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A Multi-Gas Assessment of the Kyoto Protocol

Jean-Marc Burniaux

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A MULTI-GAS ASSESSMENT OF THE KYOTO PROTOCOL

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by
Jean-Marc Burniaux

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ABSTRACT/RÉSUMÉ

The Kyoto Protocol covers emissions of a range of greenhouse gases. Yet, most attempts to quantify the economic impact of implementing the Protocol's emission targets for the period 2008-12 have focused exclusively on CO_2 emissions. This paper extends previous OECD analysis confined to CO_2 alone so as to cover also emissions of methane and nitrous oxide. The paper concludes that the economic costs of implementing the targets in the Kyoto Protocol are lower than suggested by an analysis confined to CO_2 alone. However, over the longer term, when larger cuts in greenhouse gas emissions are required in order to have any material effect on climate, most abatement will likely have to come from CO_2 and the inclusion of other gases in the analysis may not substantially alter estimates of economic costs.

JEL classification: D58, Q32, Q43

Keywords: Computable and other Applied General Equilibrium Models, Exhaustible Resources and Economic Development, Energy and the Macroeconomy.

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Le Protocole de Kyoto couvre plusieurs gaz à effet de serre (GES). Cependant, la majorité des études visant à quantifier l'impact économique du Protocole pour la période 2008-2012 prennent exclusivement en compte les émissions de dioxyde de carbone (CO_2). Le but de ce document est d'élargir l'analyse faite précédemment par le Secrétariat sur base du CO_2 seulement en prenant également en compte le méthane et l'oxyde nitreux. La conclusion principale est que les coûts économiques de mise en œuvre du Protocole sont sensiblement plus faibles que le suggéraient les analyses basées sur le seul CO_2. Dans un plus long terme cependant, lorsque des efforts plus substantiels devront être accomplis si l'on veut exercer le moindre impact concret sur le climat, l'essentiel des réductions concernera le CO_2. Dans ce contexte, la prise en compte des autres gaz ne devrait pas modifier beaucoup les estimations des coûts.

Classification JEL : D58, Q32, Q43

Mots-clés : Modèles d'Equilibre Général Appliqués et Calculables, Ressources non renouvelables et Développement Economique, Energie et Macro-économie.

TABLE OF CONTENTS

Boxes

Tables

Figures

Annex Tables

Annex Figure

A MULTI-GAS ASSESSMENT OF THE KYOTO PROTOCOL

Jean-Marc Burniaux[1]

EXECUTIVE SUMMARY

1. The Kyoto Protocol, agreed at the third conference of the parties to the UN Framework Convention on Climate Change, commits a group of countries to reduce their emissions of greenhouse gases (GHGs). These countries (known as “Annex 1 countries”) have agreed, but not yet ratified, emission constraints corresponding to a cut of emissions by around 5 per cent relative to their 1990 levels, to be achieved by the period 2008-12. However, compared to what emissions would have been without policy intervention, the cut is much more significant: for OECD countries as a group it amounts to some 20 to 30 per cent. This sizeable cut has raised concern about the associated economic costs and led to considerable research activity to determine their likely magnitude.

2. Most studies aimed at quantifying the economic costs of implementing the Kyoto Protocol (including earlier OECD work) have focused exclusively on carbon dioxide emissions, ignoring that the Protocol covers a number of other GHGs. This is likely to give an upward bias to the estimated economic costs for two reasons. First, emission trends of different gases are likely to be different in the absence of policy changes, with carbon dioxide emissions likely to grow relatively rapidly and thereby giving an exaggerated impression of reduction requirements to reach the Kyoto targets. Second, the Kyoto targets refer to overall emissions of GHGs, leaving scope to focus emission reductions on the gases which can be cut at least cost. On the other hand, considering all GHGs together tends to increase their importance relative to the size of the economy which is a factor that would raise the estimated costs of emission reductions compared to a similar relative cut in emissions of carbon dioxide alone.

3. This paper[2] extends previous OECD analysis to cover also emissions of methane and nitrous oxide and thereby expands coverage to some 80 per cent of GHG emissions covered by the Protocol. The inclusion of these gases reduces the estimated economic costs of implementing the Kyoto Protocol. Thus, if each Annex 1 country or region takes individual action to respect its emission target under the Protocol, real income may on average be a third of a per cent lower by the target period as compared with half a per cent lower in the previous analysis, that covered only carbon dioxide. Both these estimates are low because

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[1] The author is Principal Administrator in the OECD Economics Department, currently on leave at Purdue University, Department of Agricultural Economics, 1145 Krannert Building, West-Lafayette, Indiana, 47907-1145 (E-mail: Burniaux@agecon.purdue.edu). He would like to express his gratitude to Jørgen Elmeskov for improving the readability of the text, to Christophe Complainville who made all preliminary investigations that were needed for this project, to Arnaud Mazin for efficient research assistance, to Anick Lotrous for statistical assistance and to Jackie Gardel for her valuable technical support.

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the analysis abstracts from important adjustment costs (see below) but, in relative terms, the estimate based on the three gases is about a third lower than the one based on carbon dioxide alone. Among Annex 1 regions, it is particularly the European Union that seems to benefit from the inclusion of methane and nitrous oxide, notably reflecting the expected reductions in methane emissions in that region even in the absence of policy change. Among economic sectors, the expanded gas coverage implies that more of the burden of abatement falls on agriculture, which is a source of both methane and nitrous oxide, and less falls on energy-intensive sectors.

4. The Kyoto Protocol includes a number of mechanisms (for example, emission trading) which enable emissions to be cut where it can be done at least cost. Making use of these mechanisms, the costs of implementing the Protocol would be lower still than the figures quoted above. The two types of flexibility - the choice of which GHGs to cut and where to cut them - interact with each other. This is the case, on the one hand, because the inclusion of methane and nitrous oxide considerably increases the amount of “hot air” in the countries of the former Soviet Union, notably Russia and Ukraine. The term “hot air” refers to the feature that even without any policy action, emissions are likely to be significantly below target levels. In conjunction with the flexibility mechanisms, the increased amount of “hot air” can then be sold to other Annex 1 countries and used to offset their GHG emissions. On the other hand, countries differ less in terms of abatement costs when all three gases are considered, which limits the gains from emission trading.

5. While the estimated costs of implementing the Kyoto Protocol become quite low when the flexibility mechanisms are allowed a full play, it should be underlined that important components of costs are left uncovered by the analysis. The results are based on the use of the OECD’s general equilibrium model, GREEN, which assumes that labour can be reallocated in a frictionless manner guided by flexible wages and prices. In practice, frictions are important over short- and medium-term horizons and earlier analysis has shown that the existence of wage rigidities can increase the economic costs substantially - to an order of magnitude around 1-2 per cent of GDP or even above in some cases. These results were obtained by an analysis focusing only on carbon dioxide but although costs are lower when more gases are concerned they would remain substantially above estimates based on flexible wages. In any case, it needs to be borne in mind that the current analysis still ignores aspects of flexibility and cost reduction built into the Kyoto Protocol, such as the remaining GHGs and the use of sinks.

6. Over the long term, action to effectively address climate change will have to go much beyond the reduction commitments in the Kyoto Protocol and also needs to include participation by developing countries. The paper considers some long-term scenarios in order to explore how much of a difference it makes to include methane and nitrous oxide in the analysis of economic costs over this time horizon. At a general level, the impact is significantly smaller than for the first target period of the Kyoto Protocol. This is because very large emission reductions are necessary over the long term to have any meaningful impact on the climate change process, and the potential for reducing emissions of methane and nitrous oxide is limited before costs become higher than the costs of reducing carbon dioxide emissions.

7. Uncertainty about emission levels and trends, as well as the scope for emission cuts and their costs is much higher for methane and nitrous oxide than for carbon dioxide. The paper contains some illustrative model simulations to explore the importance of these uncertainties for the estimated economic costs of taking action against climate change. Based on assumptions meant to span the full range of uncertainty in the literature, the conclusions reached above seem to hold in qualitative terms though the quantitative estimates obviously differ.

1. Introduction

8. The Kyoto Protocol under the UN Framework Convention concerning Climate Change was agreed in December 1997. The Protocol, which has so far been ratified by only a few countries, obliges a

group of countries known as "Annex 1[3] countries" to reduce their anthropogenic emissions of Greenhouse Gases (GHGs). The accumulation of these gases in the atmosphere is believed to have long-run implications for the climate on earth. The emissions objective agreed in Kyoto may not sound very ambitious: relative to the 1990 level, Annex 1 countries are due to reduce their total GHG emissions by around 5 per cent on average for the period 2008-2012. However, the magnitude of this abatement effort is best viewed when the reduction is compared to the level of the emissions that would be expected in the absence of any action, referred to as the baseline or "Business-as-Usual" (BaU) level. Expressed in this way, OECD countries will have to reduce their emissions by some 20 to 30 per cent. Emission abatements of such magnitude are likely to require significant structural adjustments.

9. Much analysis has been undertaken using macroeconomic global models to quantify the economic costs of implementing the Protocol by (see Weyant and Hill, 1999; OECD, 1999). The OECD Secretariat has developed a global, multi-region, multi-sector dynamic applied general equilibrium model named GREEN (see Burniaux *et al.*, 1992; Lee *et al.*, 1994) and used it to quantify these costs under a number of different assumptions as to how the Protocol would be implemented. However, most quantitative assessments of the economic costs of the Protocol - including those based on the GREEN model - have so far only taken into account the most important greenhouse gas, CO_2.

10. Article 3 and Annex A of the Protocol specify its coverage in terms of different gases. In addition to CO_2, the Protocol includes five gases or groups of gases: methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. By focusing only on CO_2, most assessments miss three important influences of this wider coverage. First, trends in emissions of non-CO_2 gases affect overall abatement needs and thereby economic costs. Second, there may be large differences of marginal abatement costs across different gases and the fact that the Protocol allows substitution among gases implies that efficiency gains can be achieved by substituting low-cost emission cuts for high-cost ones. Third, the wider coverage implies that the GHGs covered by the Protocol have a larger weight in the economy than CO_2 alone and that costs of a given relative reduction will be correspondingly higher.

11. The evidence on the effects which the wider gas coverage has on overall economic costs is scarce so far. Gielen and Kram (1998) suggest that emissions of the non-CO_2 gases may decline autonomously over time and estimate this decline to be equivalent to a 25 per cent relaxation of the estimated cut in CO_2 emissions required to meet the European Union emission target by 2010. Results from the GTEM model (Brown *et al.,* 1999) suggest that the inclusion of methane and nitrous oxide reduces the marginal cost of meeting the Kyoto targets by a third as compared with a situation where the targets are reached through cuts in CO_2 emissions alone. Using the MIT Integrated Global System Model (IGSM), Reilly *et al.* (1999) find that taking into account the non-CO_2 gases and the potential for carbon sinks may reduce the cost of implementing the Kyoto Protocol by almost 40 per cent. Finally, Manne and Richels (2000) estimate that the inclusion of both non-CO_2 gases and carbon sinks could reduce the marginal cost of meeting the Kyoto targets by 48 per cent. Thus, overall, available studies suggest that the economic costs of reaching the Kyoto targets may be exaggerated by quantifications that focus exclusively on CO_2 abatement.

12. At the same time, the inclusion of non-CO_2 gases may increase the uncertainty regarding the environmental effectiveness of the Protocol. Indeed, non-CO_2 gas emissions are measured with much less precision than emissions of carbon dioxide. For instance, Gielen and Kram (1998) estimate that in Europe, the uncertainty regarding CH_4 emissions is in a range of ±25 per cent while estimates of N_2O emissions from fertiliser use in agriculture may vary by a factor of 2-3. Moreover, the inclusion of non-CO_2 gases under the same target as CO_2 necessitates the establishment of conversion or equivalence factors between

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[3] These countries are also, more appropriately, referred to as "Annex B" countries, since they are listed in Annex B of the Protocol. They include all OECD countries, except Korea, Mexico and Turkey. In addition, some of the successor countries to the former Soviet Union are included in Annex B - in terms of GHG emissions Russia and Ukraine are the most important.

different greenhouse gases in terms of their climate effects. However, according to the IPCC, the so-called Global Warming Potentials which translate other gases into tons of carbon equivalent have an uncertainty of ±35 per cent, reflecting the imprecise estimation of their atmospheric lifetimes, the choice of time horizon over which warming effects are considered and the assessment of the radiative forcing effect (the "warming") of given atmospheric concentrations at a particular point in time (EPA, 1999).

13. The aim of this paper is to assess how much consideration of non-CO_2 gases modifies the economic costs of the Kyoto Protocol previously estimated by the OECD Secretariat using a version of the GREEN model that incorporated only carbon dioxide (OECD, 1999). The new version of the model used for the current analysis includes endogenous determination of methane (CH_4) and nitrous oxide (N_2O) emissions. This raises the model's coverage to around 80 per cent of the climate effects from man-made GHG emissions included in the Kyoto Protocol.

14. The second section of this paper describes the various sources of methane and nitrous oxide emissions as well as the various technological options that are or soon will be available to reduce these emissions. The third section discusses the contribution by the two additional GHGs to future overall GHG emissions in the absence of any policy to restrain their growth (the "Business-as-Usual" or baseline scenario). The fourth section analyses how the inclusion of methane and nitrous oxide modifies the estimated economic costs of implementing the Kyoto Protocol, including the role of these two gases in the use of the "flexibility mechanisms". The fifth section provides an assessment of the potential for non-CO_2 gases to contribute to stabilising world GHG emissions beyond the first commitment period (2008-2010). The final section illustrates how various sources of uncertainty may affect these cost estimates.

2. Sources and abatement of methane and nitrous oxide emissions

2.1 Importance of non-CO_2 gases in total GHG emissions

15. Assessing the contribution of each GHG to climate change is not straightforward. The GHGs not only have different climate impacts at a given point in time but also have very different lifetimes. Therefore, in terms of their impact on future climate, they cannot be added up on a tonne-for-tonne basis. There is no universally accepted methodology to solve this problem. Article 5 of the Kyoto Protocol specifies that emissions of different GHGs have to be converted into carbon dioxide equivalents by using so-called Global Warming Potentials (GWPs). The GWP of a GHG is defined as the ratio of the radiative forcing of the GHG (its "warming") integrated over a given time period to the corresponding integrated radiative forcing of CO_2 over the same period. At the third meeting of the Conference of the Parties, the IPCC recommended using GWPs calculated over a period of 100 years. In the present report, and based on the same conversion key, all GHG emissions are expressed in terms of carbon equivalents (Ceq). Table 1 shows the lifetimes, global warming potentials and the corresponding carbon equivalence of the three gases considered in this analysis.

[Table 1. Global warming potentials]

16. Based on these indicators, the IPCC has estimated that carbon dioxide emissions accounted for 61 per cent of the total global warming effect of all man-made GHG emissions in 1990 (IPCC, 1990, p. 61). According to these estimates, adding methane and nitrous oxide would account for up to 80 per cent of the warming effect. The bulk of the remaining gases is accounted for by the chlorofluorocarbons that are regulated by the Montreal Protocol (9 per cent), troposheric ozone (6 per cent) and other trace gases (5 per cent). Among the three gases covered in this analysis, carbon dioxide accounted for 75 per cent of global warming potential from emissions in 1995, methane for 19 per cent and nitrous oxide for the remaining 6 per cent (Figure 1). These shares depend on the specific assumptions behind the GWPs. For instance, considering the warming potential over a shorter time horizon would increase the role of the non-CO_2

gases, in particular CH_4 that has a shorter lifetime.[4] Moreover, the existence of interactions between gases implies that different combinations of GHGs with the same overall GWP may have different impacts on aggregate radiative forcing, a fact that is not captured by the GWPs. The bottom line is that the environmental impacts of implementing the Kyoto targets are estimated with considerable uncertainty.

[Figure 1. Shares of CO_2, CH_4, and N_2O emissions in 1995]

2.2 Main sources of non-CO_2 gas emissions

2.2.1 Methane

17. Agriculture is responsible for a large part of methane emissions associated with economic activity. The livestock sector produces methane as a by-product of the digestive process of herbivores as micro-organisms break down carbohydrates into simple molecules for absorption into the bloodstream. Altogether, enteric fermentation generates between 340 and 570 million tons of Ceq annually. Although bovines are the largest source, non-bovine animals (horses, pigs, camels, …) also emit methane. The amount of CH_4 emitted depends on the type, age, weight and health of the animal, as well as its activity, but mainly on the quantity and characteristics of feed. CH_4 is also released in smaller quantities (ranging from 60 to 100 million tons of Ceq in 1995) from the decomposition of livestock manure under anaerobic conditions. These conditions occur when manure is stored in large piles or treated as liquid in lagoons, ponds, tanks or pits. By contrast, when manure is handled as a solid, in stacks or pits, or deposited on pastures, it decomposes aerobically with little or no CH_4 emissions.

18. The other principal source of methane emitted by agriculture is rice cultivation (estimated at around 290 million tons of Ceq in 1995 though within a wide uncertainty range). The flooding of rice fields yields anaerobic decomposition of plant matter that releases methane into the atmosphere through the rice plants. The amount of CH_4 emissions from rice is a function of the rice variety, the number and duration of harvests, soil types, temperatures, irrigation practices and fertiliser use.

19. The largest single source of methane after agriculture are fugitive emissions from oil and natural gas activities (around 270 million tons of Ceq in 1995). Most of these emissions originate from natural gas extraction, processing and transportation and from natural gas flaring and venting.

20. Disposal and treatment of industrial and municipal waste also produce methane. These emissions are a by-product of the anaerobic decomposition of man-made waste. Two major sources are the disposal of solid waste on landfills and the treatment of wastewater. In both cases, methane is released as bacteria break down organic matter. As data on wastewater emissions are extremely uncertain and scarce at the regional level, they have not been taken into account in this analysis.

21. Finally, coal mining and handling generate methane emissions (estimated at around 200 million tons of Ceq in 1995). The process of coal formation - coalification - generates methane that is stored in the coal and is released in the atmosphere once the pressure on the coal is reduced. For the same degree of coalification, a deeper coal seam contains more methane because the pressure on coal is higher. Surface-mined coal emits less methane than underground mining. An important part of CH_4 emissions from coal comes from post-mining activities (processing, transportation and handling). There are other CH_4 emission sources that are not covered in the present analysis, such as emissions from agricultural burning,

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[4] The choice of using GWPs based on a 100-year lifetime has been questioned on the grounds that, in order to derive optimal policy options, discounted damages of emissions from each gas separately should be considered (see, for instance, Reilly and Richards, 1993; Schmalensee, 1993; Tol, 1999; Wigley, 1998).

agricultural soil, industrial processes and waste incineration. All together, uncovered emissions (including those from wastewater) amount to perhaps some 20 per cent of estimated total CH_4 emissions.

22. Table 2 compares the 1995 emissions used as benchmarks in the GREEN model with lower and upper bound estimates from the IPCC. Total CH_4 emissions amount to 1.5 billion tons (or giga-tons Gt) of Ceq in 1995 but the range of uncertainty that surrounds this estimate is large, amounting to roughly ±40 per cent. According to the GREEN benchmark data, more than 50 per cent of world CH_4 emissions originate from agriculture.

[Table 2. Estimates of methane emissions in 1995]

2.2.2 Nitrous oxide

23. Agriculture is by far the main contributor to N_2O emissions. Direct emissions from agricultural soils result primarily from the nitrification and denitrification processes.[5] Application of nitrogenous fertiliser results in additional N_2O emissions. Direct emissions from agricultural soils is estimated at 210 million tons of Ceq in 1989 (IPCC, 1996). The use of synthetic fertilisers also gives rise to indirect emissions[6] that can be considered as closely linked to the use of synthetic nitrogen fertilisers. The IPCC estimated these indirect emissions to 160 million tons of Ceq in 1989 but, due to lack of available data, only part of these indirect emissions are covered in the model simulations. Finally, N_2O is emitted directly from soils as a result of animal production.[7]

24. Non-combustion industrial processes also emit N_2O in the atmosphere. Three sources of emissions have been identified: *i)* nitrous oxide as a by-product of the oxidation that produce adipic acid used in the manufacturing of nylon; *ii)* nitrous oxide as a by-product of the use of nitric acid in the production of fertilisers and adipic acid; and, *iii)* nitrous oxide produced by the industrial production of other chemical compounds. According to the IPCC, the first two sources account for 40 to 70 million tons of Ceq while the size of the last is unknown.

25. Finally, nitrous oxide is produced directly from the combustion of fossil fuels both by stationary and mobile sources. IPCC estimates suggest that, emissions from stationary combustion are a minor source relative to other anthropogenic sources. N_2O emissions from vehicles have only recently been studied in detail but are also thought to be small. However, emission rates from vehicles become substantially higher when some emission control technology (especially catalysts on road vehicles) are used. Other N_2O sources, such as from land clearing and crop burning, are not covered in this study.

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[5] Nitrification is the aerobic microbial oxidation of ammonium to nitrate. Denitrification is the aerobic microbial reduction of nitrate to dinitrogen gas. Both processes yield nitrous oxide as a gaseous joint product.

[6] These indirect sources involve: *i)* the volatilisation and subsequent atmospheric deposition of NH_3 and NO_x from fertiliser application; *ii)* nitrogen leaking and runoff; *iii)* human consumption of crops followed by municipal sewage treatment; *iv)* formation of N_2O in the atmosphere from NH_3; and, *v)* food processing (IPCC, 1996).

[7] Emission sources from animal production are: *i)* the animals themselves; *ii)* animal wastes during storage and treatment; and *iii)* dung and urine deposited on the soil by grazing animals. These emissions can be significant, amounting to 130 million tons of Ceq in 1989 as estimated by the IPCC. However, due to data uncertainties and difficulties of modelling, it has been decided not to incorporate N_2O emissions from animals in the current analysis.

26. Total nitrous oxide emissions - as estimated for the GREEN benchmark data - amount to 490 million tons of Ceq in 1995, of which 66 per cent is emitted by agriculture. Revisions to the IPCC methodology concerning certain N_2O emissions have not yet been followed by a complete revision of data but seem to imply that the above estimates may underestimate the true level of emissions by about a third. This divergence is however within the range of uncertainty that surrounds estimates of N_2O emissions.[8]

2.2.3 Overall emission sources

27. Incorporating methane and nitrous oxide, as opposed to considering only CO_2, implies that agriculture bears a larger share of the burden of mitigation policies. Considering the three gases, sources specific to agricultural production were responsible for 14 per cent of world GHG emissions in 1995 (Figure 2). Nevertheless, the bulk of man-made GHG emissions - around 80 per cent - still originates from the combustion of fossil fuels.

[Figure 2. World GHG emissions by source, 1995]

28. While shifting some of the burden of mitigation to agriculture, the inclusion of the non-CO_2 gases also suggests a larger potential role of non-OECD countries in future mitigation efforts than based on an analysis restricted to CO_2 alone. OECD countries accounted for only 25 per cent of world methane emissions in 1995 as opposed to about half of CO_2 emissions (Figure 3). When incorporating methane and nitrous oxide, the share of OECD countries in total 1995 world emissions falls from 53 to 47 per cent while the share of the non-Annex 1 countries increases from 36 to 43 per cent. In other words, with a wider gas coverage, the weights of OECD and developing countries in world emissions tend to become much closer to each other.

[Figure 3. GHG emissions by region, 1995]

2.3 Options for reducing non-CO_2 emissions and their modelling

29. Carbon dioxide is released in fixed proportions when fossil fuels are burned and abatement relies on a reduction in the use of these fuels through substitution by fuels with lower or no carbon contents or away from energy use in general. In contrast, abatement options for CH_4 and N_2O are much more diverse. Box 1 reviews a number of engineering estimates of the abatement potential that is technologically achievable over the foreseeable future. Unfortunately, the engineering literature frequently does not consider the costs of emission reductions.[9]

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[8] The total estimate of 490 million tons of Ceq in 1995 is in the order of magnitude of data from other models (481 million tons in Manne and Richels, 2000; 533 million tons in the IIAA Message model; 558 million tons in the AIM model).

[9] Some of these studies argue that reductions can sometimes be achieved at no cost (Gibbs, 1998).

Box 1. Abatement options for CH_4 and N_2O emissions

In order to be able to model the abatement of non-CO_2 gases, the engineering literature has been reviewed for estimates concerning the size and cost of potential abatement options. As regards methane, technical options for reducing emissions correspond to their various sources:

- ***Enteric fermentation:*** the potential to reduce methane emissions from enteric fermentation comes mainly from increasing productivity so that, for a given level of animal production, the size of herds can be reduced. The reduction potential from productivity increase is estimated at 5 to 60 per cent around the world (Müller and Bartsch, 1999). Developing countries, where livestock practices often lag behind those in high-income countries, may have a higher reduction potential. Further reductions can be obtained by changing animal feeds.[1] Riemer and Freund (1999) estimate that the cost of reducing methane emissions by changing feed may be relatively high, amounting to $10 000 per ton of methane ($1 745 per ton of Ceq). However, in practice, feed modification will also contribute to improve animal productivity, leading to additional emission reductions. Overall, Riemer and Freund (1999) estimate the total reduction potential for methane emissions from enteric fermentation to around 50 per cent by 2020.

- ***Manure management:*** abatement options are based on the principle that the methane emitted by animal manure is recovered and used as an on-farm source of energy.[2] Cost curves for reducing methane from animal manure have been estimated for the US (Gibbs, 1998). These curves indicate that reductions by around 70 per cent can be obtained at a marginal cost of $200 per ton of Ceq.

- ***Rice cultivation:*** among NH_4 sources, emissions from rice cultivation seem to have a relatively low abatement potential. Müller and Bartsch (1999) suggest that changes in nutrient management has the greatest potential (a 10 per cent reduction of emissions). Substituting inorganic for organic fertilisers could do this with the danger, however, of promoting emissions of nitrous oxide. As methane is produced only when the ground is flooded, shifting to intermittent irrigation could also reduce emissions. However, this technique is likely to be difficult to implement, especially in developing countries, as it implies a radical change of agricultural practices. An option that is easier to implement might be a more suitable selection of rice cultivars. All together, these options could potentially reduce methane emissions from rice cultivation by around 10 to 40 per cent (Müller and Bartsch, 1999; Riemer and Freund, 1999).

- ***Coal mining:*** technology surveys indicate that methane emissions from coal mines can be substantially reduced at relatively little costs. Potential recovery rates up to 70 per cent or more are often quoted (European Commission, 1999; IPCC, 1996; Müller and Bartsch, 1999; Riemer and Freund, 1999).[3] Gibbs (1998) estimates the total reduction potential for US coal mining at some 75 per cent, the remaining emissions coming mainly from surface mining and post-mining. Reductions around 70 per cent can be achieved at a marginal cost corresponding to $200 per ton of Ceq (Gibbs, 1998, p. 38).

- ***Oil and natural gas activities:*** methane from oil extraction is either released in the atmosphere (venting), burned off (flaring) or re-injected into the field. Emission reductions can be achieved through increased effectiveness of flaring and re-injection. Emissions related to natural gas extraction can be reduced by measures such as improved leak detection and pipeline inspection, preventive maintenance and the use of corrosion resistant materials. Although some authors indicate that the potential reduction is very significant (up to 80 per cent: European Commission, 1999; Müller and Bartsch, 1999; Riemer and Freund, 1999), it seems that not all of this potential is achievable over the next decade nor at low cost.[4] Abatement cost curves for the US indicate that a reduction of about 50 per cent can be obtained at a marginal cost of $200 per ton of Ceq (Gibbs, 1998, p. 55).

- ***Landfills:*** several options exist to reduce methane emissions from landfills, including the recovery of methane that can then be used to generate electricity, energy and/or heat.[5] The potential reduction of emissions by recovery could reach up to 90 per cent on many landfill sites (Müller and Bartsch, 1999).[6] However, it is more costly to recover methane from smaller landfills. Overall, the IPCC estimated that 30 to 50 per cent reductions in CH_4 emissions are economically feasible (IPCC, 1996).

Among methane sources, those originating from rice cultivation and enteric fermentation seemingly have a lower reduction potential.[7] The IPCC has estimated the overall potential reduction of CH_4 emissions from agriculture to at most 35 per cent (with lower and higher bounds respectively equal to 15 and 56 per cent: IPCC, 1996).

Information about the technological options to reduce N_2O emissions is scarcer than concerning methane. By better matching supply of nitrogen fertilisers to crop demand, it is possible to reduce the proportion that is released into the atmosphere. But here again, the potential reduction seems to be lower than for other sources: around 17 per cent according to IPCC estimates (with lower and higher bounds respectively equal to 9 and 26 per cent)(IPCC, 1996).

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1. Options include an increased level of feed intake, the replacement of roughage with concentrates and a change in the composition of concentrates. The potential reduction from changing feed seems relatively small in developed countries where most animals already receive a carefully composed diet.

2. These options involve the use of covered lagoon systems in large-scale dairies and pig farms and of digesters. In large-scale intensive farms, a lagoon is generally used to store the manure in which methane is produced due to anaerobic conditions. An impermeable cover is placed over the lagoon to recover methane. The recovered methane is used to power an electricity generator. Digesters are engineered vessels designed to enhance the anaerobic decomposition of manure and thus maximise the methane production inside the vessels for recovery. Small-scale digesters can be relatively easily installed in small farms. Large-scale digesters are usually mixed mechanically and heated and require a greater capital investment. As for covered lagoons, the methane produced in the digester is used to power an engine-generator. It is estimated that the rate of recovery of covered lagoons and digesters is between 25 and 80 per cent (Muller and Bartsch, 1999; European Commission, 1999).

3. This reduction potential involves three technological options. Because methane is highly explosive, mine air containing methane is generally vented directly into the atmosphere. A first option would be to recover this methane, preferably prior to mining, using vertical wells, horizontal bore holes and gob wells. The recovered gas is of medium quality and can be used in on-site power generation. Second, incremental recovery and use can be obtained by tightening well spacing and gas enrichment. Third, methane in ventilation air of coal mines can be eliminated by using a catalytic oxidiser.

4. Müller and Bartsch (1999) report that incremental investments in a small set of best management practice may profitably reduce emissions by 30 per cent in the US over the next decade. According to Riemer and Freund (1999), 45 per cent of emissions could be avoided at little or no net cost and a further 12 per cent, at a cost of $400 per ton of methane ($70 per ton of Ceq). However, the fact that methane released from oil and gas activities remain substantial although natural gas and oil producers have a clear economic incentive to avoid these leaks as they imply a loss of product may indicate that the costs of reducing these emissions are underestimated.

5. One option is that the amount of organic waste can be minimised. Where this is not possible, aerobic instead of anaerobic landfill management should be promoted. In aerobic conditions, organic waste is composted instead of being fermented and converted into carbon dioxide, water and compost that can be used as a soil conditioner. Finally, anaerobic landfills can be capped by an impermeable layer so as to enhance anaerobic conditions and recover the methane while preventing emissions to the atmosphere.

6. The US Clean Air Act of March 1996 specified New Source Performance Standards and Emissions Guidelines - also called the "Landfill Rule". This new rule requires large landfills to recover and combust their methane emissions. This rule is projected to reduce methane emissions by 40 to 60 per cent relative to their baseline levels in 2010 (Gibbs, 1998; IPCC, 1996). According to Gibbs (1998), a further reduction of 25 per cent could be achieved by extending methane recovery to medium and large size landfills that are not covered by the Landfill Rule, leading to a total reduction potential ranging from 65 to 85 per cent.

7. Some modellers even assume no reduction potential for ruminants and rice cultivation (Reilly *et al.*, 1998).

30. The more diverse abatement options renders the modelling of abatement possibilities for the non-CO_2 gases less straightforward than for CO_2. In the latter case, the abatement possibilities are restricted to substitutions between fuels, production factors and products. However, abatement options for the non-CO_2 gases involve substitution between alternative technologies rather than between products. Representing these abatement options by a single - exogenously given - aggregate marginal abatement cost curve for each non-CO_2 gas would make it difficult to coherently account for all the inter-sectoral and inter-regional effects that result from multi-gas abatement.[10] Therefore, a disaggregated approach has been followed in GREEN taking into account explicitly both intra- and inter-sectoral abatement possibilities.[11] The model has been disaggregated so as to better identify individual activities that generate emissions of methane and nitrous oxide. Technological options that are internal to these activities (for instance, recovery options for methane from animal waste or changing animal feed) are represented by sector-specific emission reduction response functions (see Annex 1).[12] The remaining abatement potential is dealt with by the substitutions between products and factors as they are specified in the production and consumption functions of GREEN (Burniaux *et al.,* 1992; Lee *et al*., 1994). Following this approach, the marginal abatement cost curves specific to each gas (see Box 2 below) are calculated endogenously by the model at each point of time as a combination of *i)* the engineering information specific to each abatement option (such as the reduction potential described in Table A3 of Annex 1, *ii)* the substitution possibilities between products and factors, and *iii)* the adjustment dynamics (as described by the putty-clay specification in GREEN).

3. Defining a baseline including non-CO_2 gases

3.1 Contribution of non-CO_2 gases to the projected growth of world emissions

31. The economic impacts of reaching the Kyoto targets for GHG emissions depend on the likely future emissions in the absence of any action to restrain their growth *i.e.* the Business-as-Usual (BaU) or baseline scenario. The uncertainty surrounding the definition of a plausible baseline projection is even higher for the non-CO_2 gases than for CO_2. The baseline projection discussed below therefore has to be seen as just one among numerous possible scenarios of future emissions growth. To illustrate the uncertainty related to the baseline projection and its impact on estimated economic costs, results based on a different BaU scenario are discussed in Section 6.

32. The current baseline scenario is based on the same economic and demographic assumptions as previously used to estimate the economic costs of implementing the Kyoto Protocol (OECD, 1999). In line with the previous work, the baseline scenario incorporates the assumption that technological developments will contribute to increase the efficiency of energy uses in the future. This is introduced by assuming an exogenous rate of Autonomous Energy Efficiency Improvement (AEEI).[13] A similar assumption is made for methane and nitrous oxide emissions. Thus, the rates of emission[14] for methane and nitrous oxide change over time in the baseline scenario, reflecting the assumption that a number of abatement options

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[10] Reilly *et al.* (1998) and Manne and Richels (2000) follow such an approach.

[11] The approach based on single marginal abatement cost curves does not take into account the abatement potential resulting from substitution between products or producers (for instance, methane emissions from rice cultivation can be reduced in a country by substituting imported for domestically produced rice, thereby affecting the international distribution of emissions and potentially the scope for emission trading).

[12] A similar approach is followed in Brown *et al.* (1999).

[13] In the current version of the model, the AEEI in each country/region of the model is equal to 0.4 times the annual labour productivity growth.

[14] As expressed by emission coefficients in tons of Ceq per unit of production or consumption.

will be implemented even in the absence of any specific mitigation action. The growth of the non-CO_2 emissions in the baseline scenario depends on the underlying economic and demographic assumptions as well as on the calibration of the emission rates over time based on the following assumptions:

- For **Annex 1 countries,** the FCCC provides historical data on methane and nitrous oxide emissions up to 1996-97.[15] These data have been extrapolated up to 2000. From 2000 to 2010, rates of emissions have been calibrated to be consistent with COP4 projections up to 2020 (FCCC, 1998).[16] Beyond 2010, emission rates are assumed to decline at the same average rate as for the period 1995-2010.

- For **non-Annex 1 countries,** there is much more uncertainty about emission data, in part because these countries have only recently begun to submit data following the guidelines specified by the IPCC. Even data about 1995 emission levels diverge widely among available sources. The 1995 benchmark emission rates have been estimated by comparing data from various sources[17] and their subsequent development has been calibrated so as to result in global emission growth in the range of projections from other models.[18]

33. Based on these assumptions, Table 3 shows the average growth rates for emissions of the three GHGs between 1995 and the first commitment period of the Protocol (2008-2012, in the table approximated by 2010). Growth of methane and nitrous oxide emissions is substantially lower than for carbon dioxide. For Annex 1 countries as a whole, methane emissions are even projected to decline. Major drops are envisaged in the European Union (-1.8 per cent per year) and in Eastern European countries (-1.7 per cent per year): in both cases declines continue historical trends over the 1990s as reported by the FCCC.[19] Thus, the inclusion of the two non-CO_2 gases gives a more optimistic picture of baseline emission growth: instead of 1.7 per cent when the analysis is restricted to CO_2 alone, growth is reduced to 1.4 per cent annually in the case of Annex 1 countries and it falls from 2.6 to 2.2 per cent annually for the world as a whole.

[Table 3. GHG emissions in the baseline scenario with GREEN, 1995-2010]

4. Economic costs of implementing the Kyoto Protocol

4.1 Impact of the non-CO_2 gases on the Kyoto targets

34. The Kyoto Protocol specifies limitations on emissions by individual Annex 1 Parties. Most model estimates based on CO_2 emissions alone indicate that in the first commitment period (2008-2012) the required reductions - expressed relative to BaU levels - are in the range from 20 to 40 per cent (OECD,

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[15] The UNFCCC Greenhouse Gas Inventory database is available on http://194.95.39.33/.

[16] In addition, the emission rate for methane from landfills in the US in 2010 is set equal to 60 per cent of its 2000 level to reflect the impact of the “Landfill Rule” (see Box 1 above).

[17] Brown *et al.*, 1999; Müller and Bartsch, 1999; Manne and Richels, 2000; EPA, 1994; data from the World Resource Institute (available on http://www.wri.org/facts/data-tables.html).

[18] Information on model projections for non-CO_2 gases is from the IPCC Special Report on Emissions Scenarios (SRES) (also available on http://sres.ciesin.org/).

[19] In the European Union, methane emissions have declined by 2.2 per cent per year on average over the period 1990-1997 and are projected by the FCCC to decline on average by 2 per cent per year over the period 1990-2010. Corresponding reductions for Eastern Europe are even larger: -4.7 per cent per year on average for the period 1990-1995 and -2.2 per cent per year on average for the period 1990-2010.

1999). The extension of the analysis to methane and nitrous oxide suggests that the necessary abatement relative to the baseline emissions is really somewhat lower because these non-CO_2 emissions are projected to grow less than CO_2 or even to decline in the absence of policy action. The GREEN baseline implies that the required abatement relative to BaU levels would amount to some 18 per cent in 2010 as compared with 22 per cent if only CO_2 is considered, *i.e.* implying a cut by a fifth of the reduction effort required of Annex 1 Parties (Table 4). The inclusion of the non-CO_2 gases hardly affects the assessment of the stringency of the Kyoto targets for the United States and Japan; but the impact is much more significant in the CIS, Eastern Europe and the European Union where methane and nitrous oxide emissions are projected to fall significantly during the next decade.

[Table 4. Emission cuts required to reach Kyoto targets: CO_2 *versus* multi-gas case]

4.1.1 The "hot air" issue in a multi-gas setting

35. In the context of the Kyoto Protocol, the term "hot air" refers to the possibility that some Parties might meet their commitment without any domestic abatement effort. Indeed, due mainly to economic contraction, the countries of the former Soviet Union - particularly Russia and Ukraine - are projected in the baseline scenario to have emissions during the first commitment period that are below their commitment, leaving a surplus that they can sell in emission trading without incurring any abatement cost.

36. The inclusion of methane and nitrous oxide in the analysis substantially increases the projected amount of "hot air" in the CIS: from 150 million tons of Ceq in 2010 (corresponding to 16 per cent of the CIS commitment) based on CO_2 alone to 240 million tons of Ceq for all three gases (20 per cent of the CIS commitment).[20] The increase in the amount of hot air is the result of drops in methane and nitrous oxide emissions that are even steeper than for CO_2.[21]

4.2 The economic cost of Kyoto: the no-flexibility case

37. The Kyoto Protocol makes provision for three possibilities to exchange GHG reduction commitments among Annex 1 countries and between them and non-Annex 1 countries, referred to as the "flexibility mechanisms"[22] (OECD, 1999). The aim of these mechanisms is to reduce the economic costs of meeting the Kyoto commitments by shifting abatement to where it is least costly. However, there is uncertainty about the extent to which these mechanisms will be allowed to work and will be used in practice. Therefore, a scenario in which the flexibility mechanisms are not used - referred to as the "no-flexibility scenario" - is useful as a benchmark for assessing the scope of the flexibility mechanisms to reduce costs.

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[20] The estimate of CO_2 "hot air" in this version of the model is slightly different from the one reported in OECD, 1999, p. 44 (150 million tons of Ceq. compared with 136 million tons). This difference reflects changes in the structure of the model (see Annex 1) as well as the fact that, with all three gases, the amount of carbon leakage arising in the CIS is lower than if only CO_2 is restricted, thereby increasing the amount of carbon that can be sold abroad.

[21] While the Protocol does not specify commitments for individual gases, the gap between projected emission levels and levels corresponding to a uniform cut of 8 per cent from 1990 levels - corresponding to the overall commitment - amounts to 77 million tons of Ceq for methane and 13 million tons for N_2O.

[22] The three mechanisms are *i)* Emission Trading, *ii)* Joint Implementation and the Clean Development Mechanism.

4.2.1 Impact of non-CO_2 gases on the economic costs of achieving Kyoto

38. Table 5 shows alternative indicators of the costs to Annex 1 Parties if they meet their commitments individually, *i.e.* without using the flexibility mechanisms. The marginal costs of emission abatement fall by around a quarter, from about $150 to some $112 at 1995 prices per ton of Ceq for Annex 1 countries on average, when the analysis is extended from CO_2 to cover also methane and nitrous oxide. In terms of real income, the aggregate economic costs of implementing the Kyoto Protocol[23] when non-CO_2 gases are incorporated in the analysis, amount to around one-third of a per cent for Annex 1 countries as a group. This is about a third lower than the cost estimate when only CO_2 is considered. The overall economic costs are even lower in terms of GDP and the inclusion of methane and nitrous oxide reduces them by about a quarter. The impacts on the cost estimates of extending the gas coverage is well in line with findings from other models (see above). Across countries, the major winners from multi-gas coverage are the transition economies and the European Union. By contrast, there is little gain in Japan where including the additional gases does little to change baseline emission trends.

[Table 5. Costs of implementing the Kyoto Protocol without use of the flexibility mechanisms: impact of the non-CO_2 gases, 2010]

39. The cost estimates in Table 5 are upper bound estimates in the sense that they assume no use of the flexibility mechanisms. However, interpretation of these results requires some caution. First, the low overall costs should not hide the fact that some sectors are substantially affected (see below). Second, GE models tend to underestimate the economic costs associated with GHG limitations as they do not properly incorporate adjustment costs and rigidities over the short and medium term. For instance, given the relatively high energy price increases generated by the abatement efforts, the existence of real wage rigidities may substantially amplify the aggregate costs of meeting the Kyoto targets. In OECD (1999) it was shown that the real income losses could amount to 1-2 per cent or even more, depending on the character of the real wage rigidity, when only CO_2 was considered. At these much higher cost levels, the overestimation arising from ignoring non-CO_2 gases becomes economically much more significant than in the case of perfectly flexible wages.[24]

40. Returning to the case of flexible wages, the effects on costs of including CH_4 and N_2O can be further illustrated by considering the differential impacts on the United States and Europe. The (implicit) marginal abatement cost curve in the United States is generally assumed to be flatter than in Europe.[25] On the other hand, historical trends over the nineties and future economic prospects suggest that baseline emissions in the United States are likely to grow considerably faster than in Europe over the next decade. Balancing these two effects, and at variance with some other model results, estimates from GREEN point to lower marginal abatement costs in the European Union than in the United States when only carbon dioxide is considered. As Table 5 shows, this cost gap in favour of the European Union is reinforced by the inclusion of the two non-CO_2 gases.

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[23] For a discussion of ranges of magnitude and comparisons with other model estimates, see Weyant and Hill, 1999; OECD, 1999.

[24] Additional analysis along the lines of OECD (1999) suggests that while overall costs remain much higher in the case of rigid real wages the extension of the analysis to cover methane and nitrous oxide reduces these costs by about a fifth, *i.e.* a little less in relative terms than in the case of flexible wages. However, the absolute numbers are much larger: with flexible wages, the average real income loss in the OECD area is 0.5 per cent in the CO_2 case and 0.3 per cent with the three gases; with real wages being perfectly rigid (an equally extreme assumption), the average real income loss declines from 4.7 per cent to 3.8 per cent when the analysis is extended to non-CO_2 gases.

[25] The main reasons are that the United States consumes relatively more coal and has lower energy prices than in Europe.

Box 2. The costs of reducing different GHG emissions

The inclusion of non-CO_2 gases in quantitative analysis of the Kyoto Protocol may lower the estimates of overall economic costs, *inter alia* because the marginal abatement costs may be lower than those for (additional) CO_2 abatement over some range of abatement. Reducing low-cost rather than high-cost gases may, thus, lead to efficiency gains. Differences in marginal abatement costs for given reductions are best illustrated by marginal cost curves for each gas, as those reported in Figure 4 for the European Union, the United States and China.

[Figure 4. Marginal abatement costs for three GHGs, 2010]

Marginal abatement costs depend on three factors:

- The ***emission rate*** for different gases expressed as the amount of Ceq. per 1995 dollar of corresponding output or consumption. For instance, a tax of $10 per ton of Ceq. induces a larger increase of the relative end-use price of coal compared with gas or oil because coal emits more Ceq. per terajoule than other fuels. All other things being equal, coal consumption will therefore drop more. In a similar way, a given carbon tax has a relatively larger impact in countries where prices are lower (for instance, due to the existence of consumption subsidies) than in countries with high pre-existing taxes. Table 6 shows emission rates per thousand 1995 dollars for all GHG sources in the United States, as calculated from the base-year data of the GREEN model. Rates for methane sources are much smaller than for carbon dioxide from burning fuels, suggesting that, all other things being kept unchanged, much higher taxes will be needed to reduce the emissions from these sources. In contrast, the emission rate of nitrous oxide from fertiliser use is of the same order as that for carbon dioxide from oil and gas burning.

- The ***abatement potentials*** corresponding to the set of technological options to reduce methane and nitrous oxide emissions that are already or will become available in the foreseeable future according to engineering analysis. In GREEN, this potential has been specified by using simplified “response functions” specific to each source (see Annex 1).

- The ***degree of inter-sectoral flexibility*** implied by the substitution possibilities between products and factors. The structure of production and consumption in GREEN implies a higher degree of substitution among energy sectors than among non-energy sectors.[1]

[Table 6. Emission rates from different processes in the United States, 1995]

The properties of the extended GREEN model imply that, in the European Union, the marginal abatement cost curve for methane is below that for carbon dioxide (Figure 4, Panel B). This remains true in the United States, although the cost difference is much smaller because energy is cheaper (Figure 4, Panel A). In China where coal consumption is heavily subsidised, reducing carbon dioxide emissions remains the cheapest option (Figure 4, Panel C). In contrast, reducing emission of nitrous oxide appears the most costly option in all three countries. This probably reflects the relatively low reduction potential in fertiliser use, but also the fact that the production function of agriculture in the current version of GREEN assumes no substitution between non-energy inputs which probably understates the true degree of flexibility.

This comparison of marginal cost curves also illustrates the role of energy prices on the cost-saving potential of non-CO_2 gases. In countries where energy is already taxed, such as in the European Union, significant efficiency gains may arise from reducing methane rather than CO_2 emissions. On the contrary, coal subsidies imply that the cost-saving due to non-CO_2 gases is relatively smaller in countries like China.

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1. In particular, because the first level of the production function has a Leontief structure (see Burniaux *et al.*, 1992).

41. The cost change when considering a basket of three GHGs instead of just carbon dioxide can be decomposed as the net result of three different effects. First, including the non-CO_2 gases increases the number of commodities subject to taxes or restrictions (the "weight" of the tax base in the economy) and, for any given relative reduction, this taken alone should contribute to increase the cost of implementing the Protocol. Second, some non-CO_2 gas emissions are projected to decline or grow only slowly during the next decade, reducing the overall tightness of the Kyoto constraints as compared with the impression from considering CO_2 alone. Third, considering a basket of GHGs implies a possibility to shift abatement from high- to low-cost gases.[26] The cost reduction associated with this efficiency improvement depends on whether, for a given reduction, the marginal abatement costs for other gases are lower than for carbon dioxide (Box 2).[27]

42. The reduced real income losses among Annex 1 countries from a multi-gas assessment of the Protocol arise to a large extent from the possibility to substitute among gases[28] (Figure 5). A smaller component relates to the reduced tightness of emission constraints principally in the European Union (the decomposition in Figure 5 shows the effect of non-CO_2 baseline emissions in some regions falling further relative to their 1990 levels than the reduction implied by the overall Kyoto targets). Thus, the main explanation for the larger cost reduction in Europe compared to the United States is the decline of methane emissions in the European Union in the baseline scenario. Finally, the economic losses due to the increased gas coverage appear to be negligible.

[Figure 5. Decomposition of the economic gains from multi-gas limitations with no use of the flexibility mechanisms, 2010]

43. The inclusion of methane and nitrous oxide reduces cost estimates in non-Annex 1 countries as well - even if, as a group, these countries are still estimated to suffer somewhat larger real income losses than Annex 1 countries (Table 5). The relatively better outcome arises from the fact that, as the abatements in Annex 1 countries are shifted away from energy sectors, energy-exporting economies are less affected. At the same time, agricultural producers in Annex 1 countries have to bear the burden of methane and nitrous oxide abatements, thereby benefiting agricultural producers in non-Annex 1 countries.

4.2.2 Impact of non-CO_2 gases on sectoral output

44. The sectoral distribution of output losses is somewhat different when CH_4 and N_2O are included than with CO_2 alone (Figure 6). Carbon dioxide abatement mainly affects energy-producing sectors,[29] in

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[26] Theoretically, marginal abatement costs could be higher for the other gases than for CO_2, implying a larger cutback on CO_2 emissions than in the case of CO_2 alone.

[27] The extent to which abatement is shifted from high to low-cost gases obviously depends on the use of economic instruments such as taxes or tradable permit schemes covering all three gases. The technical feasibility of levying taxes on non-CO_2 gases is discussed in: COM/ENV/EPOC/DAFFE/CFA(99)110/FINAL.

[28] This decomposition has been obtained by running *i)* a scenario in which the Kyoto targets are applied equally to each gas (*i.e.* assuming no inter-gas substitution) and *ii)* a scenario in which inter-gas substitution is allowed subject to the same multi-gas constraint as in the previous scenario (*i.e.* lower than the Kyoto targets as it excludes some gas-specific surpluses). The real income gains between these two scenarios correspond to efficiency gains and baseline effects while the difference between the scenario of the Kyoto Protocol with no use of the flexibility mechanisms and scenario ii shows the influence of gas-specific surpluses calculated on the basis of a uniform application of the Kyoto target across gases.

[29] Note that, by assumption in GREEN, the supply elasticity of crude oil production is set equal to zero in all countries/regions, with the exception of the Energy-Exporters region.

particular coal. With non-CO_2 gases, the adverse impact of abatement is reduced slightly in most sectors, with the exception of agriculture. For Annex 1 countries as a whole, rice production is projected to fall by 5 per cent in 2010.

[Figure 6. Implementing the Protocol: output losses in 2010 with and without non-CO_2 gases (and no use of the flexibility mechanisms)]

4.3 The economic cost of Kyoto: using the flexibility mechanisms

4.3.1 Emission Trading and Joint Implementation

45. Emission Trading (ET) and Joint Implementation (JI) apply to emission transactions among Annex 1 countries only. Both schemes aim to redistribute abatement to locations where it can be made more cheaply, but they have a somewhat different nature. While ET allows for "spot" transactions, JI involves the acquisition of emission reductions through projects aimed at reducing emissions or enhancing sinks. In order to estimate the cost-saving potential associated with these two instruments, it is assumed that their combined operation is equivalent to an unrestricted system of emission trading leading to full equalisation of the marginal abatement costs among Annex 1 countries.

46. Table 7 shows indicators of economic costs with and without the non-CO_2 gases and with and without emission trading. The estimates confirm that the inclusion of methane and nitrous oxide reduces the cost for Annex 1 Parties as a whole by roughly a third compared to the more restrictive analysis based on CO_2 alone. They also imply that the cost-reducing impact of the non-CO_2 gases is somewhat lower than that from the use of the flexibility mechanisms. In any case, when unrestricted use of the flexibility mechanism is introduced in a multi-gas setting, the total economic losses for Annex 1 countries in 2010 become very low (around a tenth of a percentage point of real income or GDP in the baseline scenario).

[Table 7. Gains from emission trading among Annex 1 countries with and without non-CO_2 gases, 2010]

47. Considering also CH_4 and N_2O increases the total amount of emission trading: by 2010, 527 million tons of Ceq would be exchanged compared with 424 million tons with only carbon dioxide. Figure 7 shows the net distribution of this trade by Party of origin (net sales are reported as negative amounts) and destination (net purchases are reported as positive amounts). In both the CO_2 and the multi-gas setting, the CIS is the main seller of emission rights and the United States the main buyer. The increase in traded emissions is entirely accounted for by the additional amount of non-CO_2 "hot air" originating from the CIS. This additional "hot air" is mostly acquired by the United States.

[Figure 7. Net sales and purchase of emission permits among Annex 1 countries, 2010]

48. Figure 8, panel A shows the absolute amounts of real income gains from emission trading across Annex 1 Parties. All Parties gain from emission trading (the United States gains in terms of GDP even if not in terms of real income[30]) and the distribution of the gains changes little compared with the CO_2 case (Figure 8, panel B). However, despite the additional non-CO_2 "hot air" the absolute gain from trading is somewhat lower with the three gases than with only CO_2 due to lower efficiency gains - $40 billion at 1995 prices with the three gases against $60 billion at 1995 prices with only CO_2. Efficiency gains reflect the divergence between marginal abatement costs across countries in the case where countries have to meet their obligation individually (without use of the flexibility mechanisms). The inclusion of the non-CO_2

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[30] The US real income loss arises from a deterioration of its terms of trade (see OECD, 1999, p. 44).

gases lowers the marginal abatement costs in high-cost countries (see Table 5) while the marginal cost in the CIS remains zero due to the existence of "hot air", thus reducing the divergence between marginal abatement costs across Annex 1 countries and the total efficiency gains.[31]

[Figure 8. Real income gains from emission trading, 2010]

4.3.2 The Clean Development Mechanism

49. The Clean Development Mechanism (CDM) is a project-based mechanism similar to JI though with the crucial difference that it concerns emission transactions between Annex 1 and non-Annex 1 countries. For a number of reasons, discussed in OECD (1999), actual use may fall far short of the full potential of the CDM to generate low-cost emission cuts. Even so, the cost-saving potential of the CDM is sometimes estimated by assuming that the total emission reduction specified in the Protocol is spread over the world through a global system of unrestricted emission trading, *i.e.* as if non-Annex 1 countries were allocated emission allowances equal to their BaU emissions. Under this extreme assumption, Table 8 shows that combining the three flexibility mechanisms (ET, JI and CDM) with the three GHGs could potentially reduce the cost for Annex 1 countries of achieving the Kyoto targets to virtually zero - though subject to arguments made above concerning the absence of adjustment costs in the analysis.

[Table 8. Potential gains from world-wide emission trading with and without non-CO_2 gases]

50. The CDM will benefit the non-Annex 1 countries too. The impact of implementing the Kyoto Protocol on the real income of the non-Annex 1 countries as a whole could be broadly neutral if the flexibility mechanisms were used to their full potential (Figure 9). Considering only CO_2 and no use of the flexibility mechanisms, non-Annex 1 countries would lose around $50 billion at 1995 prices in 2010 (0.7 per cent of real income), reflecting mainly the economic loss of the energy-exporting economies. In principle, these losses could be entirely compensated by the combination of inter-gas flexibility (a gain of $10 billion) and the use of the flexibility mechanisms (a gain of $41 billion). However, these losses and gains would be unevenly spread among non-Annex 1 countries. Moreover, as noted above it seems unlikely that the full potential benefit from the CDM could materialise in practice.

[Figure 9. Impact of non-CO_2 gases and flexibility mechanisms on real income in non-Annex 1 countries, 2010]

5. Longer-term potential of non-CO_2 gases in stabilising world emissions

51. The upshot of the above analysis is that the inclusion of non-CO_2 gases significantly reduces the costs of implementing the Kyoto Protocol. However, the results say little about the cost-saving potential of methane and nitrous oxide in the longer-term future, particularly in the context of more comprehensive and ambitious abatement objectives, covering also non-Annex 1 countries.

52. With that perspective, this section considers a fictitious scenario in which world emissions in Ceq are stabilised after the first commitment period of the Protocol (2010). This is a radical scenario, but even so, it may not be sufficient to achieve stabilisation of atmospheric GHG concentrations; it is included here mainly as a benchmark for other simulations. The costs of achieving this objective are estimated over the period 2010-2050 under the alternative assumptions that the flexibility mechanisms are not used (*i.e.* each

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[31] When measured in relative terms, the cost-saving impacts of inter-gas and inter-country flexibility are mutually reinforcing, implying that in this sense the gains from trading additional hot air outweighs the narrowing of marginal abatement costs (see Table 7).

country/region individually stabilises its emissions at their 2010 levels) or used in an unrestricted way on a world-wide basis (*i.e.* overall world emissions are kept constant at their 2010 levels).

53. The results obviously depend on the trends projected in the baseline scenario. For all countries, emission coefficients beyond 2010 are assumed to decline at the same average rate as for the period 1995-2010. As a result, non-CO_2 emissions tend to grow in non-Annex 1 countries (by an average of 1 per cent per year for CH_4 and 0.8 per cent per year for N_2O) while they decline for Annex 1 countries (by an average of -1 per cent per year for CH_4 and -0.1 per cent per year for N_2O).

54. For Annex 1 countries, the cost-saving impact of the non-CO_2 gases appears to decline slightly over the long term (Figure 10, panels A and B). Without using the flexibility mechanisms, the average marginal abatement costs for Annex 1 countries remain broadly constant over time: further abatement beyond the first commitment period is achieved mainly by replacing fossil fuels with non-conventional carbon-free energy sources (referred to as “backstop” technologies) available in unlimited supply at a given price.[32] Over this period, the impact of the non-CO_2 gases on marginal abatement costs falls slightly from 26 per cent in 2010 to 20 per cent in 2050. As the relatively low-cost abatement options for methane and nitrous oxide are exhausted, the marginal cost curves for these gases become very steep (Box 2, above), pushing more of the marginal abatement burden onto carbon dioxide. At the same time, the marginal abatement cost of CO_2 is bounded by the price of the carbon-free backstop. In terms of real income, and still without use of the flexibility mechanisms, the cost reduction due to the non-CO_2 gases stays broadly constant as a share of baseline real income but falls significantly relative to overall costs (from 32 per cent in 2010 to 16 per cent in 2050) (Figure 10, panel B).

[Figure 10. Economis costs of stabilising GHG emissions at their 2010 levles]

55. Including the additional gases in the analysis appears to have smaller impacts on marginal costs in non-Annex 1 countries than in Annex 1 countries (Figure 10, panels A and C). This reflects, not least, the properties of the baseline scenario, in particular the feature that methane and nitrous oxide emissions decline in Annex 1 countries while they grow in non-Annex 1 countries and that emissions from rice cultivation are more difficult to reduce. However, as for Annex 1 countries, the cost-saving potential of the non-CO_2 gases remains broadly constant over time in absolute terms. Thus, their relative impact declines over time as both marginal and total costs of stabilising emissions in non-Annex 1 countries are growing (Figure 10, panels C and D). Moreover, the inclusion of the non-CO_2 gases does not reduce real income losses in non-Annex 1 countries in the context of a global and unrestricted system of permit trading (Figure 10, panel D). This reflects their relatively smaller potential for low-cost abatements of the non-CO_2 gases that causes their net sales of emission permits to be smaller with the three gases than with only CO_2.

56. The above results suggest that, although significant in the context of the Kyoto Protocol, the cost reductions from inter-gas flexibility become more limited in a context of more substantial and comprehensive action beyond the first commitment period. This reflects that over the long-term non-CO_2 gases account for only a minor share of total GHG emissions and that, beyond a certain level of abatement, the marginal costs of further cuts become very high.

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[32] Beyond 2010, scenarios simulated with GREEN make the assumption that a number of alternative carbon-free energy sources - referred to as “backstops” - become available. These backstops are assumed to be available in infinite supply at a given constant prices. Given the emergence of these backstop energies, the role of the non-CO_2 gases tend to decline in the longer term. The reason for this decline is twofold: first, the technological potential of abatement tends to be exhausted, making any further abatement very costly (see Box 2, above); second, as the backstop sources put a ceiling on the increase of the marginal abatement cost, any further abatement is obtained by replacing carbon fuels by a carbon-free backstop source rather than reducing the non-CO_2 emission.

57. Figure 10 shows that there is a parallel in the outcomes of inter-gas and inter-country flexibility over different time horizons. Both are likely to bring most benefits in the context of relatively modest emission reductions, including those specified in the Kyoto Protocol, with the cost reductions from inter-country flexibility being in general larger than those from inter-gas flexibility. However, in the face of more ambitious efforts in a longer-term perspective, the impact of both types of flexibility falls relative to the overall costs of emission reduction. A key explanation for this evolution is the assumed existence of carbon-free "backstop" energy sources.

6. The role of uncertainty

58. The inclusion of the other gases in the analysis introduces new sources of uncertainty. As discussed in Section 2.3 and shown by Table A3 in Annex 1, estimates of the reduction potential for each non-CO_2 source involves an uncertainty range that often exceeds 50 per cent of the central value of the potential reduction. A lot of uncertainty also surrounds the projected growth of the non-CO_2 gases in the baseline scenario. The above results are based on the assumption that tendencies of the non-CO_2 emissions over the nineties to grow slowly or to fall will extend over the near future. However, this assumption may well prove too optimistic.

59. In order to illustrate the uncertainty as to how much the inclusion of methane and nitrous oxide lowers the costs of reaching the Kyoto targets, two extreme cases are defined so as to encompass a large range of intermediate situations. The "*optimistic case*" embodies the same baseline emission growth of CH_4 and N_2O as above but reduction potentials for these gases are set equal to their highest values from a literature survey (third column of the right-hand panel of Table A3 in Annex 1). In contrast, the "*pessimistic case*" is based on the premise that the technological potential for reducing non-CO_2 emissions is much lower than in the above simulations. All reduction potentials have been cut by half (first column of the right-hand panel of Table A3 in Annex 1). In addition, this case also assumes higher baseline emission of methane and nitrous oxide. Specifically, the autonomous rates of decline of the emission coefficients, have been cut by half compared to the case presented in Sections 3 and 4 (the central case) (Table 9).

[Table 9. Long-term growth of non-CO_2 emissions under alternative baseline assumptions]

60. Based on these assumptions, the simulations to reach the Kyoto targets and stabilise regional emission levels thereafter have been re-run. In neither case are the flexibility mechanisms allowed to play a role. A main impression of the results is that, for both Annex 1 and non-Annex 1 countries, the central case estimates of cost savings associated with the non-CO_2 gases come closer to those of the optimistic case (Figure 11).

[Figure 11. Cost reductions due to non-CO_2 gases under alternative technological assumptions, 2000-2050]

61. In Annex 1 countries, the pessimistic case implies that the cost saving from the non-CO_2 gases in 2010 is somewhat reduced: the reduction of marginal costs amounts to around 20 per cent against 30 per cent in the optimistic case (Figure 11, panel A). A slightly larger variation is reported for the overall economic cost in terms of real income (Figure 11, panel B). Over the longer term, however, the uncertainty about the non-CO_2 emissions plays a more limited role. The inclusion of the non-CO_2 gases tends to reduce the cost of abatement by a fifth and this proportion remains broadly unchanged on all three sets of assumptions about the future growth of non-CO_2 gases and the technological potential for reduction. This result again highlights the declining influence of the non-CO_2 gases when "backstop" technologies put a ceiling on the marginal abatement cost of cutting emissions.

62. Estimates of cost savings from the non-CO_2 gases are much more sensitive to technological uncertainties in non-Annex 1 countries than in Annex 1 countries (Figure 11, panels C and D). In particular, the pessimistic case implies fairly modest gains: the marginal cost reduction does not exceed 10 per cent on average during the period 2015 to 2030 against more than 20 per cent in the central case. The explanation relates to the smaller potentials for abatement technologies as well as to the high growth rates of emissions in the pessimistic baseline scenario. Even these modest gains progressively vanish over the longer run, falling to close to zero by 2050. Thus, under more pessimistic assumptions, the cost-saving from including methane and nitrous oxide may be very limited and of a relatively transient nature in non-Annex 1 countries. The difference compared with Annex 1 countries relates to the lower profitability of abating non-CO_2 gases relative to carbon dioxide (see Box 2, above).

Table 1. Global warming potentials[1]

	Lifetime	Global Warming Potential (GWP)	Carbon equivalence[2] (Ceq)
Carbon dioxide (CO_2)	50-200	1	0.27
Methane (CH_4)	12	21	5.73
Nitrous oxide (N_2O)	120	310	84.55

1. Calculated over a time horizon of 100 years.

2. The carbon equivalence expresses the amount of carbon equivalent (Ceq) corresponding to one ton of each gas. For instance, one ton of CO_2 contains 0.27 ton of Ceq and one ton of methane is equivalent to 5.73 (21 times 0.27) tons of Ceq.

Table 2. Estimates of methane emissions in 1995

	Lower bound[1] Million tons of Ceq	GREEN		Upper bound[1] Million tons of Ceq
		Million tons of Ceq	Percentage	
Enteric fermentation	343	453	30.2	571
Manure management	57	81	5.4	103
Rice cultivation	114	289	19.3	571
Oil and natural gas activities	171	267	17.8	343
Landfills	114	209	13.9	400
Coal mining	131	202	13.5	223
Total	**930**	**1 501**	**100.0**	**2 211**

1. IPCC (1996*b*).

Table 3. GHG emissions in the baseline scenario with GREEN, 1995-2010

Average yearly growth rates, per cent

	Carbon dioxide	Methane	Nitrous oxide	Total 3 GHGs
United States	2.1	-0.5	1.2	1.8
Other OECD	2.3	0.4	-0.1	1.8
Japan	1.7	-1.2	3.1	1.7
European Union	1.2	-1.8	0.6	0.9
Eastern Europe	1.7	-1.7	1.9	1.3
CIS	1.3	-1.0	0.1	0.9
Annex 1	**1.7**	**-0.8**	**0.9**	**1.4**
China	5.7	2.7	3.1	5.0
Brazil	1.9	0.9	-0.1	1.4
India	4.3	1.3	1.6	3.3
Dynamic Asian economies	3.1	1.2	1.3	2.6
Energy exporting countries	2.0	-0.4	-0.6	1.2
Rest of the world	2.8	0.5	0.5	1.6
Non-Annex 1	**4.0**	**1.2**	**0.9**	**3.1**
World	**2.6**	**0.5**	**0.9**	**2.2**

Source: OECD GREEN model.

Table 4. Emission cuts required to reach Kyoto targets: CO_2 *versus* multi-gas case

	Required cuts to reach target, per cent relative to baseline, 2010		Impact of the non-CO_2 GHGs in per cent [2]/[1]-1
	CO_2 alone [1]	3 gases [2]	
United States	-36	-33	-7
Japan	-33	-32	-1
European Union	-22	-18	-20
Other OECD	-30	-26	-14
Eastern Europe	-16	-9	-44
CIS	21	27	32
Total Annex 1	**-22**	**-18**	**-19**

Source: OECD GREEN model.

Table 5. Costs of implementing the Kyoto Protocol without the use of the flexibility mechanisms: impact of the non-CO_2 gases, 2010

	Marginal abatement costs 1995$ per ton of Ceq			Real income change, %			GDP change, %		
	CO_2 only [1]	3 GHGs [2]	Cost change (%) [2]/[1]-1	CO_2 only [1]	3 GHGs [2]	Cost change (%) [2]/[1]-1	CO_2 only [1]	3 GHGs [2]	Cost change (%) [2]/[1]-1
United States	237	188	-21	-0.34	-0.29	-14	-0.27	-0.21	-21
Japan	187	176	-6	-0.25	-0.27	5	-0.04	-0.04	0
European Union	185	112	-39	-0.74	-0.38	-48	-0.17	-0.11	-37
Other OECD	153	109	-28	-0.51	-0.32	-37	-0.23	-0.18	-21
Eastern Europe	34	15	-55	0.12	0.08	-38	-0.23	-0.12	-49
CIS	0	0	0	-1.73	-1.17	-32	-0.34	-0.20	-43
Total Annex 1	**151**	**112**	**-26**	**-0.48**	**-0.33**	**-32**	**-0.18**	**-0.14**	**-26**
Total non-Annex 1	**0**	**0**	**0**	**-0.72**	**-0.56**	**-21**	**-0.24**	**-0.17**	**-28**

Source: OECD GREEN model.

Table 6. Emission rates from different processes in the United States, 1995[1]

Tons of Ceq. Per 1000 1995$

Coal	18
Gas	8
Nitrous oxide from fertilisers	8
Liquid fuels	7
Methane from rice cultivation	3
Methane from natural gas extraction and distribution	1
Methane from enteric fermentation	0.77
Methane from coal extraction	0.67
Nitrous oxide from fuel combustion	0.63
Methane from oil extraction	0.04
Nitrous oxide chemicals	0.02
Methane from landfills	0.01

1. The relevant basis for these emission rates are specified in Table A2 in Annex 1.

Source : OECD Secretariat estimates.

Table 7. Gains from emission trading among Annex 1 countries with and without non-CO_2 gases, 2010

A. Average marginal abatement cost

	CO_2 only	3 GHGs	Relative change, %
	1995$ per ton of Ceq		
No flexibility	151	112	-26
Full Annex 1 trading	89	58	-34
Relative change, %	-41	-48	

B. GDP changes

	CO_2 only	3 GHGs	Relative change, %
	Billions 1995$		
No flexibility	-51	-38	-26
Full Annex 1 trading	-35	-25	-29
Relative change, %	-32	-34	

C. Real income cost

	CO_2 only	3 GHGs	Relative change, %
	Billions 1995$		
No flexibility	-103	-71	-32
Full Annex 1 trading	-30	-17	-42
Relative change, %	-71	-76	

Source: OECD GREEN model.

Table 8. Potential gains from world-wide emission trading with and without non-CO_2 gases

	Average marginal abatement costs		GDP change		Real income change	
	CO_2 only	3 GHGs	CO_2 only	3 GHGs	CO_2 only	3 GHGs
	1995$ per ton of Ceq		Billions 1995$		Billions 1995$	
Full Annex 1 flexibility	89	58	-35	-25	-3	-17
World-wide flexibility	9	7	-6	-5	-1	-7
Change, %	-90	-89	-82	-82	-67	-60

Source: OECD GREEN model.

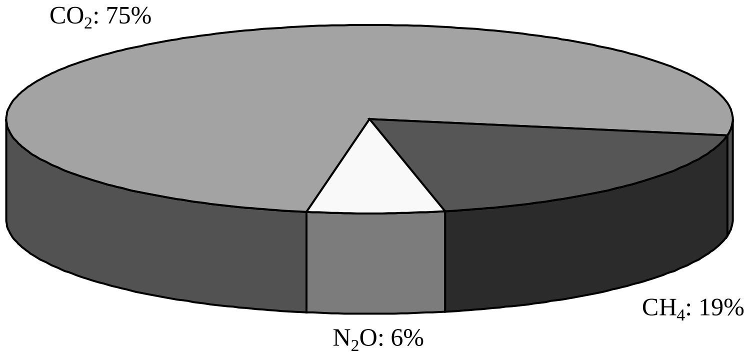
Table 9. Long-term growth of non-CO_2 emissions under alternative baseline assumptions

Average growth rate 2000-2050 (per cent)

	CO_2	Methane		Nitrous oxide	
	Central case	Central case	Pessimistic case	Central case	Pessimistic case
Annex 1 countries	1.4	-1.0	0.1	0.0	0.8
Non-Annex 1 countries	3.6	1.1	2.2	0.8	2.0
World	2.6	0.6	1.7	0.5	1.5

Source: OECD GREEN model.

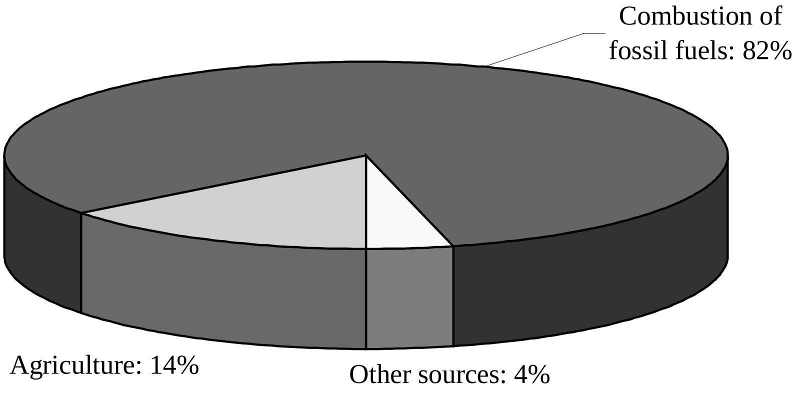
Figure 1. **Shares of CO_2,CH_4 and N_2O emissions in 1995**[1]



1. Share in total Ceq emissions of CO_2, CH_4 and N_2O.

Source : OECD Secretariat.

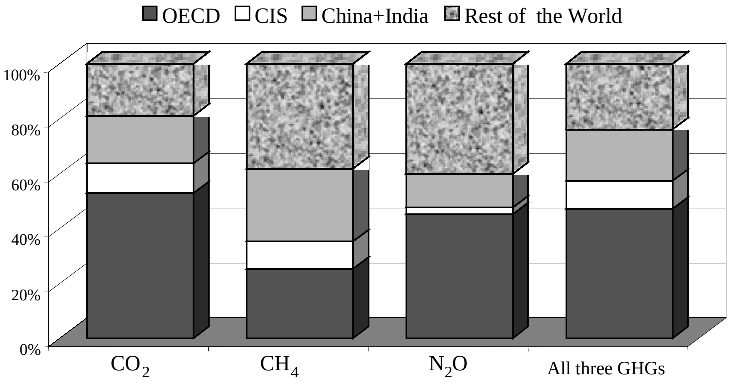
Figure 2. **World GHG emissions by source, 1995**[1]



1. Shares in total Ceq emissions of CO_2, CH_4 and N_2O.

Source : OECD Secretariat.

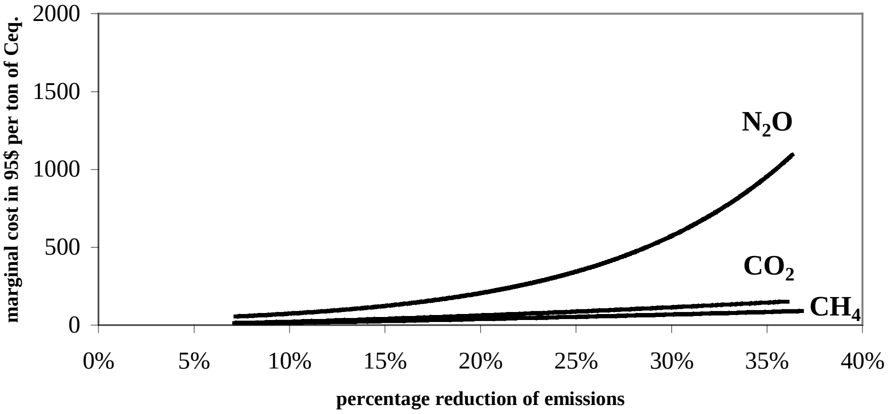
Figure 3. **GHG emissions by region, 1995**



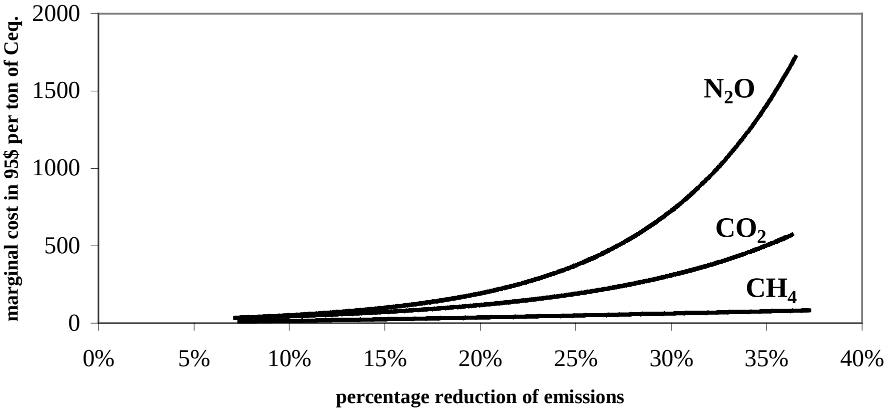
Source: OECD Secretariat..

Figure 4. **Marginal abatement costs for three GHGs, 2010**

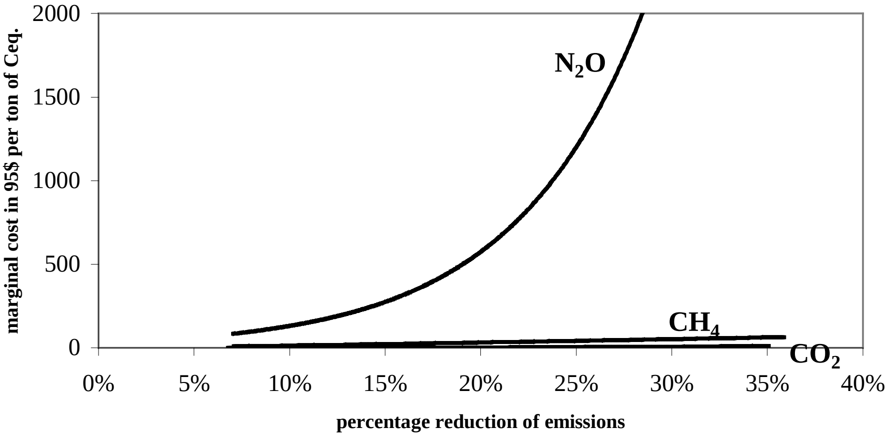
A. United States



B. European Union

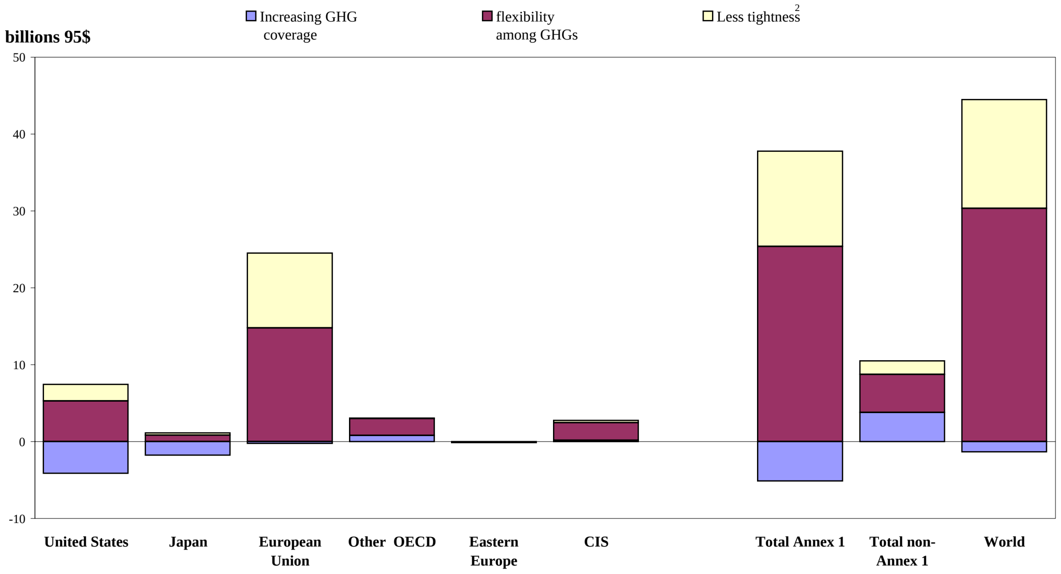


C. China



Source: OECD GREEN model.

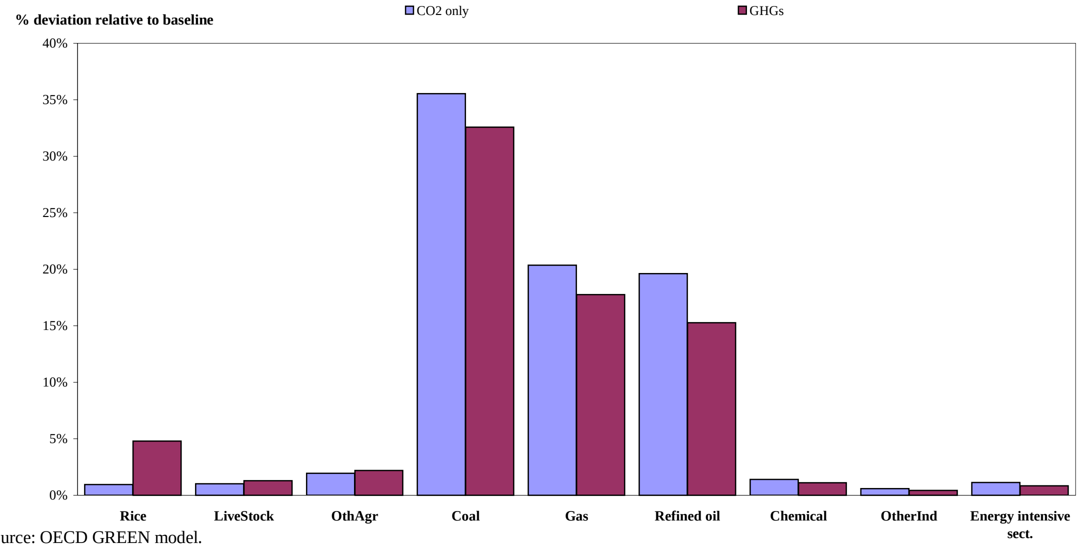
Figure 5. **Decomposition of the real income gains from multigas limitations with no use of the flexibility mechanisms,2010**[1]



1. Based on comparing results for 3 gases with corresponding results concerning CO_2 alone.
2. Effect of lower overall abatement needs due to baseline CH_4 and N_2O emissions being below the overall Kyoto target.

Source: OECD GREEN model.

Figure 6**. Implementing the Protocol: output losses in 2010 with and without non-CO_2 gases (and no use of the flexibility mechanisms).**

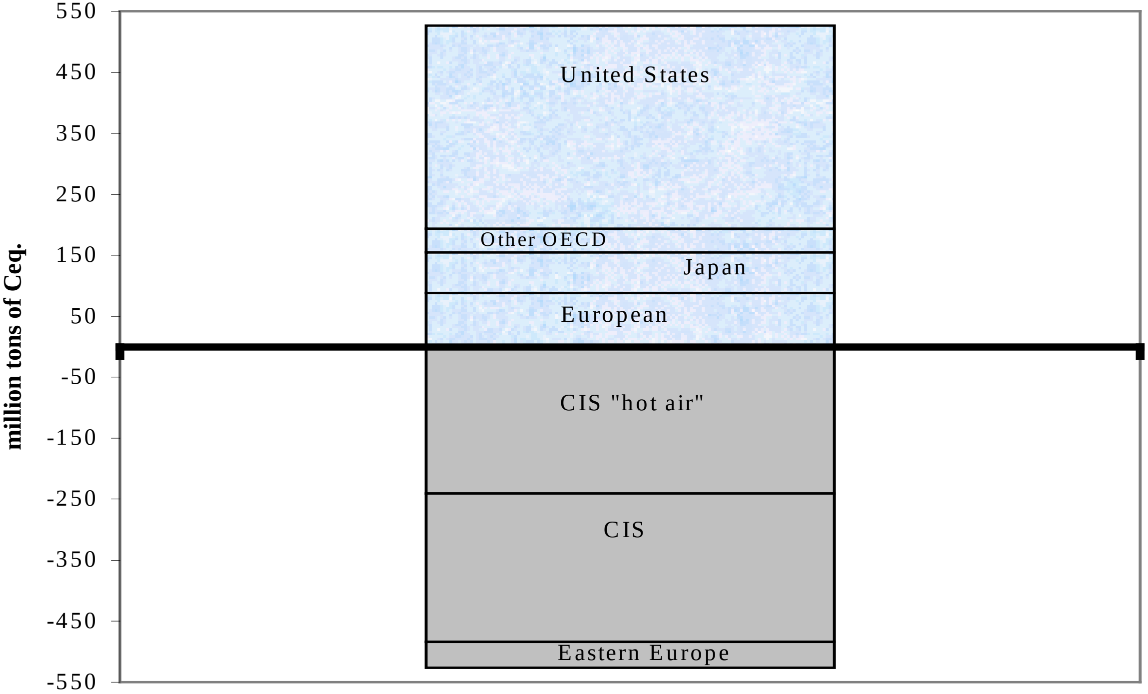


Source: OECD GREEN model.

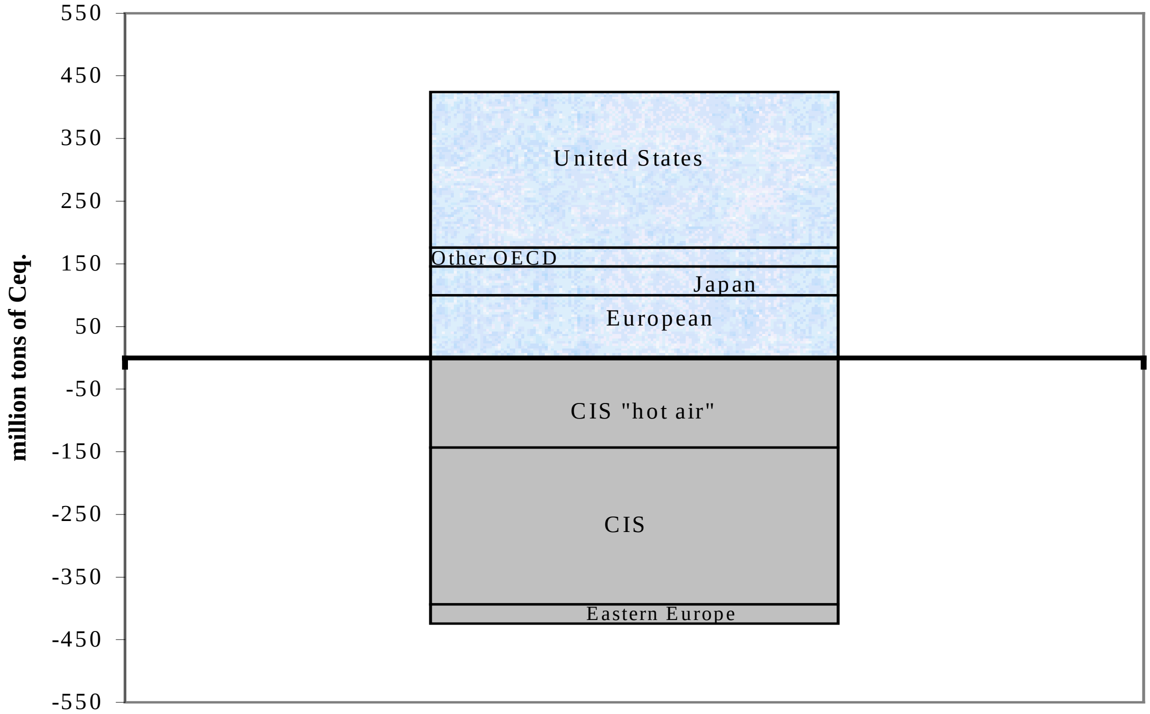
Figure 7. **Net sales and purchases of emission permits among Annex 1 countries,2010**

Million tons of carbon equivalent

A.The multi-gas case



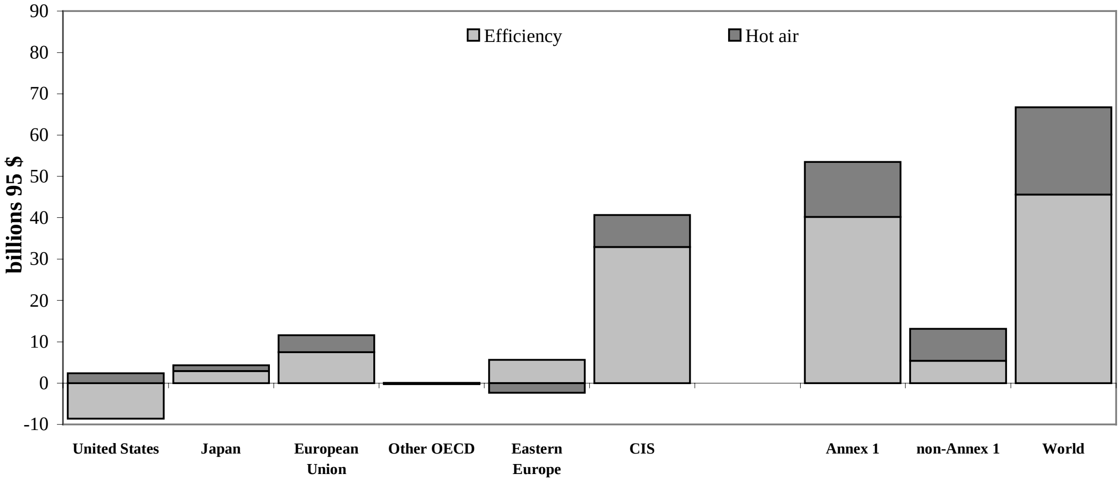
B. The CO_2 case



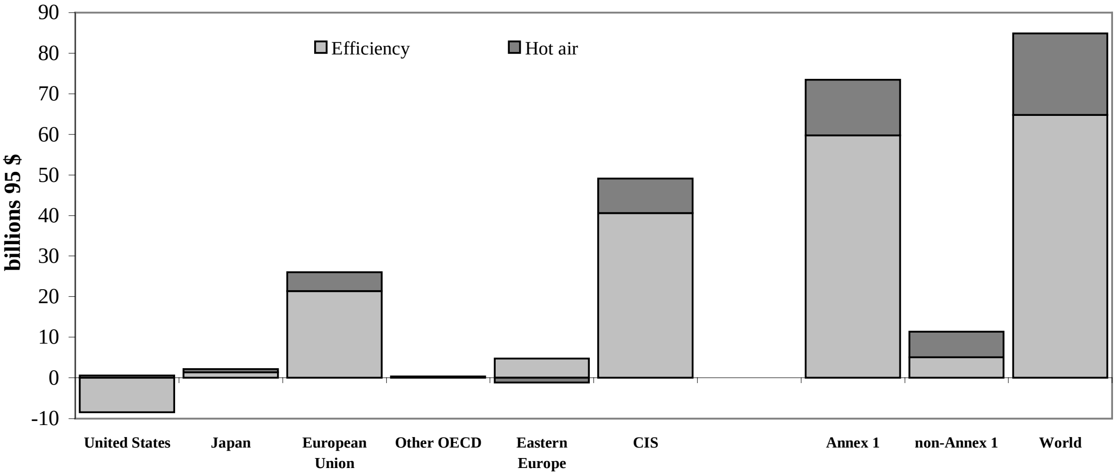
Source: OECD GREEN model.

Figure 8. **Real income gains from emission trading, 2010**
$ billions at 1995 prices

A. The multi-gas case

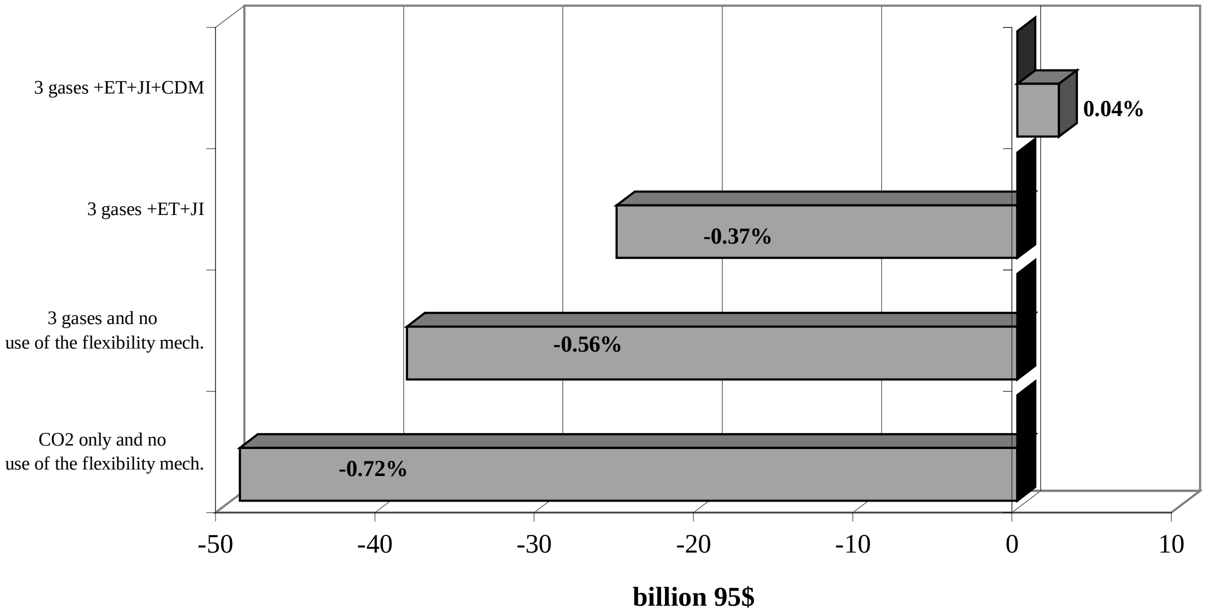


B. The CO2 case



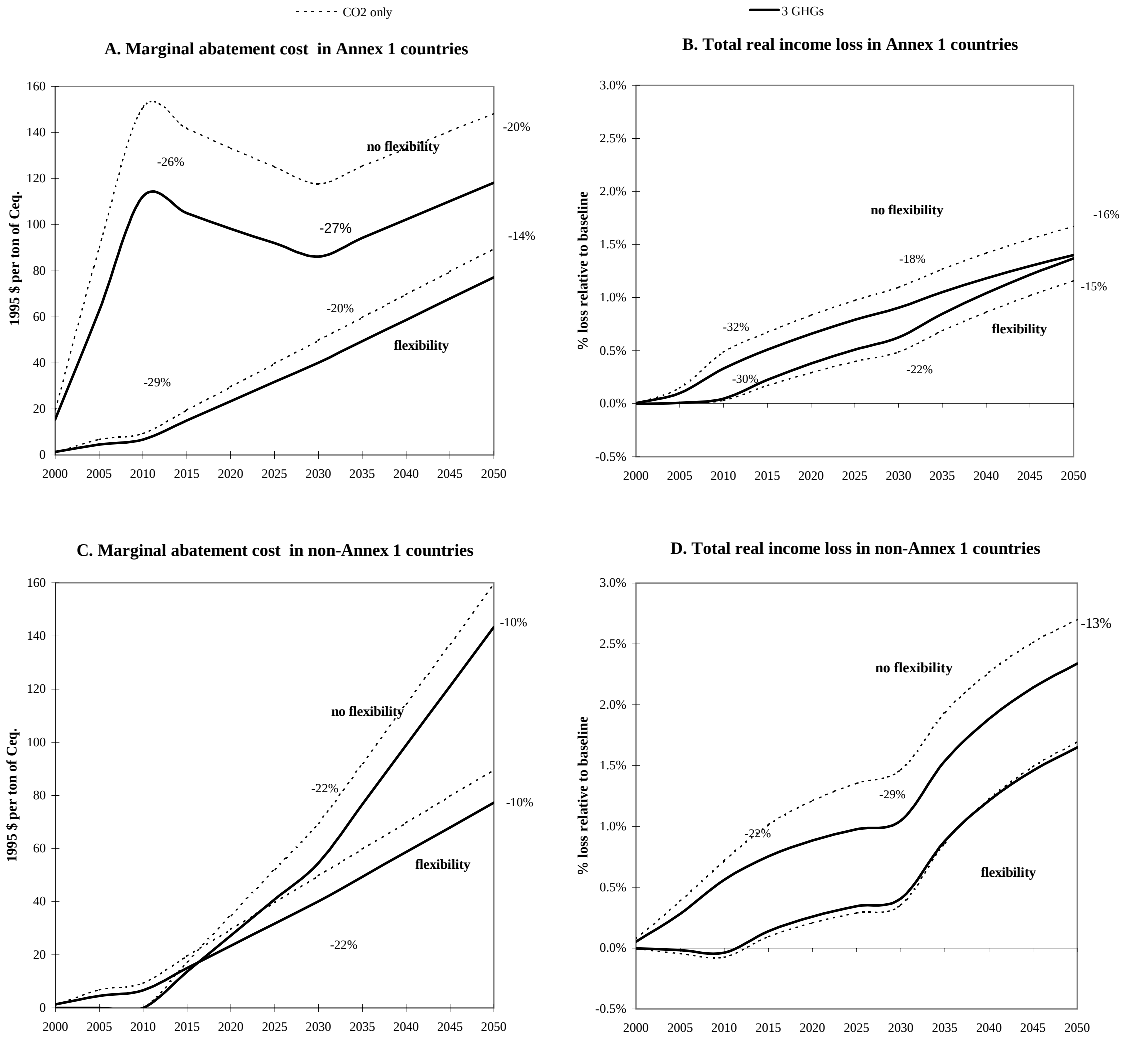
Source: OECD GREEN model.

Figure 9. **Impact of non-CO2 gases and flexibility mechanisms on real income in non-Annex 1 countries, 2010**



Note: Percentages refer to real income change relative to 2010 real income in the baseline.

Figure 10. **Economic costs of stabilising GHG emissions at their 2010 levels**



A. Marginal abatement cost in Annex 1 countries

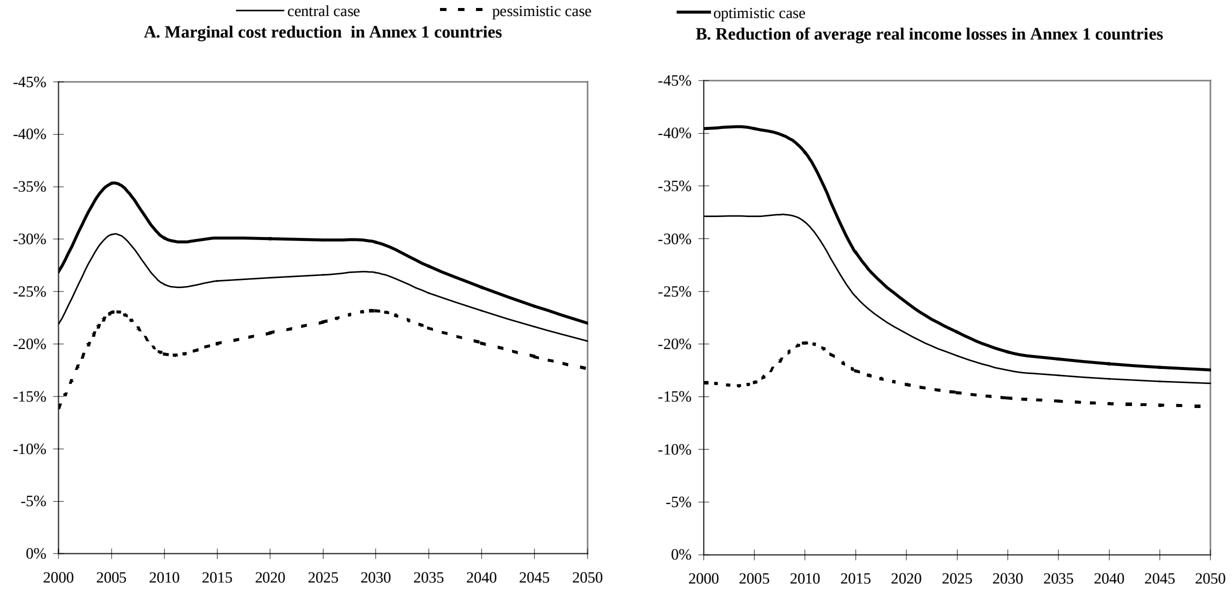
B. Total real income loss in Annex 1 countries

C. Marginal abatement cost in non-Annex 1 countries

D. Total real income loss in non-Annex 1 countries

Source: OECD GREEN Model

Figure 11. **Cost reductions due to non-CO_2 gases under alternative technological assumptions, 2000-2050**

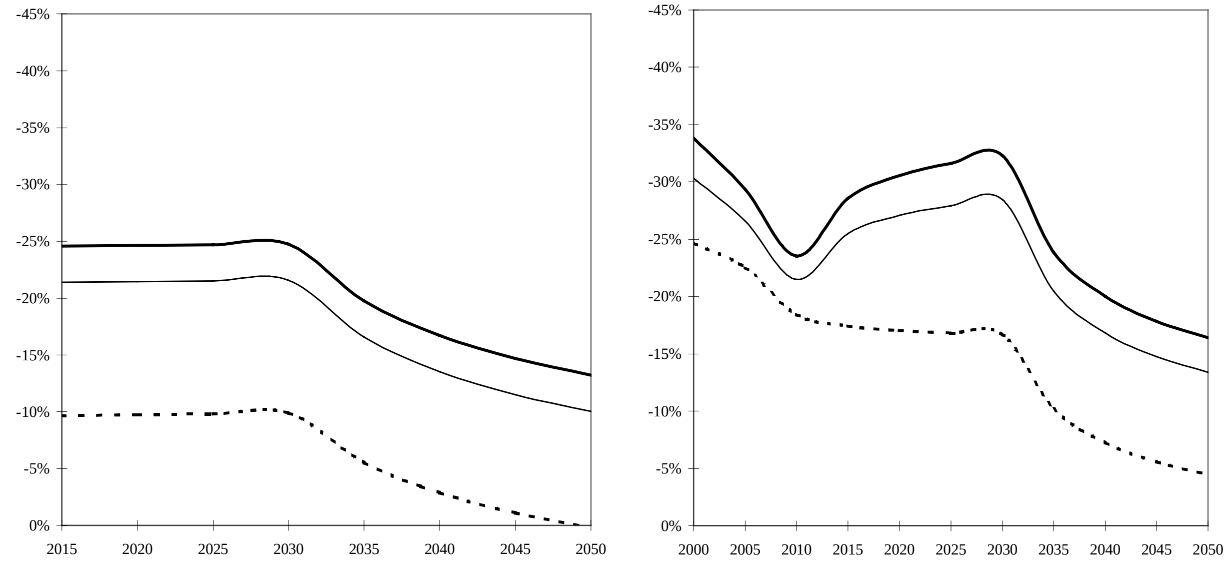


A. Marginal cost reduction in Annex 1 countries

B. Reduction of average real income losses in Annex 1 countries

C. Marginal cost reduction in non-Annex 1 countries

D. Reduction of average real income losses in non-Annex 1 countries



Source : OECD GREEN model

ANNEX 1. MODELLING NON-CO_2 GASES IN GREEN

1. Introducing methane and nitrous oxide emissions in GREEN has required substantial modifications of the structure and specification of the standard model version as described in Lee *et al.* (1994). Even so, the extensions have been specified in a way that is consistent with the general equilibrium structure of the model. Just as for carbon dioxide, emissions of non-CO_2 gases are linked to the production or the consumption of a number of commodities. The emissions are converted into carbon-equivalents using Global Warming Potentials (GWPs).

2. The sectoral breakdown of GREEN has been modified in order to better identify the non-CO_2 sources. Using the modified sectoral breakdown, emission rates for the base year 1995 have been derived by combining data on emissions with Social Accounting Matrices aggregated from the GTAP database (version 4.0). As in the case of CO_2, emission rates for the non-CO_2 gases decline over time according with exogenously set rates of autonomous efficiency improvement. For the projections over the period up to 2010, these rates are calculated as part of the calibration process. In addition, non-CO_2 emission rates also reflect induced technological responses to carbon price changes - with these responses specified in a set of "response functions". The following sections describe these steps in more detail.

New sectoral disaggregation

3. N_2O and CH_4 emissions are related to specific economic activities (see Section 2.2 of the main text). To the extent allowed by the GTAP database, the sectoral breakdown of GREEN has been extended to better identify such activities. The main modification concerns agriculture that has been disaggregated in order to identify rice cultivation and the livestock sector (Table A1). As well, the chemical industry has been identified separately in order to model emissions from fertiliser use as well as from the production of adipic and nitric acids.

[Table A1. Sectoral disaggregation in the modified version of GREEN]

4. To accommodate this new sectoral disaggregation, some aspects of the model specification have been modified. In particular, to overcome the limitations of the Armington specification,[1] rice has been treated as a homogenous commodity. Individual country/region supply functions have been specified for rice[2], with a single world price equating total world supply and demand. In each country/region, the net trade for rice is calculated as the difference between domestic demand and supply.

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[1] In countries where trade restrictions are almost prohibitive, the Armington specification may lead to inappropriate results for relatively undifferentiated goods. The case of a country for which the initial data report no import in the base year provides an extreme but intuitive illustration of this. In this country, an increase of the domestic price cannot induce any substitution towards the imported good because the corresponding Armington share is equal to zero. This peculiarity of the Armington specification makes it unrealistically costly to reduce methane emissions from rice cultivation in countries – such as Japan and China - where imported rice is a small proportion of domestic demand, as reported in the 1995 data base.

[2] The specification used here is similar to the one that rules the supply of crude oil (see Burniaux *et al.*, 1992; Lee *et al.*, 1994). Upward supply elasticities (*i.e.* the elasticity values used if rice cultivation is

Base-year emission rates

5. Base-year emissions are estimated based on FCCC data in conjunction with a number of other sources (see references in main text). These emissions are then related to specific activities of the GREEN model in order to calculate base year emission rates. For instance, the amount of methane emitted through anaerobic decomposition in rice fields is compared to the output of the rice sector. The corresponding emission rate is expressed in tons of Ceq. per 1995 dollar of rice output. The relevant bases for emission rates of methane and nitrous oxide are presented in Table A2.

[Table A2. Non-CO_2 emission rates in GREEN]

Autonomous efficiency changes

6. Up to 2010, non-CO_2 emission rates are calibrated on FCCC projections for countries/regions where these were available. Beyond 2010, extrapolation has been used. Where IPCC projections were not available, the emission rates are projected so as to produce baseline forecasts of non-CO_2 emissions that are in the range of existing scenarios. In most Annex 1 countries, the calibration process yields emission rates that decline over time, implying some autonomous efficiency improvement.

Induced technological response

7. A number of technologies are available to reduce the emissions of each non-CO_2 sources. The substitution among these technological options is represented by means of aggregate and continuous “response functions” that calculate the emission reduction achieved at a given marginal cost, using the following specification:

$$\alpha_{i,t} = \alpha_{i,t}^{\min} + (\overline{\alpha}_{i,t} - \alpha_{i,t}^{\min}) \bullet \left[\frac{\overline{\alpha}_{i,t} - \alpha_{i,t}^{\min}}{\overline{\alpha}_{i,t}} \right]^{\varepsilon \cdot MC} \qquad [1]$$

where $\alpha_{i.t}^{\min}$ is the minimum emission rate given the abatement potential that is technologically achievable over the foreseeable future; $\overline{\alpha}_{i.t}$, the calibrated emission rate in period *t* in the baseline scenario; MC, the corresponding marginal cost or tax level in dollar per ton of Ceq.; $\alpha_{i.t}$, the emission rate corresponding to this marginal cost; and ε, an elasticity that controls how fast the effective emission rate $\alpha_{i.t}$ converges towards the minimum emission level $\alpha_{i.t}^{\min}$.

8. In equation [1], $\frac{\left(\overline{\alpha}_{i.t} - \alpha_{i.t}^{\min}\right)}{\overline{\alpha}_{i.t}}$ expresses the reduction potential as a fraction of the baseline emission rate. The specification implies that emissions cannot be reduced by more, even at the price of very high marginal abatement costs. By contrast, for a marginal cost equal to zero implying no abatement effort, the effective emission rate in period *t* is equal to the corresponding rate in the baseline scenario ($\alpha_{i.t} = \overline{\alpha}_{i.t}$). The parameters $\alpha_{i.t}^{\min}$ and ε have been calibrated for each emission source using the information provided by engineering assessments available in the literature (see main text and the

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extending) have been set equal to unity in the US, to 2 in the other OECD countries and to 3 in the non-OECD countries. Downward elasticity values are equal to 0.5 in all countries/regions.

overview in Table A3). Figure A1 shows as an example the response function for methane emissions from landfills. The reduction potential is much lower in the US to the extent that methane abatement that is achievable under the "Landfill rules" are included in the baseline scenario and, therefore, excluded from the estimate of the reduction potential (see Box 1 in the main text). In other Annex 1 and non-Annex 1 countries, the reduction potential is assumed to be the same and equal to close to 60 per cent. Taking into account that, on average, landfills in non-Annex 1 countries are smaller, the elasticity of convergence towards the minimum emission rate (ε in equation [1]) has a lower value than in Annex 1 countries.

[Table A3. Review of estimates reduction potentials for non-CO_2 gases]

[Figure A1. Marginal abatement curves for methane from landfills]

Table A1. Sectoral disaggregation in the modified version of GREEN

Old		New
Agriculture	{	Livestock
	{	Paddy rice
	{	Other agriculture
Coal mining		Coal mining
Crude petroleum		Crude petroleum
Natural gas		Natural gas
Refined oil products		Refined oil products
Electricity		Electricity
Energy-intensive industries	{	Chemical, rubber, plastic products
	{	Other energy-intensive industries
Other industries and services		Other industries and services

Table A2. Non-CO_2 emission rates[1] in GREEN

Non-CO_2 sources	Bases for emission rates
Methane:	
Enteric fermentation	Livestock production
Manure management	Livestock production
Rice cultivation	Rice production
Coal mining	Coal production
Oil and natural gas activities	Oil and gas production
Landfills	Total household consumption
Nitrous oxide:	
Nitrogenous fertilisers	Expenditures of chemical products by producers of rice and other agricultural products
Non-combustion industrial processes	Production of chemical, rubber and plastic products
Fossil fuels combustion	Oil and gas consumption

1. Emission rates are expressed as Ceq. per 1995 dollar.

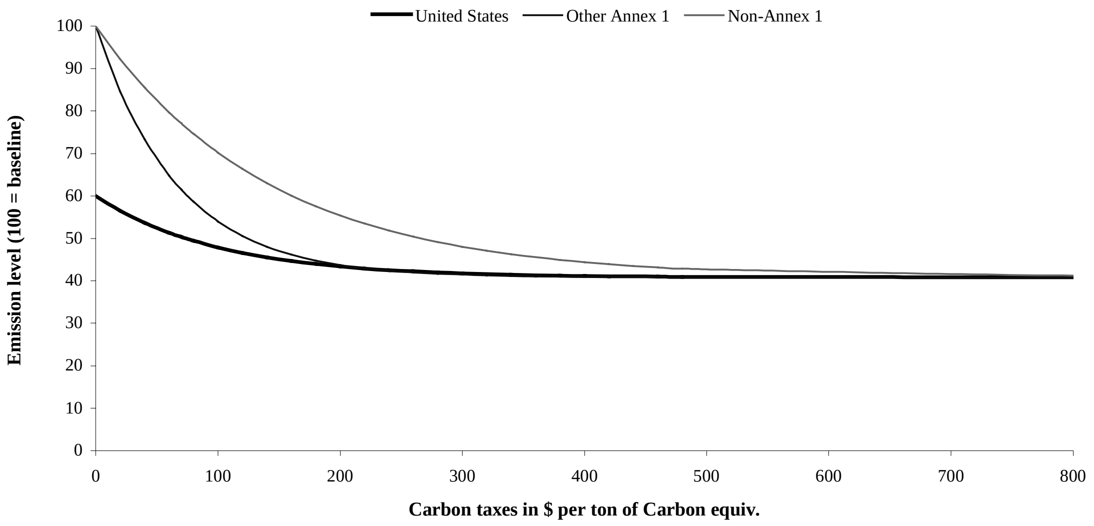
Table A3. Review of estimated reduction potentials for non-CO_2 gases

Emission sources	Sources	Reduction potential	Values used in GREEN		
			Lower bound[1]	Central	Higher bound[1]
Methane:					
Enteric fermentation	Müller and Bartsch (1999)	5 to 60%	15% in Annex 1 30% in non-Annex 1	30% in Annex 1 60% in non-Annex 1	60% in Annex 1 60% in non-Annex 1
Manure management	Müller and Bartsch (1999) Gibbs (1998) EU Commission (1999)	25 to 80% 70% 70-80%	40%	80%	80%
Total livestock[2]	Riemer and Freund (1999)	53% by 2020	30%	60%	67%
Rice cultivation	Müller and Bartsch (1999) Riemer and Freund (1999)	9%<20%<35% 40% by 2020	10%	20%	40%
Total agriculture	IPCC (1996) Riemer and Freund (1999)	15%<35%<56% 35% by 2020	23%	46%	57%
Coal mining	Müller and Bartsch (1999) EU Commission (1999) IPCC (1996) Gibbs (1998) Riemer and Freund (1999)	50 to 70% 20 to 70% 30 to 90% 75% 70%	38%	75%	90%
Oil and natural gas activities	Müller and Bartsch (1999) Riemer and Freund (1999) EU Commission (1999) IPCC (1996) Gibbs (1998)	10 to 80% 80% by 2020 50 to 80% 80 to 90% 50%	25%	50%	80%
Landfills	Gibbs (1998) IPCC (1996)	75% More than 50%	30%	60%	75%
Nitrous oxide:					
Nitrogen fertilisers	IPCC (1996)	9%<17%<26%	9%	26%	26%
Industrial processing			25%	50%	50%
Fuels combustion			25%	50%	50%

1. Used in sensitivity analysis.

2. Total livestock is the relevant production sector in GREEN and it is only the reduction potential in this line that is directly relevant to the model..

Figure A.1 **Marginal abatement curves for methane from landfills.**



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