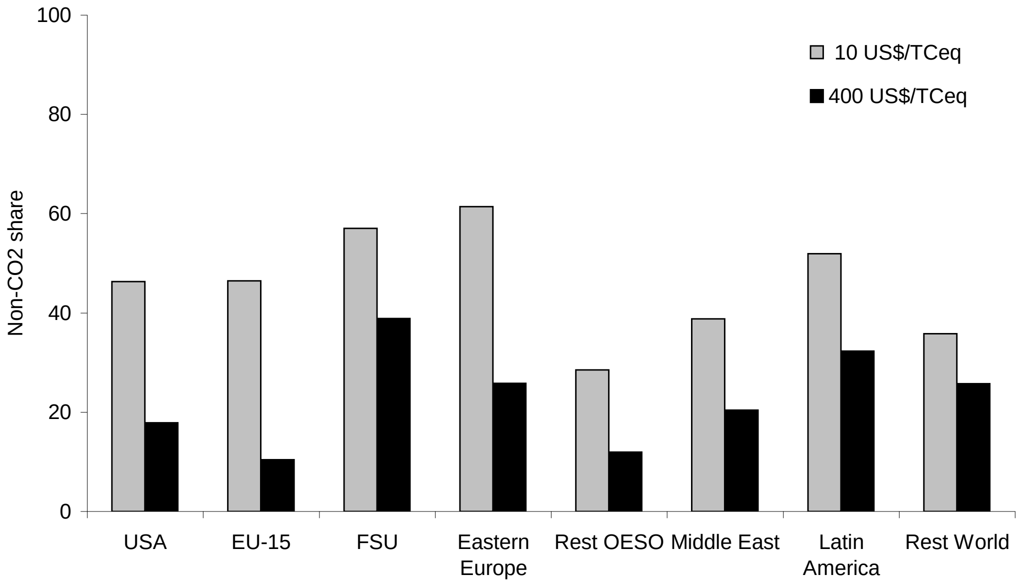


Figure 4.3 shows the importance of non-CO_2 greenhouse gases in total abatement at different emission prices for the different regions. For all regions, the share of non-CO_2 gases falls with higher emission prices . This shows that low-cost abatement options for non-CO_2 gases are exhausted at intermediate emission prices. Non-CO_2 greenhouse gases thus offer low-cost abatement options, lowering abatement costs, but once these options are exhausted, abatement has to come from CO_2 again.

However, as shown in the next section, abatement of non-CO_2 gases can lower abatement costs substantially for all regions, although the size of the cost reduction varies over regions. For the former Soviet Union, the share of non-CO_2 gases in total reductions is initially high, and remains high at higher emission prices because of the large potential for reductions through ITC and the considerable co-benefits. The same holds for Eastern Europe and Latin America, though the shares of non-CO_2 gases are somewhat lower for these regions. For the EU-15, the USA and especially the Rest of the OECD, on the other hand, the share of non-CO_2 gases in total reduction is modest and declines rapidly at higher cost levels. For these regions, the abatement options through ITC are limited, especially at higher emission prices. Firstly, the 'low hanging fruit' is already reaped in the baseline, as production in these developed countries is already relatively emission extensive for non-CO_2 gases, so that the reduction potential is limited.

Secondly, most of the non-CO_2 emissions in these regions stem from sources for which there is no or only limited reduction potential to start with.

Figure 4.3 Share of non-CO_2 greenhouse gas emission reductions in the total reductions for different emission prices (P_E = 10 $/tCeq and P_E = 400 $/tCeq).



4.2 Economic impacts of including non-CO_2 gases

In this section, we compare two cases. In the first case, we impose an emission target on all greenhouse gases, while climate policy is only directed at CO_2. In the second case, the target is the same as in the first case, but now climate policy is aimed at CO_2 as well as methane and nitrous oxide. This gives us an estimate for the gains from what-flexibility. We expect these gains to be positive, as a multi-gas strategy allows for a cost-minimising distribution of abatement efforts over CO_2 and non-CO_2 greenhouse gases.

In Section 4.2.1 and 4.2.2, we describe the regional and sectoral pattern when only CO_2-emissions are abated. In Section 4.2.3 and 4.2.4, we discuss the changes in these patterns when a multi-gas strategy is applied. In both cases, it is assumed that the Kyoto targets are implemented in all so-called Annex B countries (including the USA and Australia that have not ratified the Protocol) except for the former Soviet Union. The former Soviet Union is excluded as this country faces negative emission targets. This so-called 'hot air' would reduce overall costs and reduction levels greatly. The targets are applied to all countries simultaneously. Furthermore, we do not allow for emission trading, as we want to focus on the effect of including non-CO_2 gases in the analysis. The focus is on the year 2010, which lies in the middle of the first commitment period of the Kyoto Protocol (2008- 2012).

4.2.1 Abatement of CO_2 only: regional effects[18]

Climate policy has a differential impact on the different regions. These regional effects of CO_2 abatement are shown in Table 4.1.

Table 4.1 Regional effects of CO_2-only abatement in percentage change relative to baseline in 2010

	CO_2 emissions	Non-CO_2 emissions	Marginal abatement costs in US$/tCeq[b]	GDP per capita
Germany	– 8.1	– 1.9	42.3	– 0.1
France	– 7.7	– 0.6	57.9	– 0.1
United Kingdom	– 13.4	– 3.4	77.2	– 0.3
The Netherlands	– 14.1	– 3.6	84.9	– 0.5
Belgium and Luxembourg	– 19.3	– 4.2	134.9	– 0.8
Italy	– 10.6	– 1.5	84.3	– 0.4
Spain	– 2.1	– 1.0	13.1	0.0
Rest of Europe	– 7.3	– 0.4	46.6	– 0.2
USA	– 18.9	– 8.6	67.6	– 0.2
Rest OECD	– 8.6	– 2.1	38.3	– 0.1
Eastern Europe	0.3	– 0.4	0.0	0.1
Former Soviet Union[a]	0.3	– 0.6	-	– 0.0
Middle East and Northern Africa[a]	0.6	– 0.9	-	– 0.1
Turkey[a]	0.4	– 0.1	-	0.1
Latin America[a]	0.7	– 0.2	-	0.1
Rest of World[a]	0.3	– 0.1	-	0.1

[a] Region without reduction commitment
[b] Absolute change relative to baseline

There is substantial regional variations in marginal abatement costs, with costs ranging from 0 US$/tCeq in Eastern Europe to 134.9 US$/tCeq in Belgium and Luxemburg, implying that there is quite some scope for emission trading. Furthermore, we see that there are sizeable non-CO_2 co-benefits for some regions such as the USA, the United Kingdom, the Netherlands and Belgium and Luxembourg, but smaller co-benefits in other regions. Finally, the fall in per capita GDP is only modest. GDP per capita even rises for some non-Annex B countries. Not surprisingly, the fall in GDP per capita is the largest for the countries with high marginal abatement costs. The main cause of the fall in per capita GDP in Annex B regions is the introduction of inefficiencies by the imposition of an emission tax. The inefficiencies are caused by sectoral restructuring which lowers overall productivity.

GDP per capita also falls in some of the regions without reduction commitments, such as the Middle East and Northern Africa and the former Soviet Union. These regions are large exporters of fossil fuels, so that they are hurt by the fall in demand for fossil fuels resulting from the imposition of an emission tax in Annex B countries. The costs of climate policy are thus partly shifted to these regions.

[18] For a more elaborate analysis of the impact of CO_2-only policy, see Bollen *et al.* (2002) and Bollen *et al.* (2001).

However, there are also regions which benefit from climate policy, such as the WorldScan region “Rest of World”. As a result of an increase in the producer prices of energy intensive products in Annex B regions, the competitiveness of non-Annex B regions improves. The energy intensive sectors in these regions thus expand, leading to so-called carbon leakage: the emissions of CO_2 in these regions increase, as can be seen in Table 4.1.

4.2.2 Abatement of CO_2 only: sectoral effects

The sectoral effects of the imposition of an emission tax on CO_2 emissions are presented in Table 4.2 for a selection of sectors and regions.

The imposition of an emission tax leads to substitution between products and sectors. Firstly, within the class of energy carriers, energy carriers with high carbon content such as coal will be substituted for energy carriers with lower carbon content such as gas and petrol. Indeed we see in Table 4.2 that the coal sector generally loses most.

Table 4.2 Sectoral effects of CO_2 reductions (percentage change in value added relative to baseline in 2010)

	Germany	France	USA	Former Soviet Union[a]	Middle East and Northern Africa[a]	Rest of World[a]
Coal	– 23.3	– 30.5	– 33.0	– 1.1	– 4.0	– 1.7
Oil products	– 4.0	– 5.1	– 17.6	0.5	1.7	1.1
Gas	– 6.0	– 7.8	– 10.7	– 1.7	– 2.0	– 1.1
Oil	– 8.8	– 4.0	– 15.0	– 2.1	– 3.4	– 6.3
Electricity	– 3.0	– 0.8	– 8.9	0.4	0.3	0.2
Energy intensive products	– 0.1	0.0	– 0.2	0.3	0.4	0.2
Chemical products	– 0.1	– 0.0	– 0.7	0.5	0.7	0.4
Transport	– 0.3	– 0.6	– 2.3	0.8	1.2	0.6
Rice	– 1.0	– 1.1	– 1.0	0.4	0.8	0.2
Livestock	0.3	0.3	0.3	0.3	0.7	0.1
Rest agriculture	0.2	0.3	– 0.6	0.5	1.0	0.2
Services	0.1	0.1	0.4	– 0.0	0.0	0.0
Macro GDP	– 0.1	– 0.1	– 0.2	– 0.0	– 0.1	0.1

[a] Region without reduction commitment.

Secondly, within a region, energy carriers will be substituted for other production factors or products. In production, energy carriers will be substituted for labour and capital, while consumption will shift from energy intensive products to services. Indeed the service sector and some agricultural sectors expand in Annex B regions, while the share of energy intensive sectors such as transport, chemical products and electricity declines in Annex B regions. Finally, there will be international substitution as the production of energy intensive goods will relocate to non-Annex B regions (carbon leakage), as Table 4.2 shows. The energy intensive sectors expand in these regions, and the fall in demand for energy carriers has less severe consequences for these regions than for the Annex B countries. The size of this latter effect depends on import and export taxes, substitution effects between foreign and domestic products and on transport costs.

4.2.3 Multi-gas strategy: regional effects

For the second simulation, the same targets are imposed as in the CO_2-only variant discussed in Section 4.2.1 and 4.2.2, but now climate policy is directed at carbon dioxide as well as at the non-CO_2 greenhouse gases. The regional effects of a multi-gas strategy relative to a CO_2-only policy are presented in Table 4.3. The additional reduction options from non-CO_2 gases have several effects. Firstly, the fall in GDP per capita is generally lower than in the case of CO_2-only policy. Moreover, marginal abatement costs fall considerably in most regions. This reflects the availability of cheap abatement options for non-CO_2 emissions. However, this decline varies across regions because of regional differences in the availability of abatement options.

Table 4.3 Regional effects of a multi-gas strategy (percentage *relative to CO_2-only policy* in 2010)

	CO_2 emissions	Non-CO_2 emissions	Marginal abatement costs in US$/tCeq[b]	GDP per capita
Germany	1.9	– 15.8	– 12.0	0.0
France	3.8	– 12.9	– 30.3	0.1
United Kingdom	3.0	– 20.2	– 21.8	0.1
The Netherlands	3.8	– 22.5	– 25.9	0.2
Belgium and Luxembourg	2.1	– 18.1	– 19.1	0.1
Italy	1.5	– 12.5	– 14.7	0.1
Spain	1.0	– 5.0	– 6.2	0.0
Rest of Europe	1.0	– 4.8	– 7.8	0.0
USA	7.6	– 22.5	– 19.6	0.0
Rest OECD	1.5	– 9.8	– 8.4	0.0
Eastern Europe	– 0.1	0.6	0.0	– 0.1
Former Soviet Union[a]	– 0.1	0.5	-	0.0
Middle East and Northern Africa[a]	– 0.1	0.8	-	0.0
Turkey[a]	– 0.1	0.5	-	– 0.0
Latin America[a]	– 0.1	0.3	-	0.0
Rest of World[a]	– 0.0	0.2	-	– 0.0

[a] Region without reduction commitment.
[b] Change in level compared to the baseline

Thirdly, the required abatement targets for CO_2 fall as a result of the availability of low-costs abatement options for the non-CO_2 gases. In some cases, CO_2-emissions are even allowed to rise relative to the CO_2-only case. This effect is particularly important for the industrialised countries. In the industrialised countries, the share of non-CO_2 gases in the total reduction volume is higher than their total emission share. This implies that CO_2-emissions need not fall as much as in the CO_2-only case. However, this effect is only important at moderate emission prices, since at higher abatement volumes, the low-cost abatement options for non-CO_2 emissions quickly become exhausted (see also Section 4.1 for an illustration of this point for the EU-15). All together, the Annex B regions benefit somewhat from the inclusion of non-CO_2 greenhouse gases.

4.2.4 Multi-gas strategy: sectoral effects

The sectoral effects for a selection of regions and sectors are presented in Table 4.4. Several effects play a role when climate policy is also directed at the non-CO_2 greenhouse gases. Firstly, a larger part of the burden will fall on the agricultural sector than in the case of a CO_2-only policy. The imposition of an emission tax leads to a price increase in this sector. The price increase in turn leads to a fall in demand and hence to a lower production in Annex B regions. The demand for these products partly shifts to non-Annex B regions, and partly to other products. Indeed, the share of agricultural sectors in the Annex B countries is lower than in the CO_2-only case.[19] Also the share of the gas sector in total value added is now reduced, for the same reason. In the non-Annex B regions, the share of agriculture and gas production is now higher as compared to the CO_2-only policy.

Secondly, the output price of energy sectors does not rise as much as in the CO_2-only case, as part of the burden is now borne by sectors that produce non-CO_2 gases. Table 4.4 shows that the share of oil products is now higher than in the CO_2-only case.

For the coal sector , both opposing effects play a role. While there is a negative effect on production due to the tax on non-CO_2 related emissions, there is also a positive effect on production, as the tax on CO_2-related emissions is now lower than in the case of a policy directed solely at CO_2.

[19] This effect appears to be especially large for the rice sector. However, this is merely an artifact, as rice production is almost zero in the Annex B countries, so that small absolute fluctuations in the production volume give rise to a large relative effect.

Table 4.4 Sectoral effects of a multi-gas strategy (percentage change in value added *relative to CO_2-only strategy* in 2010)

	Germany	France	USA	Former Soviet Union[a]	Middle East and Northern Africa[a]	Rest of World[a]
Coal	3.9	– 7.0	7.9	0.4	2.3	0.7
Oil products	1.2	3.4	5.0	– 0.1	– 0.4	– 0.3
Gas	– 6.5	– 10.0	– 2.0	1.0	1.4	1.1
Oil	1.2	0.7	1.6	0.5	0.9	1.8
Electricity	0.8	0.5	2.0	– 0.1	– 0.1	– 0.1
Energy intensive products	0.1	0.1	0.1	– 0.1	– 0.1	– 0.1
Chemical products	– 0.1	– 0.1	– 0.0	– 0.1	– 0.2	– 0.1
Transport	0.1	0.6	0.7	– 0.3	– 0.4	– 0.2
Rice	– 6.0	– 6.1	– 4.2	0.1	0.0	0.1
Livestock	– 1.8	– 0.8	– 4.3	0.2	0.4	0.3
Rest agriculture	– 0.5	– 0.6	– 1.1	0.1	0.0	0.1
Services	– 0.0	– 0.0	– 0.1	0.0	– 0.0	– 0.0
Macro GDP	0.0	0.1	0.0	0.0	0.0	– 0.0

[a] Region without reduction commitment.

5 Conclusions

In this paper, the WorldScan energy model is extended to include emissions from the non-CO_2 greenhouse gases methane (CH_4) and nitrous oxide (N_2O). These greenhouse gases are important for several reasons. Firstly, they account for 10 to 40% (depending on the region) of the greenhouse gas emissions in the so-called Kyoto-basket (weighted by the Global Warming Potential). Furthermore, some of the non-CO_2 emission sources offer reduction options at low costs, suggesting that the gains from what-flexibility can be large. Moreover, the sectoral emission profile for methane and nitrous oxide is different from that of CO_2, indicating that including non-CO_2 greenhouse gases in the analyses may change the sectoral effects. The agricultural sector, for instance, is only a minor source of CO_2, while it is an important source of both methane and nitrous oxide in many regions. Finally, regions differ in the availability of low cost reduction options for non-CO_2 gases, so that the regional effects may also vary.

Climate policy entails the introduction of a tax on emissions. Emissions from both CO_2 and non-CO_2 gases can be reduced by improving either the emission efficiency or by reducing the level of the activity responsible for the emissions (e.g. for CO_2 gases the production volume of energy intensive goods). The modelling of emissions from non-CO_2 gases differs from the modelling of emissions of CO_2 in the sense that the many factors contributing to the emission efficiency are not modelled explicitly but are collected in a ‘catch-all’ factor, the emission factor. Reducing emissions by improving the emission efficiency comes at a cost of reduced productivity. For CO_2, this means that the mix of energy inputs is changed compared to baseline towards energy inputs with lower CO_2 emissions. For non-CO_2 gases, this is not modelled explicitly, but is instead reflected in a decline in total factor productivity. A firm thus faces a trade-off between paying the emission tax and improving emission efficiency. The optimum is contained implicitly in bottom-up marginal abatement cost (MAC) curves showing the emission volume that can be reduced at a certain cost. However, general equilibrium effects and inter-gas interactions (the so-called ‘co-benefits’) are also important. By including bottom-up MAC-curves into the applied general equilibrium model WorldScan, bottom-up information is combined with general equilibrium effects.

General equilibrium marginal abatement cost curves can be derived from the model. These curves give a first indication of the importance of the different effects. In Section 4.1 it is shown that the importance of general equilibrium effects varies over regions. These differences can be explained by referring to the relative importance of the non-CO_2 gases in total emissions in that region and the shape of the regional marginal abatement cost curves. For instance, for the former Soviet Union, there are many low cost reduction options available. In addition, there are considerable co-benefits. By contrast, for the EU-15 countries, the contribution of non-CO_2 gases to the full MAC-curve is only modest. The reason is that only a limited share of the non-CO_2 emissions in the EU stem from sources with a positive reduction potential, while many of the inexpensive abatement options are already exhausted in the baseline. Moreover, the co-benefits are only small as a result of the sectoral composition of the emissions.

For all regions, non-CO_2 abatement lowers total abatement costs, although the size of the cost reduction varies across regions. For the former Soviet Union, the share of non-CO_2 gases in total reductions is high even at higher emission prices as a result of the large potential for reductions through induced technological change and the considerable co-benefits. The same holds for Eastern Europe and Latin America, though the shares of non-CO_2 gases are somewhat smaller in these regions. For the EU-15, the USA and the other OECD countries, on the other hand, the share of non-CO_2 gases in the total reduction volume is modest and declines rapidly at higher prices. In general, the analysis shows that there is a limited role for non-CO_2 gases at higher emission prices. At higher emission prices, low cost reduction options for non-CO_2 gases are exhausted. All together, the regional effects on GDP per capita of including non-CO_2 gases are limited. Marginal abatement costs fall, but the effect on GDP per capita is limited.

At the sectoral level, there is an important shift in burden. In some regions, the share in value added of oil, coal and gas products is now higher than under a CO_2-only policy. By contrast, the output share of agricultural sectors is reduced relative to a CO_2-only policy. Several effects play a role. Firstly, the price increase for agricultural products due to emission taxes will result in a fall in demand and hence to lower production in Annex B regions. The demand for these products partly shifts to non-Annex B regions, and partly to other products. Secondly, the output price of energy sectors does not have to increase as much as in the CO_2-only case, as part of the burden is now borne by non-CO_2 gases.

Note that the sectoral effects of extending climate policy to non-CO_2 greenhouse gases may be underestimated in this work, as it is assumed that the reduction potential in the livestock sector is zero as there are no data available. In reality, the reduction potential in this sector might be considerable, even though this potential may be hard to realise because of the dispersed nature of the emission sources. This is especially important for the analysis of the effects of climate policy in countries such as China and India that have a large agricultural sector. The gains of what-flexibility for those countries are potentially large, once the reduction potential in the livestock sector is taken into account.

6 References

Brown, S., D. Kennedy and C. Polidano ,1999, ‘Economic Impacts Of The Kyoto Protocol. Accounting for the three major greenhouse gases’, ABARE research report, Canberra.

Burniaux, J.-M., 2000, ‘A Multi-gas Assessment of the Kyoto Protocol’, OECD Economics Department Working Papers 270, Paris.

Bollen, J.C., A.J.G. Manders and P.J.G. Tang, 2001, Winners and Losers of Kyoto, CPB and RIVM, the Netherlands.

Bollen, J.C., H.L.F. de Groot, A.J.G. Manders, P.J.G. Tang, H.R.J. Vollebergh and C.A. Withagen, 2002, ‘Klimaatbeleid en Europese Concurrentieposities’, CPB Document 24, The Hague, the Netherlands.

Bollen, J.C., T. Manders and M. Mulder, 2004, *Four Futures for Energy Markets and Climate Change*, CPB and RIVM, The Hague, the Netherlands.

Capros, P., N. Kouvaritakis and Dr. L. Mantzos, 2001, *Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change; Top-down Analysis of Greenhouse Gas Emission Reduction Possibilities in the EU*, Athens, Greece.

CPB, 1999, *WorldScan: the core version*, The Hague, the Netherlands.

CPB, 2003, *Four futures of Europe*, The Hague, the Netherlands.

Copeland, B.R. and M.S. Taylor, 2003, ‘Trade, Growth and the Environment’, NBER Working Paper 9823, Cambridge MA.

Dimaranan, B. V. and McDougall, R.A., 2002, *Global Trade and Assistance and Protection: The GTAP 5 Database*, Center for Global Trade Analysis, Purdue University.

EPA, 2001, Addendum to the US Methane Emissions 1990-2010: 2001Update for Inventories, Projections, and Opportunities for Reductions, Washington D.C.

EPA, 2003, International Methane and Nitrous Oxide Emissions and Mitigation Data for EMF 21 (available from http://www.stanford.edu/group/EMF/home/index.htm).

Hendriks, C., D. de Jager, K. Blok, J. de Beer, J. Harnisch, S. Joosen, D. Phylipsen, M. Kerssemeeckers, C. Byers, M. Patel, J. Bates, C. Brand, P. Davison, A. Haworth and N. Hill, 2001, Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change Bottom-up Analysis of Emission Reduction Potentials and Costs for Greenhouse Gases in the EU; Updated, Utrecht, the Netherlands.

Hayhoe, K., A. Jain, H. Pitcher, C. MacCracken, M. Gibbs, D. Wuebbles, R. Harvey, D. Kruger, 1999, ‘Costs of Multigreenhouse Gas Reduction Targets for the USA’, *Science*, 286, p. 905-906.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. De Masin and H.D. Jacoby, 2002, ‘Modeling Non-CO_2 Greenhouse Gas Abatement’, MIT Joint Program on the Science and Policy of Global Change, Report No. 94, MIT, Cambridge MA.

Jensen, J. and M.H. Thelle, 2001, ‘What are the Gains from a Multi-Gas Strategy’, Working Paper CLIM 84.01.

Manne, A. and R. Richels, 2001, ‘An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases’, *Nature*, 410, p. 675-677.

Reilly, J. M. Mayer, and J. Harnisch, 2003, ‘Multiple Gas Control Under the Kyoto Agreement’, MIT Joint Program on the Science and Policy of Global Change, Report 58, Cambridge MA.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, and C. Wang, 1999, ‘Multi-gas assessment of the Kyoto Protocol’, *Nature*, 401, p. 549 – 555.

RIVM, 2001, ‘The IMAGE 2.2 implementation of the SRES scenarios’, RIVM CD-ROM 481508019, Bilthoven, the Netherlands.

Appendix A: Bottom-up MAC-curves and their parameterisation

The bottom-up MAC-curves are fitted using Equation (3.4). This yields two parameters, δ and ε, which are presented in the table below. The MAC-curves for the various emission sources are shown in the figures below.

Table A.1 Fit of the parameter technical reduction limit ε for bottom-up MAC-curves

	Paddy rice	Leakages coal	Leakages oil	Leakages gas	Adipic and nitric acid production
Europe-15	0.57	0.52	1.00	0.49	0.92
USA	0.57	0.88	0.21	0.56	0.92
Rest OECD	0.57	0.76	0.29	0.55	0.92
Eastern Europe	0.57	0.73	1.00	1.00	0.92
Former Soviet Union	0.57	0.61	0.38	0.43	1.00
Middle East	0.57	0.86	0.43	0.60	1.00
Turkey	0.57	1.00	1.00	0.62	0.92
Latin America	0.57	1.00	0.35	0.59	1.00
Rest of World	0.57	0.80	0.32	0.53	0.92

Table A.2 Fit of the parameter convergence speed δ for bottom-up MAC-curves

	Paddy rice	Leakages coal	Leakages oil	Leakages gas	Adipic and nitric acid production
Europe-15	23.2	0.1	5.5	10	0.05
USA	23.2	5.1	12.2	139	0.05
Rest OECD	23.2	2.2	13.2	132	0.05
Eastern Europe	23.2	0.1	1.8	142	0.05
Former Soviet Union	23.2	3.0	12.2	15	1.00
Middle East	23.2	0.1	5.5	119	1.00
Turkey	23.2	0.1	1.8	96	1.00
Latin America	23.2	1.0	5.5	64	1.00
Rest of World	23.2	0.6	10.5	63	0.05

Figure A.1 Global MAC-curve of emissions from fertilizer use (Brown et al., 1999)

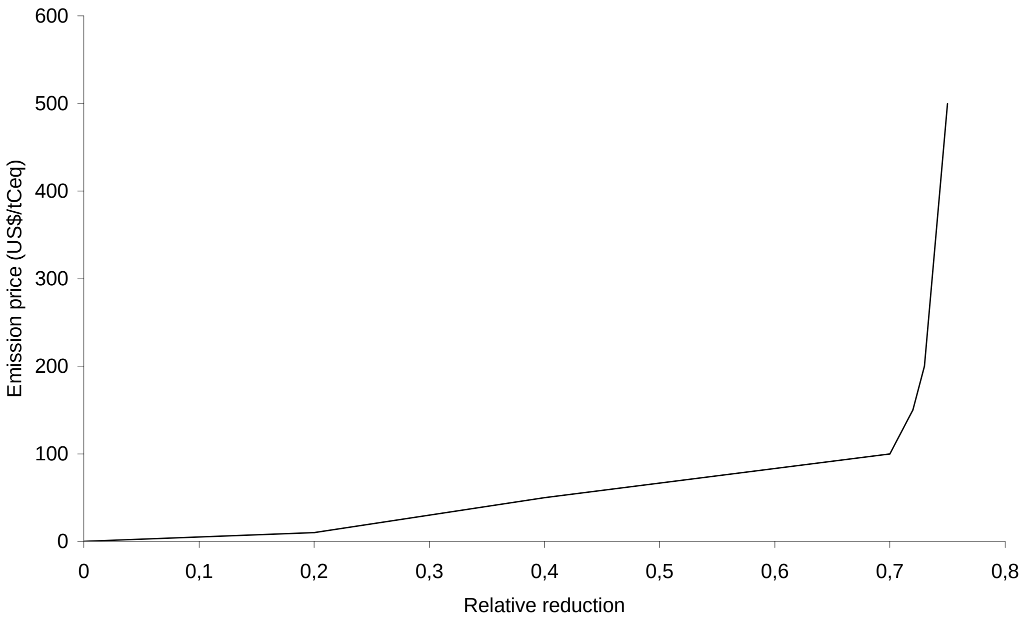


Figure A.2 Global MAC-curve for emissions from paddy rice (Brown et al., 1999)

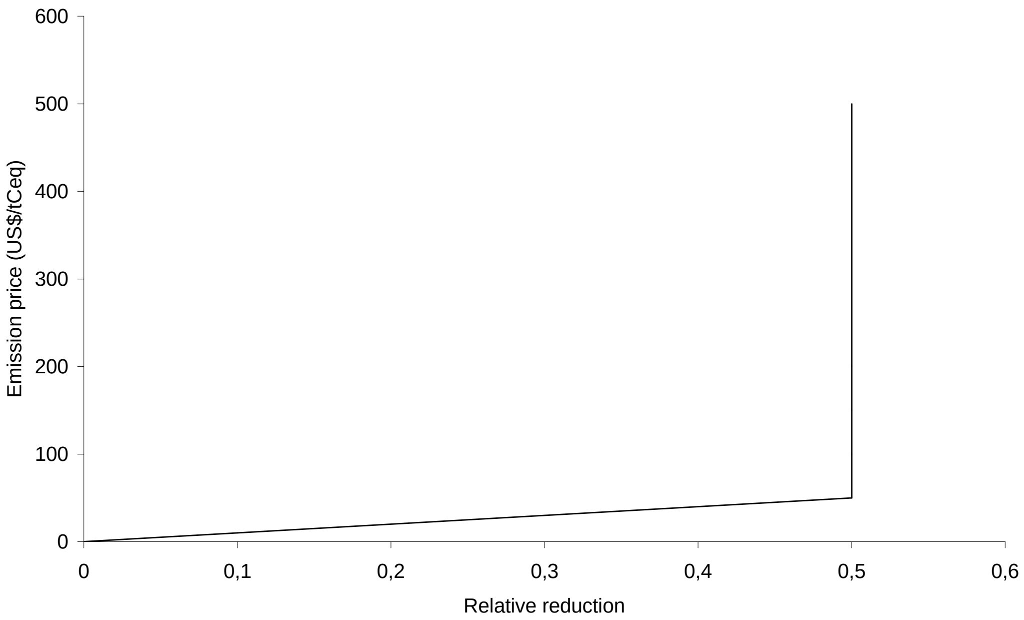


Figure A.3 **Regional MAC-curves for emissions from the production of adipic ant nitric acid (EPA, 2003).**

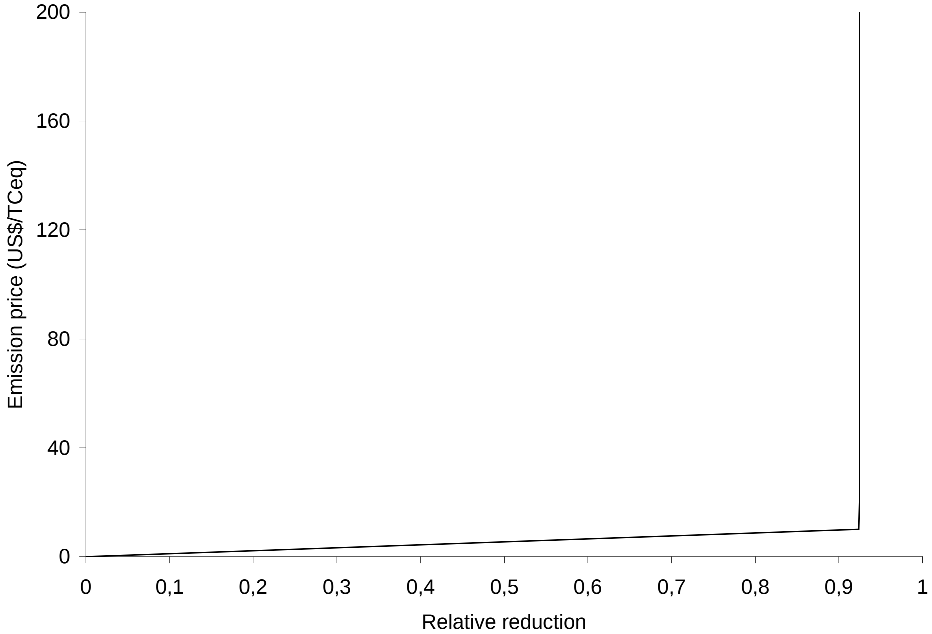


Figure A.4 **Regional MAC-curves for emissions from losses and leakages from gas production and distribution (EPA, 2003).**

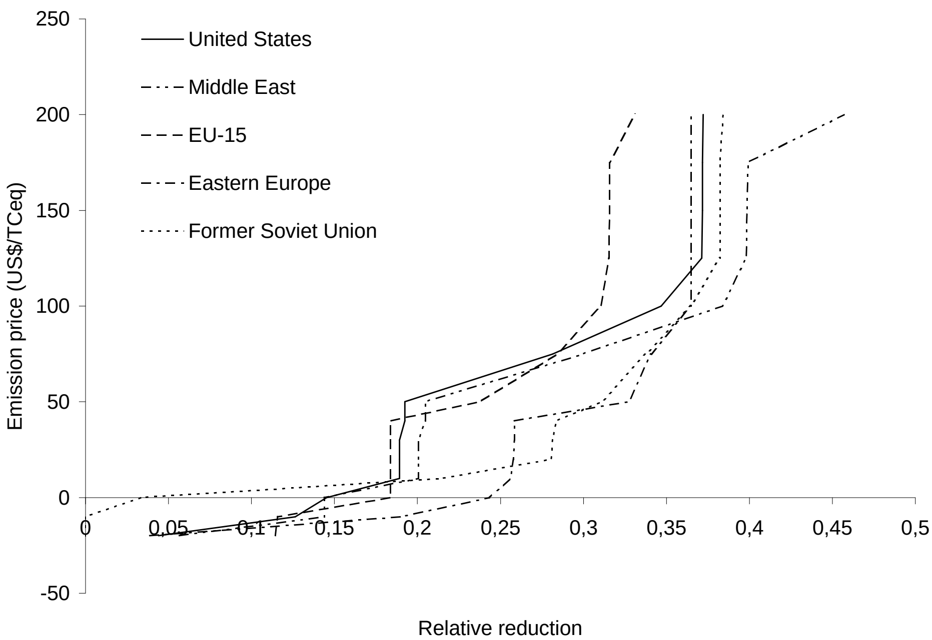


Figure A.5 Regional MAC- curves for emissions from losses and leakages from coal mining (EPA, 2003).

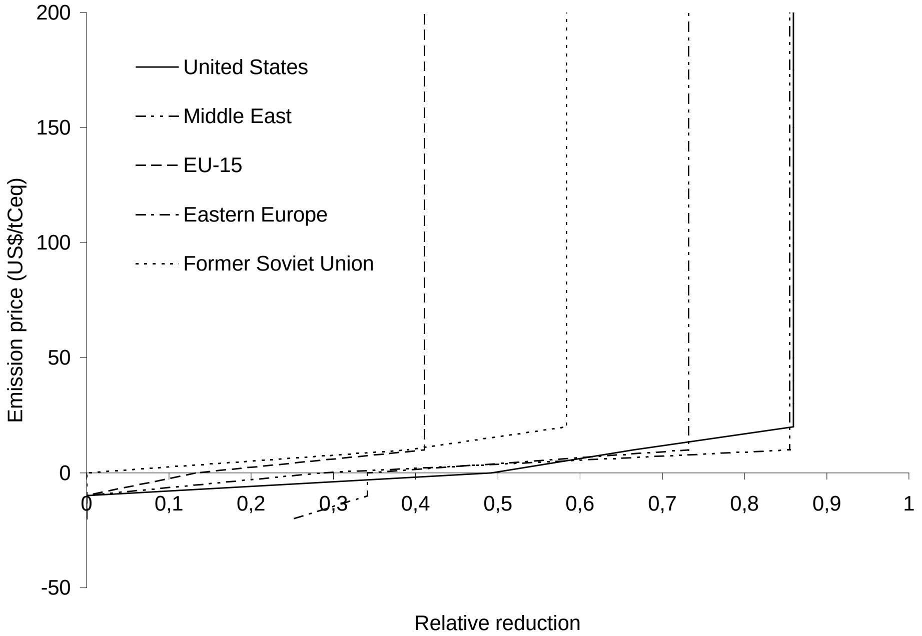
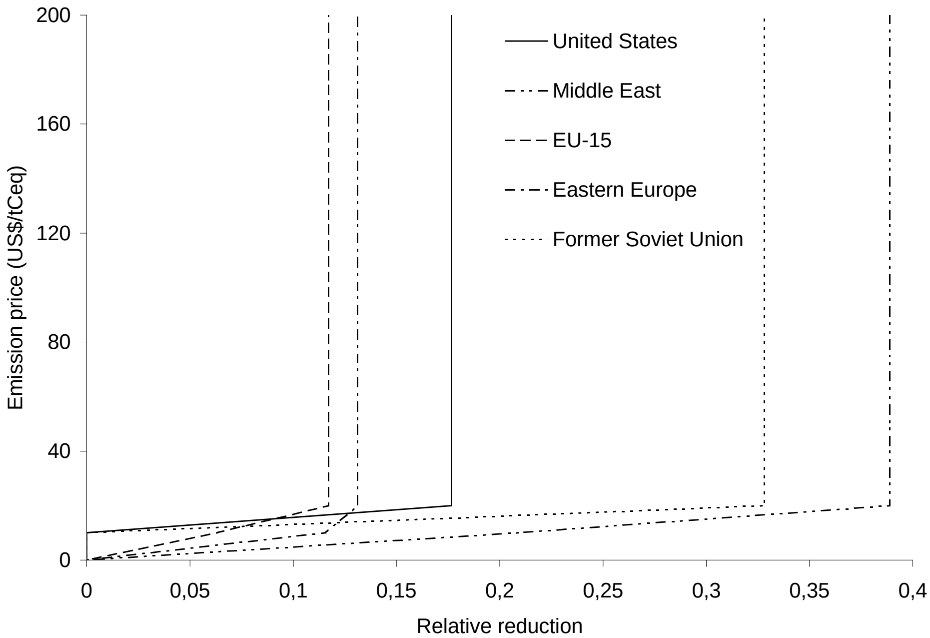


Figure A.6 Regional MAC-curves for emissions from losses and leakages from oil production (EPA, 2003).



Appendix B: Derivation of the productivity function

The emission factor E^F is defined by:

$$E^F(r(P_E)) = \overline{E}^F \cdot (1 - r(P_E)) \qquad ,with\ \ r(P_E) = r_A + r_{ITC}(P_E)\ , \tag{B.1}$$

with $\overline{E}^F$ the emission factor in the base year, and *r* the reduction as a function of the emission price P_E. The reduction *r* is the sum of the reduction as a result of climate policy (r_{ITC}) and the autonomous reduction in the baseline (r_A).

Assuming that emissions are taxed at production Q, the profit of the firm Π becomes:

$$\Pi = p \cdot A \cdot Q - c \cdot Q - P_E \overline{E}^F \cdot (1-r) \cdot Q\ , \tag{B.2}$$

where *p* is the producer price, and *c* is the marginal cost of production excluding abatement. The productivity A is a decreasing and concave function of the emission reduction r : the more resources are diverted to abatement, the less output is available for sale. The first order condition for the optimal reduction reads:

$$\frac{\partial \Pi}{\partial r} = p \cdot A' Q + P_E \overline{E}^F \cdot Q = 0 \tag{B.3}$$

We assume zero profits. The firm chooses the optimal abatement level given an emission response function $P_E(r)$. We assume that the emission response function takes the following form:

$$P_E(r) = \frac{\delta \cdot (r - r_A)}{\varepsilon - r} \quad \text{for } r_A \le r \le \varepsilon \tag{B.4}$$

with r_A the reduction through AEEI, ε denoting the technical limit to the possible emission reduction, and δ the speed of convergence . Abatement efforts affect the productivity *A* of a sector. The effect of productivity on profit defines an optimal abatement level. The two key equations are the zero-profit condition and the first order condition for the optimal reduction levels. At the optimal abatement level *r* , and thus also for r_{ITC} because r_A is a constant, it holds that:

$$0 = p \cdot A \cdot Q - c \cdot Q - P_E \overline{E}^F \cdot (1-r) \cdot Q \tag{B.5}$$

$$0 = p \cdot A' Q + P_E \overline{E}^F \cdot Q \tag{B.6}$$

Combining these two equations yields:

$$\frac{A'(r_{ITC})}{A(r_{ITC})} = \frac{-\overline{E}^{F} \cdot P_E}{c + P_E \cdot (1-r) \cdot \overline{E}^{F}} \tag{B.7}$$

Substitution (B.4) into this differential equation and integrating over r_{ITC}, we get:

$$\ln\left(A\left(r_{ITC}\right)\right) = -\phi \int_{0}^{r_{ITC}} \frac{x dx}{-\phi x^2 + \lambda x + \mu} + \theta \tag{B.8}$$

with

$$\phi = \overline{E}^{F} \delta, \quad \lambda = \phi(1 - r_A) - c, \quad \mu = c(\varepsilon - r_A)$$

and ✓ a constant of integration. Solving this integral yields:

$$\ln\left(A\left(r_{ITC}\right)\right) = \frac{1}{2}\ln\left(-\phi r_{ITC}^{2} + \lambda r_{ITC} + \mu\right) - \frac{\lambda}{\sqrt{4\mu\phi + \lambda^2}} \tanh^{(-1)}\left(\frac{2\phi r_{ITC} - \lambda}{\sqrt{4\mu\phi + \lambda^2}}\right) + \theta \tag{B.9}$$

with the constant of integration ✓ following from the constraint A(0) = 1. After some rewriting and simplification, this leads to the Equation (3.5) from the main text.