RIVM report 550006001/2005

A Multi-gas abatement analysis of the Kyoto Protocol

P.L. Lucas
M.G.J. den Elzen
D.P. van Vuuren

This investigation has been performed by order and for the account of MNP-RIVM, within the framework of project S/550006, ‘Integrated modeling of energy and material flows’.

RIVM, P.O. Box 1, 3720 BA Bilthoven, telephone: 31 - 30 - 274 91 11; telefax: 31 - 30 - 274 29 71

National Institute for Public Health and the Environment (RIVM)
Global Sustainability and Climate (KMD)
Netherlands Environmental Assessment Agency
P.O. Box 1, 3720 BA Bilthoven
The Netherlands
Telephone : +31 30 2744549
Fax : +31 30 2744464
E-mail : Paul.Lucas@rivm.nl
Website : http://www.rivm.nl/ieweb

Abstract

A Multi-gas abatement analysis of the Kyoto Protocol

This report presents an analysis of the costs and the abatement distribution of the Kyoto Protocol on the basis of a multi-gas approach, accounting for all six Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6). Results are compared to earlier analyses, in which the Protocol was evaluated taking only CO_2 into account. Consistent with earlier analyses, banking of emission allowances is a necessary requirement for the creation of a viable emission trading market, resulting in an international permit price in the range of 15 and 40 €/tCeq. In such case, of the 490 MtC-eq reduction effort under the Protocol about half in permit demanding regions is achieved through international trading. Approximately 30% of the emission reduction target is realized through implementation of sinks or by the purchase of surplus emission allowances. As several low-costs emission reduction options exist for the non-CO_2 emission sources, their share in total abatements is large, while CO_2 represents about 30% of the emission reductions. Among the non-CO_2 greenhouse gases, the largest contribution comes from CH_4, for which most reductions originate in the gas sector, mainly in the Ukraine and the Russian Federation. Other important non-CO_2 abatement sources are CH_4 emissions from coal production and landfills, and N_2O emissions from adipic and nitric acid production, mainly for the EU-25, Japan and Canada. In terms of percentage reduction from the baseline, the reductions for CH_4 and the F-gases are much larger than the reductions in the CO_2 emission, while in absolute terms, the largest reduction share still comes from CO_2 emissions from energy use. Compared to the CO_2-only analyses, a decline of both the international permit price and the total costs can be seen along with an increase of reduction in greenhouse gas emissions (in case of banking from 250 to 400 MtC-eq). These gains are somewhat reduced if banking of emission permits is assumed.

Keywords: Kyoto Protocol, multi-gas, mitigation, abatement costs

Rapport in het kort

Een multi-gas analyse van het Kyoto Protocol

Dit rapport analyseert de kosten van het Kyoto Protocol en de belangrijkste emissie-reductiebronnen op basis van een multi-gas benadering (alle Kyoto gassen worden hierin meegenomen: CO_2, CH_4, N_2O, HFCs, PFCs, en SF_6). De resultaten zijn vergeleken met eerdere analyses, waarin alleen naar CO_2-reductiemogelijkheden is gekeken.

Het sparen van de surplus emissierechten van de Oekraïne en de Russische Federatie is een absoluut vereiste om een vatbare emissiehandelsmarkt te bewerkstelligen, wat resulteert in een marktprijs tussen de 15 en de 40 €/tCeq. Ongeveer de helft van de reductiedoelstelling van de permit-kopende landen kan verkregen worden door de emissiehandel. Ongeveer 30% van de emissiereducties kan verkregen worden door de handel in surplus emissierechten en door het inzetten van sinksprojecten. Het aandeel van CO_2 in de totale emissieverminderingen is vrij klein ten opzichte van het aandeel van CO_2 in het basispadscenario (circa 30%). Voor de niet-CO_2 broeikasgassen komt het grootste reductieaandeel van CH_4, waarvoor de meeste reducties in de gassector plaatsvinden; hoofdzakelijk in de Oekraïne en de Russische Federatie. Andere belangrijke niet-CO_2-emissiereductiebronnen zijn CH_4 emissies uit kolenproductie en van stortplaatsen, en N_2O-emissies uit de industrie; voornamelijk uit de EU-25, Canada en Japan. Ten opzichte van het basispadscenario, zijn de emissiereducties procentueel groter voor CH_4 and the F-gassen dan voor CO_2, terwijl in absolute termen CO_2-emissies uit energiegebruik nog steeds de belangrijkste reductiebron vormen.De vergelijking met CO_2-only benaderingen laat zien dat het meenemen van alle Kyoto-gassen enerzijds resulteert in een daling van zowel de internationale prijs voor verhandelbare emissierechten als de totale kosten voor de landen die kwantitatieve verplichtingen op zich hebben genomen en anderzijds in een toename in vermeden emissies (van 250 naar 400 MtC-eq). De winst die gemaakt wordt door het meenemen van alle Kyoto gassen in de analyses wordt echter sterk verminderd door deze banking strategie.

Keywords: Kyoto Protocol, multi-gas, mitigatie, abatement kosten

Contents

1 Introduction

In the process leading up to the Kyoto Protocol entering into force, the first international agreement containing binding emission targets for greenhouse gas (GHG) emissions has been confronted with several threats jeopardizing its existence. One of the most important challenges was the announcement of the Bush administration not to ratify the Kyoto Protocol (later followed by non-ratification of Australia); this put the future of the protocol in the hands of the Russian Federation[1]. However, now that UN Secretary-General, Kofi Annan, has received the ratification of the Russian Federation (per 18 November 2004) the Protocol may enter into force 90 days after ratification, in other words, 16 February 2005.

With the Protocol in place, analysis of its environmental effectiveness and economic efficiency have become more relevant. The Protocol includes several so-called flexible mechanisms, which allow the Annex I countries to fulfill their commitments as cost-effectively as possible. These mechanisms include various forms of flexibility to encourage reduction of emissions –via the Kyoto mechanisms, International Emission Trading (IET), Joint Implementation (JI) and the Clean Development Mechanism (CDM) – in the timing of reductions (2008-2012 period) and in the way emissions are abated (full substitution different greenhouse gasses & accounting for sinks).

In our previous work, environmental effectiveness and economic efficiency of the Kyoto Protocol, including the Bonn Agreement ((Den Elzen and De Moor, 2001b) and the Marrakesh Accords (Den Elzen and De Moor, 2001c), were evaluated on the basis of CO_2 emissions and abatement only. However, as already stated, the Kyoto Protocol covers not only CO_2 but a set of six GHGs in which full substitution is allowed.[2] Therefore the inclusion of the non-CO_2 Kyoto gases will result in a large increase in flexibility, since this inclusion is charcterised by large amounts of abatement potential for these gases and their different emission sources. Furthermore, for several of the non-CO_2 emission sources, low abatement costs are expected because these emissions are easy to abate. Including these emission sources could thus significantly reduce the overall costs of implementing the Protocol, which was already concluded by Reilly et al. (2000; 1999) and Jensen and Thelle (2001).

In this study we re-evaluated the cost impacts of the Protocol by including the complete set of GHGs, taking our earlier CO_2-only studies as starting point. As the Ukraine and Russian Federation are the dominant sellers on the market, we also re-evaluated their role using such a multi-gas approach. Furthermore, next to assessing the impacts on the

[1] For the Kyoto Protocol to enter into force it is necessary that 55 Parties to the Convention ratify (or approve, accept, or accede to) the Protocol, including Annex I Parties, accounting for 55% of that group's carbon dioxide (CO_2) emissions in 1990 (Article 25.1). As the US share accounts for 36.1% of the 1990 emissions, the Russian share of 17.4% is crucial to fulfilling the 55% requirement Berk, M.M. and den Elzen, M.G.J., 2004. What if the Russians don't ratify? Report no. 728001028, National Institute for Public Health and the Environment, Bilthoven, the Netherlands..

[2] This set of Kyoto greenhouse gases includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons[2] (PFCs) and sulphur hexafluoride (SF_6).

overall and regional costs, we also assessed the abatement shares of the different GHGs and their emission sources in total and regional emission reductions.

Section 2 describes the methodology and the assumptions made, while Section 3 evaluates the differences between the original CO_2-only analysis and the new analysis, encompassing all Kyoto gases. Section 4 evaluates the abatement shares of the different gases and sources for the different world regions. Section 5 puts the analysis into perspective by presenting a sensitivity analysis on the key factors influencing the main outcomes of our analyses, while section 6 presents the final conclusions.

2 Methodology

The FAIR 2.0 model (Den Elzen and Lucas, 2003) was used to evaluate the costs of the Kyoto Protocol under a multi-gas abatement strategy and to determine the shares of abatement options in total mitigation. The model consists of three linked models: i.e. a climate model, an emissions allocation model and a cost model. In the analysis presented here we only use the cost model, which has been improved with respect to FAIR 1.1 by incorporating cost information on abatement options for the non-CO_2 GHGs.

2.1 Main Assumptions

As a baseline for our analysis (future situation without climate policy) we used the IMAGE 2.2 implementation of the IPCC SRES A1B scenario, which describes the development of regional GHG emissions for the different sectors and sources (IMAGE-team, 2001). This scenario can be characterized as showing increasing globalization, a rapid introduction of new and more efficient technologies and high economic growth (IPCC, 2000).

Next, we assume implementation of the Kyoto targets in the participating countries, allowing for emission trading among Annex I parties. The analysis takes into account the most important developments following the agreement to the Kyoto Protocol (UNFCCC, 1997) at the third session of the Conference of Parties (COP3) in 1997. These developments include the withdrawal of the USA and Australia from the protocol, the Marrakech Accords on the use of sinks, and the recent ratification of the Ukraine and the Russian Federation. For the regions participating under the Protocol we assume their original assigned amounts, taking into account the country-specific base-years other than 1990 (see Den Elzen and De Moor, 2001a, for details). The difference between the assigned amounts and the reference emissions in 2010 is the emission reduction burden, i.e. the effort a region must make to comply with its target. This effort can be made domestically or abroad by making use of the flexible Kyoto mechanisms, as defined under the Kyoto Protocol, i.e. International Emission Trading (IET), Joint Implementation (JI) and the Clean Development Mechanism (CDM). For the use of these flexible Kyoto mechanisms, transaction costs, consisting of a constant 2 €/tCeq emissions plus 2% of the total costs are assumed. Because CDM is a project-based mechanism to be operationalized in developing countries, only a limited amount of the abatement potential is assumed to be readily available on the market (at least in the short term). Therefore, this availability is set at 10% of the theoretical maximum in 2010, while for IET and JI full availability is assumed (even though this is probably a too optimistic assumption).

The analysis assumes a least-cost approach with respect to the contribution of different gases. The concept of CO_2-equivalent emissions is used to substitute among the different GHGs, equalizing the contribution of different gases to global warming using Global Warming Potentials (GWPs) with a 100-year time horizon, as adopted at the third meeting of the Conference of the Parties (UNFCCC, 1997). Although 100-year GWPs are suggested by the IPCC, several researchers point out that the choice of a time horizon is arbitrary and that the results can change significantly by switching to GWPs with a 20-year or 500-year time horizon (Reilly et al., 1999). Furthermore, the concept can only partly take into account the impacts of the different lifetimes of the various gases, or the economic efficiency of reducing them. Different metrics for comparison have been proposed (Manne and Richels, 2000; Reilly et al., 1999). Nevertheless, despite this continuing scientific debate, the concept is regarded as convenient and to date no alternative measure has attained a comparable status.

2.2 Cost calculations

Cost calculations have been done on the basis of Marginal Abatement Cost (MAC) curves. MAC curves reflect the additional costs of reducing the last unit of CO_2-equivalent emissions, differing per country and per source. They allow for relatively simple and transparent calculations of the costs (assuming a least-cost approach) of different regions in reaching their respective Kyoto targets. The intersection formed by the aggregated MAC curves (total supply) and emission reduction objectives (total demand) of Parties determines the international market equilibrium permit price (henceforth referred to as permit price). Depending on the national/regional MAC curves and reduction objectives this market price determines if Parties will import permits to meet their individual targets, or will abate more than is required to sell this surplus on the international permit trading market. The MAC curves can thus be used to determine marginal and total abatement costs and to examine the gains of emissions trading (Ellerman and Decaux, 1998). Regional and sectoral demand and supply curves are constructed from the regional and sectoral MAC curves to take abatement cost differences for the different regions, sectors and gases into account.[3] For the cost calculations we use the 1999 euro, which equal to the 1995 US$.

Although this methodology based on MAC curves has the great advantage of being transparent and easy to apply, it also has a number of limitations. MAC curves only represent direct cost effects without accounting for the feedback to the overall economy; this means that there is no direct link with macroeconomic indicators such as GDP or utility losses. Furthermore, the MAC curves have been created outside the system and can therefore not respond to the actual interactions resulting from mitigation action such as those resulting from abatement efforts in other countries (carbon leakage, technology transfer).

Different sets of MAC curves have been used in this analysis. For CO_2 abatement options and cost estimates for energy- and industry-related emissions (energy, feedstock and cement production), impulse response curves from the energy system model,

[3] For details on the cost calculations for the CO_2-only calculations, see den Elzen and Both Den Elzen, M.G.J. and Both, S., 2002. Analysing emissions trading and abatement costs with FAIR. Report no. 728001021, National Institute for Public Health and the Environment, Bilthoven, the Netherlands., and den Elzen and Lucas Den Elzen, M.G.J. and Lucas, P.L., 2003. FAIR 2.0 - A decision-support tool to assess the environmental and economic consequences of future climate regimes. Report no. 550015001, National Institute for Public Health and the Environment, Bilthoven, the Netherlands. for the multi-gas extension.

TIMER 1.0 (De Vries et al., 2001) are used. This model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and renewable energy technologies. A carbon tax on fossil fuels is imposed for constructing the MAC curves to induce emission abatements, taking into account technological developments, learning effects and system inertia (Van Vuuren et al., 2004). As an extra CO_2 potential, activities related to abatement sinks are included for which exogenous assumptions have are made. These assumptions relate to Article 3.3 activities on agricultural management, country-specific caps on forest management and the 1% cap for base-year emissions for CDM sinks (credits generated through sinks projects in non-Annex I countries). The estimates are based on FAO data and Appendix Z of the Kyoto Protocol described in-depth in Den Elzen and De Moor (2001a). As there is no global set of MACs for sinks available and related costs under the Kyoto Protocol are expected to be very low, we have assumed them to be available at zero cost. In this way, the full potential of sinks options (108 MtCeq total) is used before other abatement options are applied.

For the non-CO_2 GHG emissions, we used the set of MAC curves from the EMF-21 project 'Multi-Gas Mitigation and Climate Change' (Weyant and Delachesnaye, 2003).[4] The set includes curves for CH_4 and N_2O emissions from both energy- and industry-related (Delhotal et al., 2004) and agricultural sources (DeAngelo et al., 2004). The energy-related curves include abatement options for CH_4 emissions from oil, gas and coal production, mainly due to losses and leakage during production and transport, and for N_2O from the transport sector. The industrial N_2O emission reductions reflect adipic and nitric acid production. With respect to agricultural sources, CH_4 reductions include rice cultivation, livestock enteric fermentation and manure management, along with N_2O emission reductions through fertilizer-use management. The set of curves further include abatement options for the set of halocarbons (Schaefer et al., 2004). These emissions have their origin in the manufacturing of semi-conductors, magnesium and aluminum production, HCFC-22 production, electric power systems and air conditioning and refrigeration. The non-CO_2 MAC curves have been corrected for measures already applied under our baseline scenario; this is to increase consistency within the analysis (see Van Vuuren et al., 2003 for the methodology used).

[4] EMF (Energy Modelling Forum) is a structured forum within which energy experts from government, industry, universities, and other research organizations can meet to study important energy and environmental issues of common interest (http://www.stanford.edu/group/EMF/home/). The objective of EMF-21 is to compare and contrast CO_2-only mitigation with multi-gas mitigation (including sinks) for given scenarios and targets.

3 Gains from a multi-gas approach

This Chapter analyses the costs and environmental impacts of the Kyoto Protocol under a multi-gas approach – and, in particular, the difference in economic efficiency between a CO_2-only and a multi-gas approach. This comparison is particularly relevant as many previous analyses on the Kyoto Protocol actually focused on CO_2-only (often based on the assumption that CO_2 represents not only by far the largest share of emissions, but also of reductions). The economic efficiency is expressed in terms of the price of one tonne of CO_2-equivalent emission reductions on the international market (permit price) and the total costs for the Annex I countries that have joined the protocol (all Annex I countries except the USA and Australia). For the CO_2-only analysis, the regional Kyoto targets are set for the CO_2 emissions only, while in the multi-gas approach, the targets are set for all GHG emissions (CO_2-equivalent emissions). Therefore, the reductions obtained from the multi-gas approach are larger than those of the CO_2-only approach.

3.1 CO_2-only versus multi-gas

As shown in Table 1, the inclusion of the five non-CO_2 GHGs results in an increase of the total abatement effort by approximately 20%, while the total surplus emission allowances (‘hot-air’)[5] increase by a slight 10%. This lower increase in hot-air supply of Ukraine and the Russian Federation is mainly due to a stronger decline, between 1990 and 2010, of their CO_2 emissions than their non-CO_2 emissions (see Table 7 for details). Despite the fact that the total emission reduction objective is larger for the multi-gas approach compared to CO_2-only, the permit price is more than 50% lower. The lower permit price is a result of the large availability of non-CO_2 abatement options, with relatively low costs compared to CO_2 abatement in the energy sector. The much lower permit price results in even much lower Annex I costs (combined costs of the EU-15, Canada and Japan) and gains (combined gains for Ukraine and the Russian Federation) – despite the larger reduction objectives. A multi-gas approach thus leads to more reductions at less cost, but also to fewer gains. Regional costs and effort rates (costs as percentage of GDP) are given in Tables 2 - 4 of Appendix A.

3.2 The costs and benefits of banking

As indicated by Den Elzen and De Moor (2001c), , the amount of ‘hot-air’ may exceed the demand on the emission trading market under the Kyoto Protocol; this could drive the permit price down to zero, resulting in a dysfunctional market. This situation became more likely after the US and Australian withdrawal from the Kyoto Protocol. Den Elzen and de Moor (2001b) conclude that it would be a rational action for the dominant sellers

[5] Baseline emissions of many countries in transition are expected to be lower than their targets under the Kyoto Protocol as a result of their economic downturn (certainly after corrections for sinks under the Bonn Agreement and Marrakech Accords). The difference permitted to be traded is referred to as surplus emission allowances or ‘hot-air’.

to exercise their market power and curtail permits from the market so as to raise the permit price. This kind of strategic behaviour is called ‘banking’.

Table 1: Results of the CO_2-only versus the multi-gas approach

		Reduction effort (MtCeq/yr)	Total hot-air (MtCeq/yr)	Permit price (€/tCeq)	Annex I Costs / Gains (€ x bill./yr)*
Kyoto Protocol excl. optimal banking	CO_2 only	410	231	26	8.6 / 6.0
	Multi-gas	487	251	10	3.6 / 2.7
Kyoto Protocol incl. optimal banking	CO_2 only	410	162	43	13.2 / 7.2
	Multi-gas [6]	487	75	33	10.2 / 4.2

- Annex I costs reflect the combined costs of the permit-demanding regions (EU-25, Canada and Japan), while Annex I gains reflect the combined gains of the Ukraine & the Russian Federation.

Under the Kyoto Protocol, banking is allowed to save emission permits for consecutive commitment periods (CP). Curtailing permits from the international market lowers supply, resulting in a higher permit price. The higher permit price can result in higher revenues for the permit-supplying regions. Curtailing as many permits as necessary to maximize the revenues from permit sales is called ‘revenue maximization’ (Böhringer and Löschel, 2001; Burniaux, 1999), while the incentive to curtail permits can also be called ‘welfare maximization’ (Böhringer, 2001). Although both methods result in substantial banking of emission permits, Babiker et al. (2002) and Klepper and Peterson (2002) argue that revenue maximization results in a larger number of curtailed permits; however, they do state that this is dependent on the permit allocation within the hot-air-supplying regions. Where the overall emission reduction objective of a consecutive CP is supposed to be more stringent than the objective in the current period, emission permits can also be banked to lower the objective of this future commitment. When the permit price of the consecutive period is expected to be much higher, saving credits can lower the combined costs of both CPs, while foresight can also be used to maximize the revenues over several CPs (Van Steenberghe, 2002).

Because the negotiations on commitments after the first CP (2008-2012) of the Kyoto Protocol have not yet begun, it is not possible to apply a strategy that assumes foresight. For this reason, we have assumed a strategy of revenue maximization in the first CP by the main hot-air-supplying countries – the Ukraine and the Russian Federation – assuming that they have enough market power to significantly affect the permit price. Using the FAIR model, we analyzed the impacts of such a revenue maximization strategy by curtailing the supply of permits in these two countries enough to maximize their combined revenues. It is, however, still unclear if countries like the Ukraine and the Russian Federation will co-operate. The lack of co-operation and therefore market power would lower the number of curtailed permits. On the other hand, hot-air-

[6] The numbers presented here differ slightly from the analysis of Berk and den Elzen Berk, M.M. and den Elzen, M.G.J., 2004. What if the Russians don't ratify? Report no. 728001028, National Institute for Public Health and the Environment, Bilthoven, the Netherlands., reflecting an update of the mitigation potential in the Ukraine & the Russian Federation.

supplying countries (including countries in Central Europe) are expected to prefer JI projects to hot-air selling, as these projects result in lower GHG emissions and promote development. While the magnitude of both effects is still unclear, our analysis assumes that the two effects generally outweigh each other and also that an optimal banking strategy is possible.

Table 1 also shows the CO_2-only and the multi-gas scenarios, including the proposed optimal banking strategies (second row). For the CO_2-only case the optimal banking percentage was determined to be 30%, while for the multi-gas approach this was 70%. Part of the increase can be explained by the small increase in hot-air compared to the overall emissions, while the remainder can be explained by the large number of relatively cheap abatement options (mainly non-CO_2 emission reductions) in the hot-air supply regions. Curtailing hot-air credits from the market raises the permit price. This increases the revenues from the selling of cheap emission reductions, as the curtailed credits can easily be replaced by the low-cost reductions without too much loss of revenues. However, the cost reductions of the multi-gas approach (compared to CO_2-only) are sharply reduced under an optimal banking strategy, as the much larger optimal banking percentage increases the overall Annex I costs disproportionately compared to the CO_2-only scenario. In absolute terms, the conclusion in Section 3.1 that a multi-gas approach leads to more reductions at less cost still holds.

4 Multi-gas abatement distribution

In the previous chapter a multi-gas approach was shown to be more economically efficient than an approach focusing on CO_2 only. In this chapter, we analyze the shares of the different Kyoto gases and their respective economic sectors in the total abatement effort. The analysis draws on the multi-gas analysis, taking optimal banking into account.

4.1 Reduction distribution over the gases

The regional domestic reductions and emission permits traded on the market (including sinks and hot-air) under a multi-gas approach are graphically presented in Figure 1. Net-permit importing regions are the European Union (EU-25), Japan and Canada. Approximately 50% of the Annex I emission reduction objective is realized through emissions trading, while 20% is achieved through hot-air (Ukraine and the Russian Federation), 10% through CDM (the non-Annex I countries) and 30% by trading through IET (excluding hot-air) or JI projects (in the Ukraine, Russian Federation and the 10 countries that have recently joined the EU).

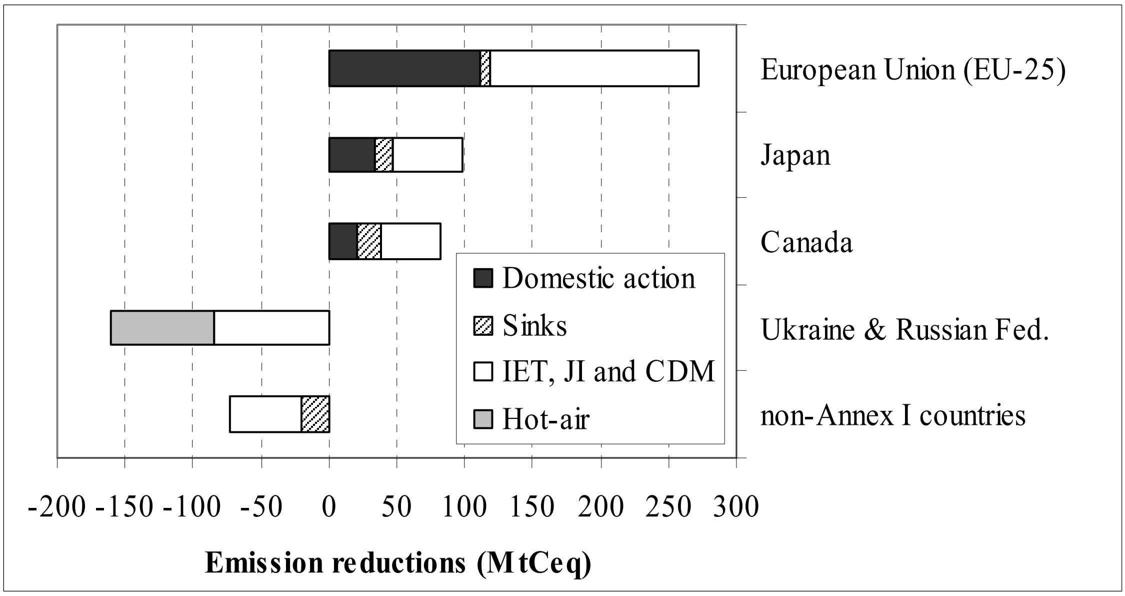
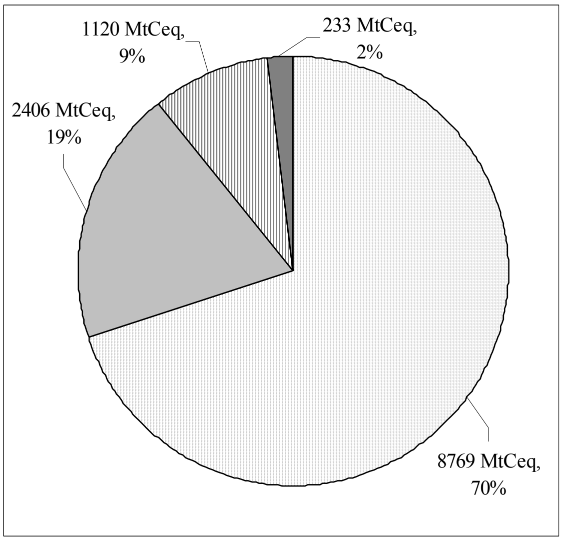


Figure 1: Regional demand and supply of emission permits including sinks and hot-air. Note: as sinks are assumed to cost zero, they are included in the hot-air for the Ukraine and Russian Federation, and account for 45 MtCeq. Furthermore, to illustrate the role of hot-air, it is excluded from IET and presented separately.

Figure 2 shows the shares of the different Kyoto gases in the total world emissions in 2010 and the shares of the different Kyoto gases in total abatement. The CO_2 share in total abatement is much lower than its share in total 2010 emissions (47% versus 70%). The same holds for the N_2O emissions. The much smaller abatement shares for CO_2 and N_2O are compensated by a much larger share for CH_4 and the F-gases. In fact, the contribution of CH_4 to total abatement almost equals that of CO_2, despite the fact that

CH_4 only contributes to about one-fifth of the total emissions. This is caused by the large availability of relatively cheap abatement options in the different CH_4 and F-gas sectors, which also explains the drop in overall Annex I abatement costs, as presented in the previous chapter. For N_2O it should be noted that the lion's share of the emissions originates in agricultural sources – for which no easily implemental short-term reduction options have been identified.



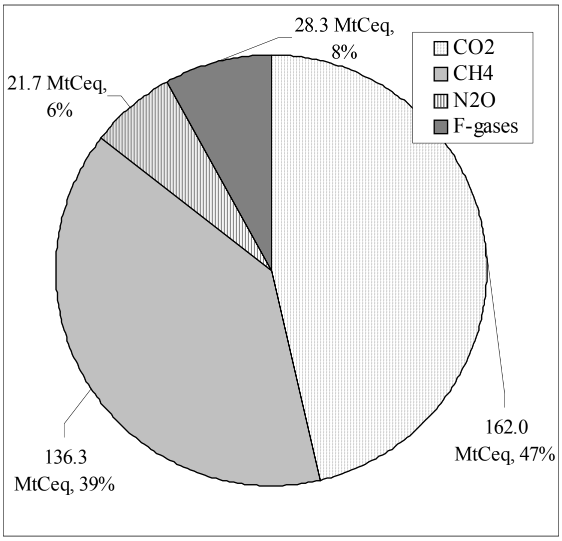


Figure 2: Share of different GHGs in total 2010 emissions (left) and the share of the different GHGs in total emission reductions (right). Note: these figures do not include the abatement effort through the use of sinks.

The shares of the different gases, sinks and hot-air in the total abatement effort are presented in Figure 3 for both the permit-supplying (left figure) and permit-demanding regions (right figure). CDM sinks (credits generated through sinks projects in non-Annex I countries) are included on the supply side, while domestic sinks (credits generated through sinks projects in Annex I countries) are included on the demand side.[7] Approximately 15% of the emission reduction objective is realized by emission uptake through sinks (domestic and CDM sinks together), while another 15% is realized through the purchase of hot-air. The share of CO_2 abatements is relatively small compared to the share of the CO_2 emissions (as shown in Figure 2). In fact, the abatement share of CO_2 is much smaller for the selling countries than for the buying countries. The same holds for N_2O and the F-gases. For the share of CH_4 abatements it is the other way around, with the largest share coming from the non-Annex I countries and the Ukraine and Russian Federation. Both CO_2 and CH_4 account for approximately 30% of the total abatement effort, while N_2O and the F-gases account for approximately 5% each.

The shift in abatement options, mainly from CO_2 towards CH_4, due to emissions trading can be explained by differences in volume of emissions and the costs of the abatement options for the different sources between and within regions. In the largest permit-

[7] As costs of sinks are assumed to be zero, these are included in the amount of hot-air for the Ukraine and Russian Federation.

selling countries, Ukraine and the Russian Federation, CH_4 emissions make up a large share of their total emissions, of which a considerable share can be abated at relatively low costs. In the next section, we will further discuss this in terms of the sectoral composition of the total regional emission reductions. It should be noted that the share of CH_4 in total emissions is even larger in the non-Annex I regions. However, most of these emissions originate from the agriculture sector and are much more difficult to abate. Furthermore, these regions can only participate in emission trading through CDM projects for which a lower accessibility is assumed; this lowers their share in total emissions traded significantly.

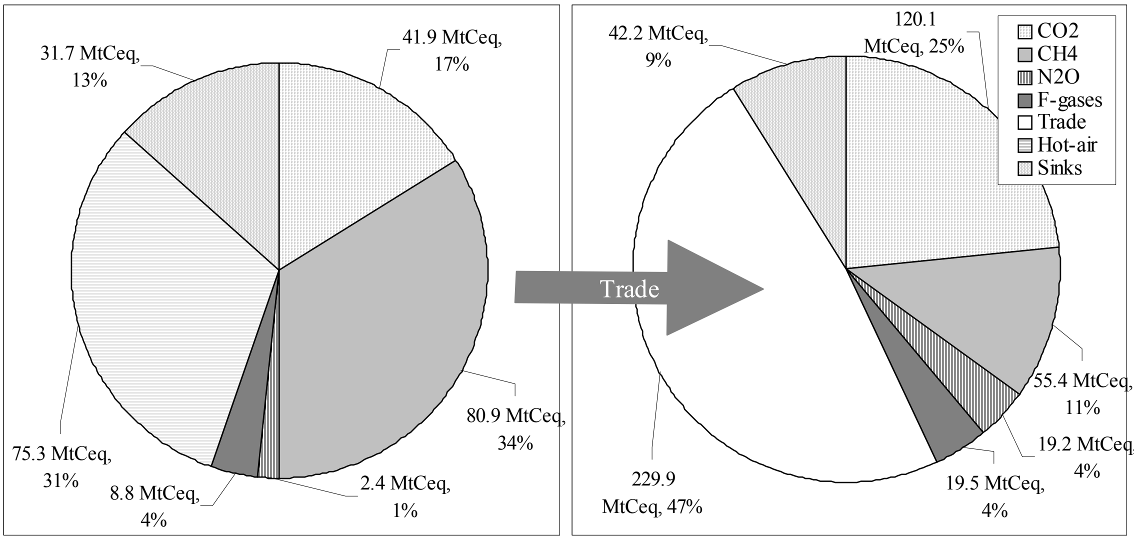


Figure 3: Abatement shares of the different Kyoto gases (including hot-air and sinks) for the permit-supplying regions (left) and the permit-demanding regions (right). Note: the arrow spanning the two figures represents emissions trading and includes IET, JI and CDM.

4.2 Distribution over the sources

While the previous section drew conclusions on the shares of the different Kyoto gases in total abatements, this section further analyses these shares by looking at the abatements in the different economic sectors. We focus on the EU-25, and the Ukraine and Russian Federation, as they are the largest buyer and supplier, respectively, on the international market. Tables 6 and 7 of Appendix A present baseline emissions for both 1990 (base-year) and 2010 (Kyoto-year) and the emission reductions in the Kyoto period for these two regions for the different gases and sources , while Tables 8 to 10 present the results for the remaining regions.

The abatements for the different sources are brought into perspective by first overviewing their developments in the reference scenario. Globally, the carbon equivalent emissions are projected to increase by approximately 45% in the 1990-2010 period, mostly in the non-Annex I countries. Emissions from the EU-25 increase by 17%, while for Ukraine and the Russian Federation, emissions are predicted be still 19% below 1990 levels in 2010. For the EU-25, the largest share of the increase comes from CO_2 emissions from energy use, while CH_4 and N_2O emissions are in fact already projected to decrease in the baseline, mainly due to a decrease in coal production and decreasing emissions from adipic and nitric acid production. In the Ukraine and Russian Federation, N_2O emissions are reduced significantly in the baseline (mainly in fertilizer use). Also CO_2 emissions from energy use are still significantly below 1990 levels in 2010 (following the collapse of these emissions in the early 1990s). Finally, CH_4 emissions in the reference scenario in this region decrease slightly as a result of opposing trends in improvements in infrastructure, decline in overall energy use and significant increase in gas production .

In terms of emission reductions (in case of implementation of the Kyoto Protocol) within the EU-25, the largest share in CH_4 reductions comes from the coal production sectors and landfills, where the captured emissions are used mainly for energy production (utilization of recovered gas). The largest reduction sources for N_2O are adipic and nitric acid production, while both sources already decrease significantly at baseline, as they are relatively easy to avoid. N_2O emissions from transport are projected to increase by a factor of 4 as a result of increasing transport levels and further penetration of catalytic converters in cars. Their very low abatement share reflects the fact that almost no reduction potential is available for this source in our analysis. In relative terms, CO_2 emissions from energy production are abated less than the non-CO_2 emissions, but in absolute terms they still form the largest share.

In the Ukraine and Russian Federation the largest emission reductions are projected for CH_4 in the gas sector, which is also the largest CH_4 emission source. These reductions are the result of improvements in inspection and maintenance, for example, and improvements in the networks and utilization of recovered gas. The relatively high emissions from natural gas production and transport provide cheap options for reductions, as prevention from leakage not only decreases greenhouse gas emissions but also increases the efficiency of natural gas production itself. Other important abatements take place mainly for CH_4 in the coal production sectors and in relation to landfills, where utilization of the recovered gas can make these reductions economically more attractive.

5 Sensitivity analyses

The outcomes of our analysis are dependent on a number of key factors, such as the reference scenario on the reduction objective, and the cost curves chosen on the abatement potential and costs estimates. In this section we analyze the sensitivity of our results with respect to some of these factors. In particular, we will look at their influence on the permit price and the abatement distribution over the gases, using low- and high-end assumptions, comparing the results to the reference case. The key factors analyzed will be the reference scenario, the set of non-CO_2 MACs used, the GHGs involved and the level of hot-air banking.

For the baseline scenario, the IMAGE implementation of the IPCC SRES B2 and A1f scenarios (IMAGE-team, 2001) are used as low and high emission scenarios, respectively. For the non-CO_2 MAC curves, the set from the GECS project[8] (Graveland et al., 2002), which also includes all GHGs, is used as an alternative for the EMF21 set used in the reference case. Although the influence of the GHGs (CO_2-only versus multi-gas) involved was already carried out in Chapter 3, the results are included in the sensitivity analysis for the sake of completeness. Furthermore, as Chapter 3 only presents optimal banking cases, we will include here the full range to illustrate the consequences of the lack of market power and the influence of excluding hot-air completely from the trading market. The first three key factors are analyzed, both without banking and with an optimal banking strategy, as this can change the overall outcomes significantly.

5.1 The permit price

The influences of the key factors identified on the permit price are presented in Figure 4, with our reference case noted at 10 €/tCeq for a no-banking case and 33 €/tCeq for an optimal banking case. In the analysis, all factors examined are set at the reference level, while the variable is the factor being analyzed. The banking percentage is set at 70% for the optimal banking cases, as determined in Chapter 3.

An important factor determining the permit price is the amount of hot-air banked. Another important uncertainty factor with a large influence on the outcome is the baseline scenario. Obviously, baseline scenarios with low emission projections result in a low permit price, while baselines with high emission projections result in a high permit price, as the emission increase compared to the base-year (mainly 1990) directly determines the reduction objective. When no banking is applied, the influence of a multi-gas versus a CO_2-only approach has the similar impact as the baseline that is assumed. The use of an alternative set of non-CO_2 MAC curves has a relatively low

[8] The goal of the GECS (Greenhouse Gas Emissions Control Strategies) project is to develop global (world) scenarios in order to analyse the impacts of post-Kyoto policies under flexibility mechanisms for emission reduction, including options to reduce emissions resulting from land use change and options for strengthening carbon sinks.

impact on the permit price, leading to the conclusion that fairly robust cost estimates are used here.

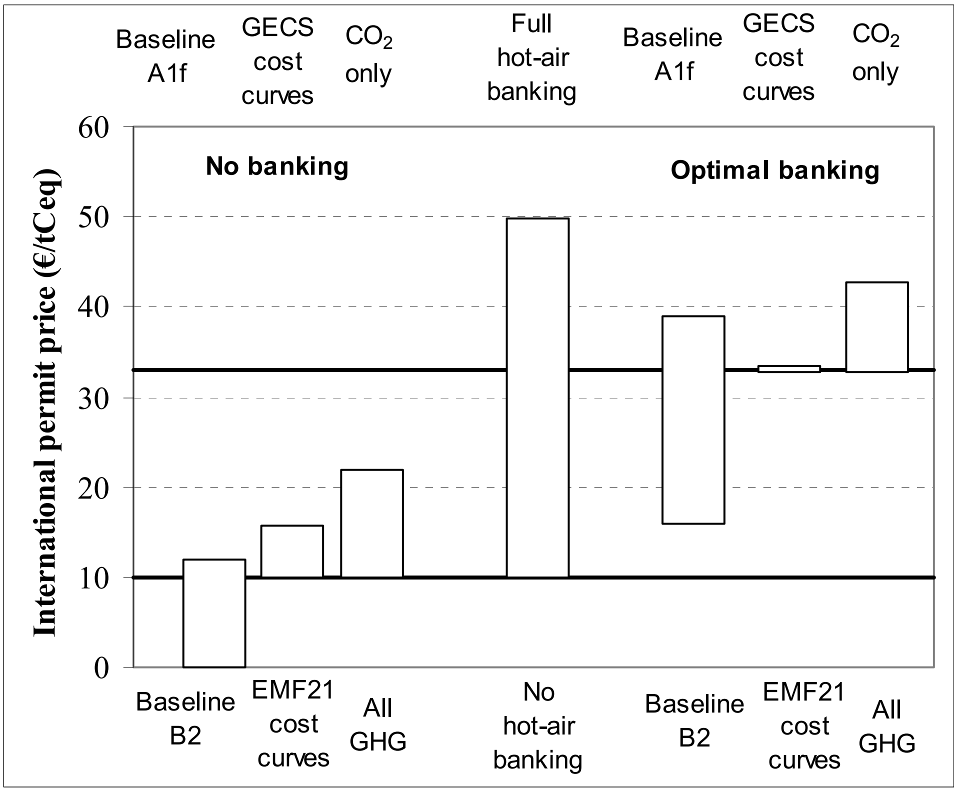


Figure 4: The impact of key factors on the permit price.

Taking into account the full range shown in Figure 4, a permit-price between 0 and 50 €/tCeq is possible in case of Kyoto Protocol implementation. Banking enhances the viability of the emission trading market and the benefits of the dominant traders on the market. Considering the interest of these dominant sellers, the most likely outcome is a permit price between 15 and 40 €/tCeq. The uncertainty introduced by using another set of MACs does not change the outcome significantly. It should finally be noted that the influence of using either a CO_2-only or a multi-gas approach is only relevant as a scientific exercise, since the Kyoto Protocol already covers all gases.

5.2 The gas abatement distribution

Figure 5 presents a sensitivity analysis of the key factors in the gas abatement distribution, i.e. the distribution of the abatement effort over the different gases. Again, all factors examined are set at a reference level, while the factor being analyzed is varied. In this analysis, no distinction is made between optimal banking and no banking, as in the previous chapter. The optimal banking cases are only included for assessing the influence of the reference scenario and the cost assumptions, and the reference variants with no and full banking. The figure does not show the abatement effort obtained through the use of sinks and hot-air trading, since these are determined exogenously.

The largest differences when compared with the reference case are observed for the baseline scenario and in the absence of hot-air banking. Both cases show a large shift from CO_2 abatement to the non-CO_2 GHGs. This can be explained by the much lower permit price (10 to 16 €/tCeq) resulting from a lower reduction objective or the higher supply of hot-air credits. This lower permit price results in less domestic abatement and thereby in an increase in IET, JI and CDM projects, which show a larger share of non-CO_2 reductions. Furthermore, as the abatement options for the non-CO_2 sources are relatively cheaper than CO_2 abatement in the energy sector, domestic reductions too show a larger share of non-CO_2 abatement. As can be expected, full banking shows the opposite effect. As the permit price is larger than the reference case (approximately 50 €/tCeq), more reductions are taken domestically. This leaves less space for JI and CDM projects and thereby less non-CO_2 abatement from imported credits as a higher share of CO_2 abatement in domestic reductions. Finally, the use of an alternative set of non-CO_2 MACs (from the GECS project) results in higher CO_2 and CH_4 abatement, while abatement of the F-gases and N_2O declines. The difference can be explained by a more optimistic estimate of abatement potential for both gases in the EMF 21 set, where the GECS projects limited reduction options for N_2O emissions from adipic and nitric acid production.

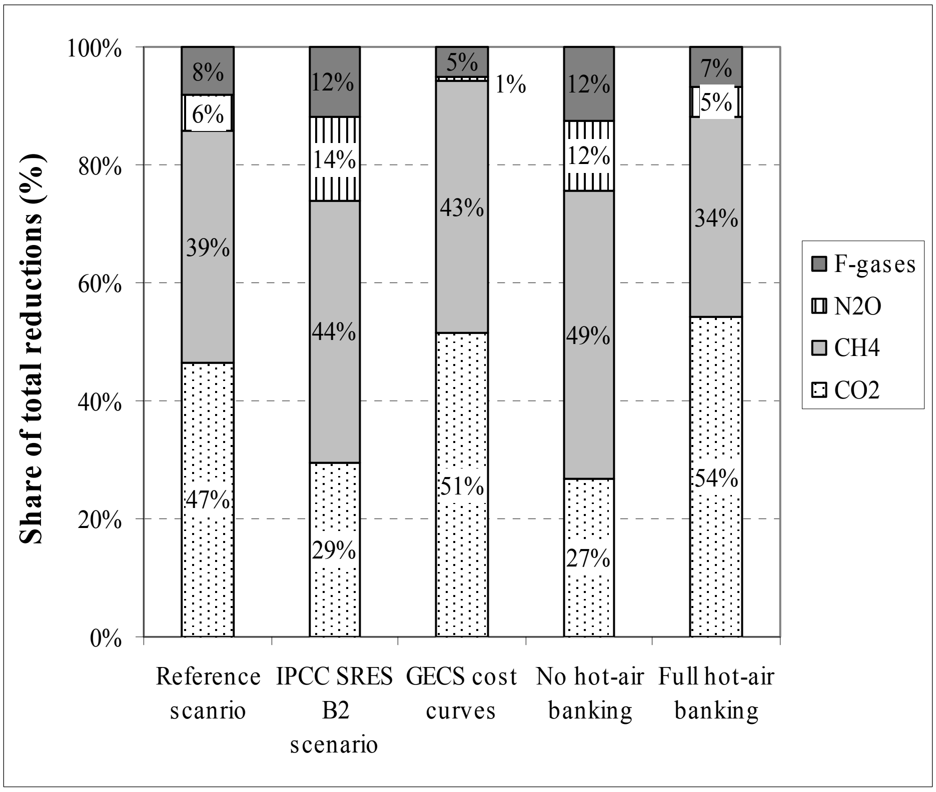


Figure 5: The impact of key factors in gas abatement distribution.

We already concluded in Section 4.1 that emissions trading results in a shift from CO_2 abatements, mainly towards CH_4 abatement and, to a lesser extent, also to the other non-CO_2 GHGs. This conclusion is underscored by the results of Figure 5. Taking into account all the uncertainties and conclusions from Figures 4 and 5, we can conclude that the share of CO_2 in total abatements (excluding sinks projects and hot-air trading) accounts for approximately 30% to 50%; for CH_4, this is 40% to 50%, for N_2O, 1% to 15% and, finally, for the F-gases, it is 5% to 12%.

6 Conclusions

In our analysis, we have shown that the multi-gas approach that is adopted in the Kyoto Protocoal can lead to signficantly lower Annex I emission reduction costs than a strategy that would be based on reducing CO_2 only. When all uncertainties are taken into account, the international permit price can vary between 0 and 50 €/tCeq, while a value between 15 and 40 €/tCeq seems most likely. The main factor influencing this price is the reference emission scenario, which determines the overall emission reduction objective and, together with the relative costs estimates, the total abatement potential. The amount of hot-air banked alters the supply of emission permits on the market and so, also the permit price. Hence, the amount of hot-air banked also influences the overall costs and gains of implementing the Kyoto Protocol. Although overall costs are significantly lower under a multi-gas approach than under a CO_2-only approach, the cost reductions are reduced under an optimal banking strategy due to a much higher banking percentage. Approximately 15% of the emission reduction objective can be met by emission uptake through sinks, while another 15% can be met through the purchase of hot-air (largely dependent on the level of market power that can be exercised by the Ukraine and the Russian Federation).

The lower overall cost is the direct result of including the non-CO_2 Kyoto gases, which significantly increases the relatively cheap abatement potential. The largest number of cheap abatement options are found in the Ukraine and Russian Federation; these transport-related options are mainly associated with CH_4 emissions from natural gas production. Other important sources of reduction are CH_4 emissions from coal production and landfills, and N_2O emissions from adipic and nitric acid production, mainly for the EU-25, Japan and Canada. As the share of non-CO_2 in total reduction potential for the permit supplying region (Ukraine and the Russia Federation and the Annex I countries) is much larger than for the permit demanding regions (EU-25, Canada and Japan), trading results in a shift in the abatement share from CO_2 reductions to non-CO_2. In general, the largest relative reductions from the baseline are expected for CH_4 and the F-gases, while in absolute terms, the largest reduction share is still expected for CO_2 emissions from energy use.

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Appendix A Detailed results

Table A2: Detailed results for the CO_2-only case without optimal banking

	Costs/yr (b€)	Effort (% GDP)
EU-25	6.2	-0.05
Canada	0.9	-0.10
Japan	1.6	-0.02
Ukraine & the Russian Federation	-6.0	0.74
Annex I (excl. USA +Australia)	2.6	-0.01
Non-Annex I	-1.2	0.01

Table 3: Detailed results for the multi-gas case without optimal banking

	Costs/yr (b€)	Effort (% GDP)
EU-25	2.3	-0.02
Canada	0.6	-0.07
Japan	0.7	-0.01
Ukraine & the Russian Federation	-2.7	0.32
Annex I (excl. USA+Australia)	0.9	0.00
Non-Annex I	-0.5	0.00

Table 4: Detailed results for the CO_2-only case with optimal banking

	Costs/yr (b€)	Effort rate (% GDP)
EU-25	9.4	-0.08
Canada	1.4	-0.16
Japan	2.4	-0.04
Ukraine & the Russian Federation	-7.2	0.89
Annex I (excl. USA+Australia)	6.0	-0.02
Non-Annex I	-2.5	0.02

Table 5: Detailed results for the multi-gas case with optimal banking

	Costs/yr (b€)	Effort (% GDP)
EU-25	6.3	-0.05
Canada	1.7	-0.20
Japan	2.1	-0.03
Ukraine & the Russian Federation	-4.2	0.52
Annex I (excl. USA+Australia)	6.0	-0.02
Non-Annex I	-2.8	0.02

Table 6: Baseline emissions and emission reductions for the EU-25 for the multi-gas case with optimal banking

	1990 Emissions	2010 Emissions	Emission growth (1990-2010)	Emission reductions	Reductions compared to 1990	Reductions compared to baseline
	MtCeq	MtCeq	%	MtCeq/yr	%	%
CO_2	**1145**	**1380**	**21%**	**98.2**	**12%**	**-7.1%**
Emissions	1145	1380	21%	86.0	13%	-6.2%
Sinks	--	--	--	12.2	--	--
CH_4	**184**	**172**	**-6%**	**43.5**	**-30%**	**-25.3%**
Coal production	36	28	-24%	18.0	-73%	-64.8%
Oil production	1	1	16%	0.1	2%	-11.8%
Gas production	19	19	2%	3.8	-18%	-20.0%
Landfills	36	44	22%	17.3	-26%	-39.5%
Rice	1	1	33%	0.0	33%	0.0%
Animals	72	68	-5%	3.9	-11%	-5.8%
Animal waste	11	11	-7%	0.3	-10%	-2.7%
Rest	8	1	-91%	--	--	--
N_2O	**141**	**126**	**-11%**	**17.1**	**-23%**	**-13.6%**
Transport	1	3	335%	0.1	324%	-2.5%
Adipic acid prod.	13	3	-76%	2.9	-99%	-96.0%
Nitric acid prod.	19	15	-23%	12.9	-91%	-88.9%
Fertlizer	50	48	-5%	1.1	-7%	-2.3%
Rest	58	57	-1%	--	--	--
F-gases	**20**	**58**	**193%**	**12.1**	**132%**	**-21.0%**
HFC	6	51	737%	10.6	562%	-21.0%
PFC & SF_6	14	7	-49%	1.5	-60%	-21.2%
Total	**1489**	**1736**	**17%**	**170.9**	**5%**	**-9.8%**

Table 7: Emissions and emission reductions for Ukraine and the Russian Federation for the multi-gas case with optimal banking

	1990 Emissions	2010 Emissions	Emission growth (1990-2010)	Emission reductions	Reductions compared to 1990	Reductions compared to baseline
	MtCeq	MtCeq	%	MtCeq/yr	%	%
CO_2	**773**	**587**	**-24%**	**53.8**	**-31%**	**-9.2%**
Emissions	773	587	-24%	20.0	-27%	-3.4%
Sinks	--	--	--	33.8	--	--
CH_4	**245**	**236**	**-4%**	**57.6**	**-27%**	**-24.3%**
Coal production	16	11	-29%	9.5	-89%	-84.8%
Oil production	9	6	-35%	2.0	-56%	-32.1%
Gas production	118	140	19%	38.0	-14%	-27.2%
Landfills	10	15	45%	6.2	-16%	-42.1%
Rice	1	1	-26%	0.0	-26%	0.0%
Animals	44	33	-24%	1.9	-28%	-5.8%
Animal waste	5	4	-26%	0.0	-26%	0.0%
Rest	42	27	-37%	--	--	--
N_2O	**61**	**42**	**-32%**	**0.6**	**-33%**	**-1.5%**
Transport	0	0	-29%	0.0	-32%	-3.0%
Adipic acid prod.	0	0	-26%	0.0	-26%	0.0%
Nitric acid prod.	3	1	-50%	0.0	-50%	0.0%
Fertlizer	28	17	-38%	0.6	-40%	-3.7%
Rest	30	23	-24%	--	--	--
F-gases	**12**	**17**	**41%**	**6.0**	**-8%**	**-34.6%**
HFC	0	6	1525%	2.0	962%	-34.6%
PFC & SF_6	12	12	-4%	4.0	-37%	-34.6%
Total	**1092**	**883**	**-19%**	**118.0**	**-30%**	**-13.4%**

Table 8: Emissions and emission reductions for the world for the multi-gas case with optimal banking

	1990 Emissions MtCeq	2010 Emissions MtCeq	Emission growth (1990-2010) %	Emission reductions MtCeq/yr	Reductions compared to 1990 %	Reductions compared to baseline %
CO_2	**5771**	**8769**	**52%**	**238.0**	**48%**	**-2.7%**
Emissions	5771	8769	52%	162.0	49%	-1.8%
Sinks	--	--	--	107.8	--	--
CH_4	**1893**	**2406**	**27%**	**136.3**	**20%**	**-5.7%**
Coal production	200	199	-1%	36.1	-19%	-18.2%
Oil production	54	77	42%	4.6	34%	-6.0%
Gas production	268	426	59%	49.9	40%	-11.7%
Landfills	156	261	68%	34.9	45%	-13.3%
Rice	197	204	3%	0.9	3%	-0.4%
Animals	518	641	24%	9.5	22%	-1.5%
Animal waste	51	56	9%	0.3	8%	-0.6%
Rest	449	543	21%	--	--	--
N_2O	**907**	**1120**	**24%**	**21.7**	**21%**	**-1.9%**
Transport	9	14	53%	0.1	51%	-0.9%
Adipic acid prod.	30	11	-64%	4.2	-78%	-39.4%
Nitric acid prod.	32	31	-3%	14.2	-47%	-45.3%
Fertlizer	250	336	34%	3.1	33%	-0.9%
Rest	585	728	24%	--	--	--
F-gases	**87**	**233**	**168%**	**28.3**	**135%**	**-12.2%**
HFC	21	162	674%	19.1	582%	-11.8%
PFC & SF_6	66	71	7%	9.2	-7%	-13.0%
Total	**8658**	**12529**	**45%**	**424.3**	**40%**	**-3.4%**

Table 9: Emissions and emission reductions for Canada and Japan for the multi-gas case with optimal banking

	1990 Emissions	2010 Emissions	Emission growth (1990-2010)	Emission reductions	Reductions compared to 1990	Reductions compared to baseline
	MtCeq	MtCeq	%	MtCeq/yr	%	%
CO_2	**404**	**518**	**28%**	**64.1**	**12%**	**-12.4%**
Emissions	404	518	28%	34.1	20%	-6.6%
Sinks	--	--	--	30.0	--	--
CH_4	**42**	**66**	**58%**	**11.9**	**30%**	**-17.9%**
Coal production	3	2	-36%	0.5	-53%	-26.7%
Oil production	1	1	-10%	0.3	-34%	-26.8%
Gas production	10	19	93%	3.4	58%	-18.2%
Landfills	14	19	38%	6.7	-10%	-34.6%
Rice	4	5	19%	0.0	19%	0.0%
Animals	8	9	10%	1.0	-3%	-11.5%
Animal waste	1	2	17%	0.0	17%	0.0%
Rest	1	10	826%	--	--	--
N_2O	**21**	**25**	**22%**	**2.2**	**11%**	**-8.5%**
Transport	1	1	12%	0.0	9%	-2.8%
Adipic acid prod.	4	1	-77%	0.9	-99%	-96.0%
Nitric acid prod.	1	1	-21%	0.9	-91%	-88.9%
Fertlizer	7	11	60%	0.3	55%	-2.8%
Rest	7	11	53%	--	--	--
F-gases	**13**	**24**	**94%**	**7.4**	**35%**	**-30.5%**
HFC	3	17	396%	5.0	247%	-30.1%
PFC & SF_6	9	8	-17%	2.4	-43%	-31.4%
Total	479	634	32%	85.6	14%	-13.5%

Table 10: Emissions and emission reductions for the non-Annex I regions for the multi-gas case with optimal banking

	1990 Emissions	2010 Emissions	Emission growth (1990-2010)	Emission reductions	Reductions compared to 1990	Reductions compared to baseline
	MtCeq	MtCeq	%	MtCeq/yr	%	%
CO_2	**2051**	**4398**	**114%**	**21.9**	**113%**	**-0.5%**
Emissions	2051	4398	114%	21.9	113%	-0.5%
Sinks	--	--	--	31.7	--	--
CH_4	**1125**	**1635**	**45%**	**23.3**	**43%**	**-1.4%**
Coal production	83	98	18%	8.1	8%	-8.3%
Oil production	34	63	85%	2.2	78%	-3.5%
Gas production	66	185	178%	4.7	171%	-2.5%
Landfills	27	103	274%	4.7	257%	-4.6%
Rice	189	195	3%	0.9	3%	-0.5%
Animals	324	460	42%	2.7	41%	-0.6%
Animal waste	22	28	27%	0.1	27%	-0.2%
Rest	378	502	33%	--	--	--
N_2O	**534**	**758**	**42%**	**1.8**	**41%**	**-0.2%**
Transport	1	2	133%	0.0	133%	-0.3%
Adipic acid prod.	2	4	147%	0.4	125%	-8.9%
Nitric acid prod.	4	10	136%	0.4	126%	-4.4%
Fertlizer	134	215	61%	1.0	60%	-0.5%
Rest	394	527	34%	--	--	--
F-gases	**14**	**69**	**406%**	**2.8**	**386%**	**-4.0%**
HFC	1	36	5474%	1.4	5251%	-4.0%
PFC & SF_6	13	33	154%	1.3	144%	-4.0%
Total	3724	6860	84%	49.8	83%	-0.7%