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What are the Gains from a Multi-Gas Strategy?

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SUMMARY

The Kyoto Protocol assigns limits for the aggregate emissions of six greenhouse gases, but most economic analyses focus on CO2 abatement. What are the potential gains if policy makers exploit the flexibility in a multi-gas abatement strategy? We extend the EDGE model to include sinks and non-CO2 gases and show that a multi-gas strategy reduces costs by 20-35% in the Western Annex B countries. Marginal abatement costs decrease around 30%, and the cost-effective abatement mix involves relatively more abatement of the non-CO2 gases, which offers many low costs abatement options. Lower marginal abatement costs decrease domestic action by reducing the costs of emissions imports, whereas more low cost abatement options increases domestic action. The low cost abatement options increase domestic action, whereas lower marginal abatement costs reduces domestic action by making imports of emissions cheaper. The net effect of a multi-gas strategy on domestic action is therefore not given a priori. We show that a multi-gas strategy reduces domestic action around 2% in the United States and increases domestic action by around 8% in the European Union. Our sensitivity analyses finally show that the relatively weak growth in non-CO2 baseline emissions accounts for a large share of the savings associated with a multi-gas strategy.

CONTENTS

1. Introduction

The Kyoto Protocol assigns emissions limits to all countries listed in Annex B to the protocol. The limits apply to the ***aggregate*** emissions of six greenhouse gases and this give each country the flexibility to individually control the emissions of each gas. Most of the existing economic analyses of the Kyoto Protocol focus exclusively on controlling the most important gas, CO_2, but our analysis shows that a multi-gas control strategy may lower costs significantly.

Specifically, most of the existing analyses ignore the effects of abatement of the five non-CO_2 greenhouse gases included in the Kyoto Protocol: CH_4, N_2O, HFCs, PFCs and SF_6.[1] This naturally raises the question: What are the effects on costs and abatement if policy makers exploit the multi-gas flexibility in the Kyoto protocol?

We address this question by extending the EDGE model (Jensen ***et al.*** [2000a]) to include emissions data and abatement options for the five non-CO_2 gases. We assume unlimited trading among all Annex B countries with emissions of all six gases and our results focus on some of the key concerns to policy makers when designing climate policies: Marginal costs, welfare costs, domestic action, and the abatement mix of the six gases.

Our preliminary results suggest that a multi-gas strategy reduces costs significantly. Marginal abatement costs decrease around 30%, when replacing a strategy of controlling CO_2 only with a multi-gas strategy. Welfare costs in the Western Annex B countries decrease 20-35%, whereas the countries in the Former Soviet Union and Eastern Europe experience a loss in welfare of almost 40% due to lower revenues from emissions exports.

In most regions, non-CO_2 emissions account for less than 20% of total greenhouse gas emissions in 2010, but the non-CO_2 emissions offer many low cost abatement options. The non-CO_2 gases therefore account for a relatively larger share in a cost-effective abatement mix.

We also analyse the consequences for domestic action, which we define as the share of domestic abatement divided by total abatement, where the latter equals the difference between the (hypothetic) baseline emissions and the Kyoto commitment. More low cost abatement options tend to increase domestic action, whereas lower marginal abatement costs reduces domestic action by making imports of emissions cheaper. The net effect of a multi-gas strategy on domestic action is therefore not given a priori. Our results show that domestic action increases slightly in all Western Annex B regions, except in the United States where domestic action decreases as higher imports of emissions dominate the effects of domestic non-CO_2 abatement.

Our results are generally consistent with the few existing analyses of multi-gas abatement. Burniaux [2000] and Manne and Richels [2000] extend the GREEN and the MERGE models, respectively, to cover CO_2, CH_4 and N_2O, but both models ignore the other three gases. Their analyses apply different aggregate emissions targets when comparing the

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[1] See for example the multi-model evaluation in Weyant [1999].

multi-gas strategy with the strategy of controlling CO_2 only; that is, the two strategies do not imply the same environmental improvement. Reilly ***et al.*** [1999] extend the MIT-EPPA model to include CO_2 sinks and all six greenhouse gases. Their analyses apply identical emissions targets, which make their results comparable to ours, but they do not analyse the potential gains from international trade with emissions in the case of multi-gas abatement.

We extend this literature in several respects. First, our comparison of a multi-gas strategy with a single-gas (CO_2) strategy applies identical emissions targets ***and*** assumes unlimited emissions trading among the Annex B countries. Second, we review the literature on the costs of abating the five non-CO_2 gases and estimate continuous marginal abatement cost curves for use in the analyses. Third, we include sensitivity analyses of some of the key assumptions regarding non-CO_2 abatement. These analyses have been motivated by some of the uncertainties surrounding the limited data on non-CO_2 emissions, and similar analyses are only available in Reilly ***et al.*** [1999]. Finally, our results include the effects on domestic action, which have not been reported by any of the existing analyses.

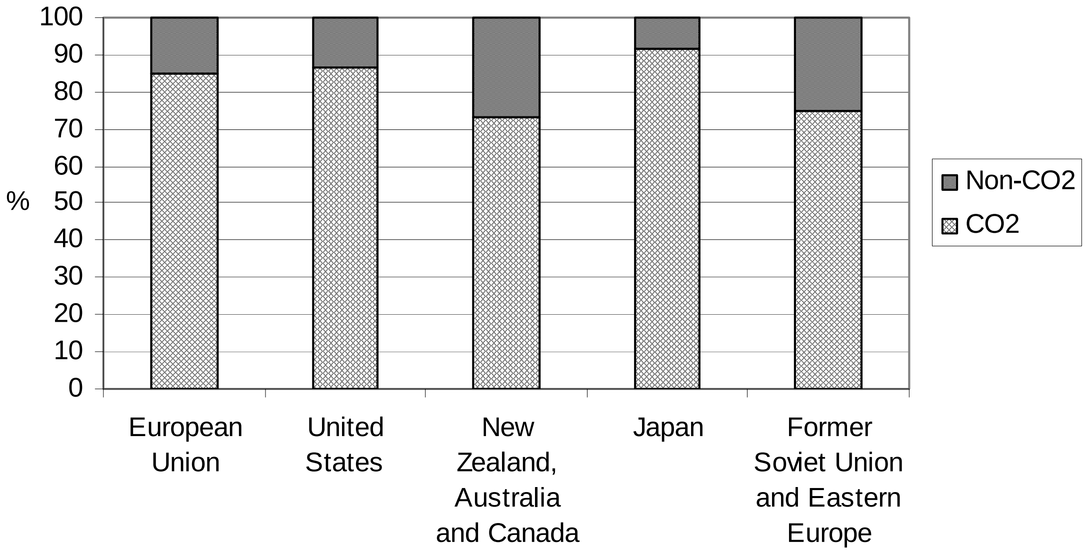
The next section gives an overview of sinks and abatement of non-CO_2 gases, and this provides the background for our analysis of a multi-gas control strategy. Section 3 then introduces the EDGE model and outlines the extensions necessary for multi-gas analysis. Section 4 defines the policy scenarios and section 5 discusses the numerical results. Section 6 presents the sensitivity analyses and the last section summarizes the main findings and discusses natural extensions of the analysis.

2. Economic analysis of multi-gas abatement and sinks

Most of the existing economic analyses of the Kyoto Protocol focus exclusively on abatement of energy related CO_2 emissions. This has been a natural first step given the wide availability of energy data and the long experience with energy modelling, for example for planning purposes. Furthermore, this approach covers the quantitatively most important of the six greenhouse gases included in the Kyoto Protocol (illustrated in Figure 1).

The following sections present the first steps towards incorporating sinks and non-CO_2 emissions. Specifically, we provide an overview of the main sources of emissions of non-CO_2 gases, the abatement requirements, and the most important abatement options. We also discuss issues related to CO_2 sinks, including the modelling challenges the sinks involve.

Figure 1. Greenhouse gas emissions (excluding sinks), 2010.



Emissions of non-CO_2 greenhouse gases

The greenhouse gases covered by the Kyoto Protocol are listed in Table 1 along with the main sources of emissions. The agricultural sector accounts for many of the emissions of CH_4 and N_2O, but waste (for example landfills) and energy supply (for example coal mining) also contribute significantly. HFCs, PFCs and SF_6 are also known both as the industrial greenhouse gases because of their origin, and as the HGWP gases because of their high global warming potentials.

Table 1. Main emission sources for greenhouse gases.

Greenhouse gas	Global Warming Potential[a]	Main emissions sources
CO_2	1	Combustion of fossil fuels (coal, oil, and gas)
CH_4	21	Livestock, rice, natural gas, waste and coal
N_2O	310	Agricultural soils, fertiliser, livestock, industrial production
HFCs[b]	140-11700	Air conditioning and foam blowing
PFCs[b]	6200-9200	Aluminium and semiconductors
SF_6	23900	Magnesium, semiconductors and electrical switchgear.

[a] 100 year GWP.

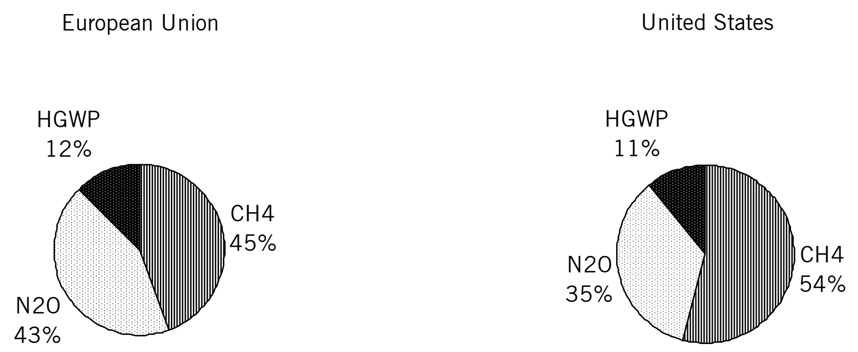
[b] Includes several different gases.

The gases have different impacts on the climate as well as different lifetimes in the atmosphere, and they are therefore not directly comparable on a tonne-for-tonne basis. Since the limits for emissions in the Kyoto Protocol apply to aggregate emissions of the six greenhouse gases, we need a method to establish equivalency in terms of climate effects in order to compare reductions in emissions of the different gases.

We follow the Kyoto Protocol and use 100-years global warming potentials to convert all emissions into carbon equivalents (CE). This method supposedly establishes equivalency in terms of climate effects over a time horizon of 100 years, but it has been subject to a number of criticisms.[2] In particular, the choice of a 100 year horizon is arbitrary, as a shorter (longer) horizon would imply higher (lower) global warming potentials for the shorter lived gases (for example CH_4).

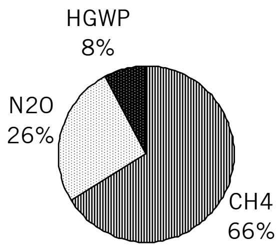
The quantitative importance of each gas varies by country, but in most countries CH_4 and N_2O emissions account for most of the non-CO_2 emissions (Figure 2). The three industry gases, HFCs, PFCs, and SF_6, currently have little importance, except in Japan, but their high global warming potentials imply that even small changes in emissions may have large climate effects.

Figure 2. Distribution of non-CO_2 emissions, 2010.

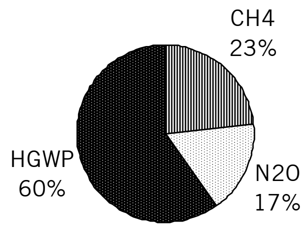


[2] See Reilly *et al.* [1999] and Manne and Richels [2000] for economic analyses of alternative methods.

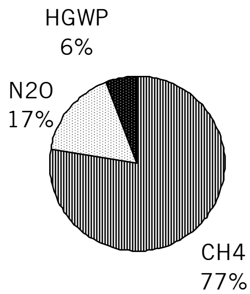
New Zealand, Australia and Canada



Japan

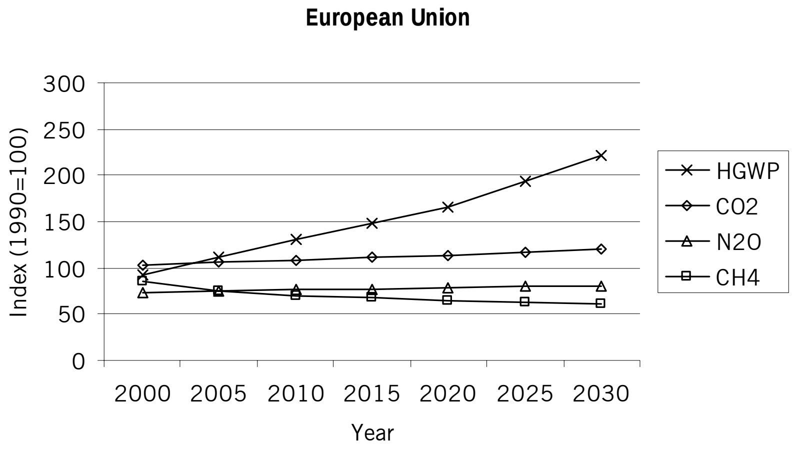


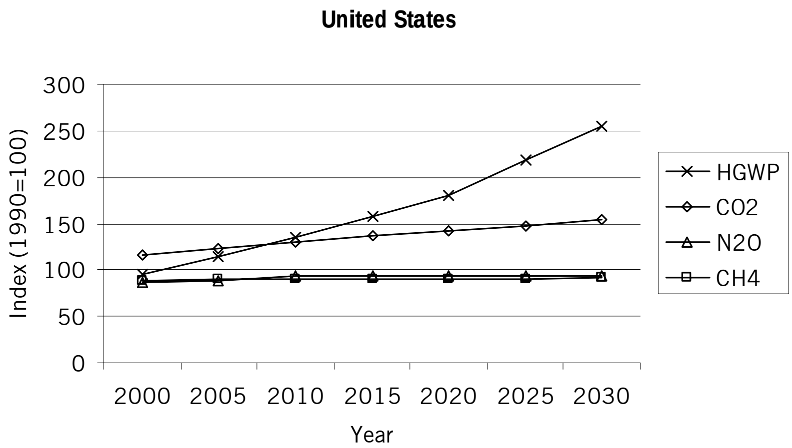
Former Soviet Union and Eastern Europe

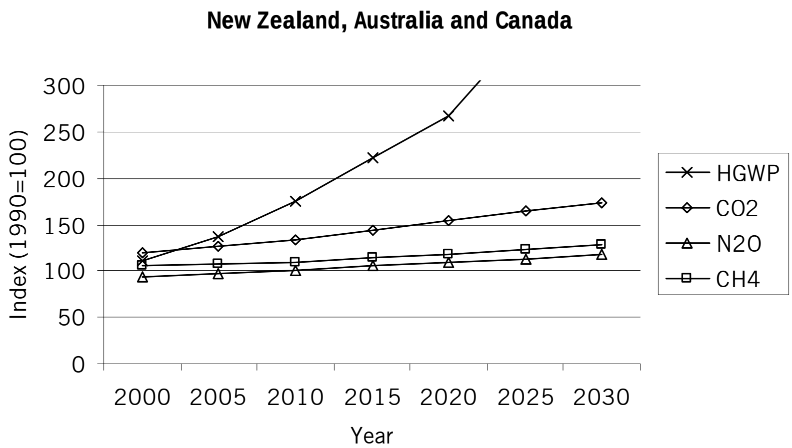


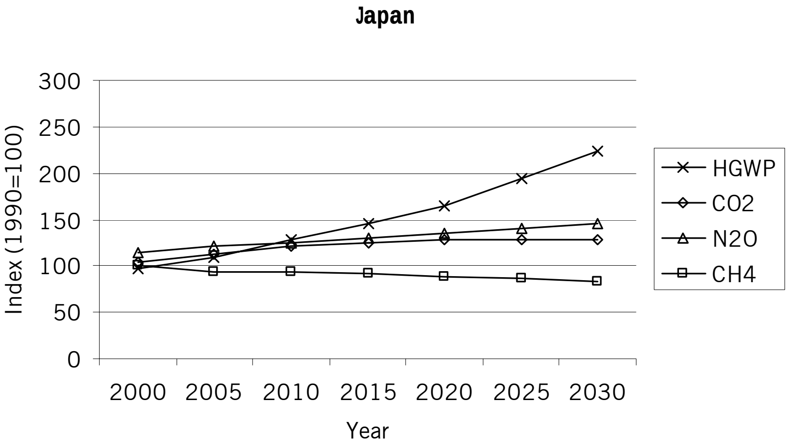
In most countries, economic growth is the key driver for CO_2 emissions. Expectations about future economic growth imply that energy outlooks typically expect CO_2 emissions in 2010 to exceed 1990 emissions by 10-30% in most Western Annex B countries (see Figure 3). In several countries undergoing transition to a market economy, the Kyoto commitments are expected to exceed emissions in 2008-2012. This difference, also known as Hot Air, can then be traded with other Annex B countries along with other "real" emissions reductions.

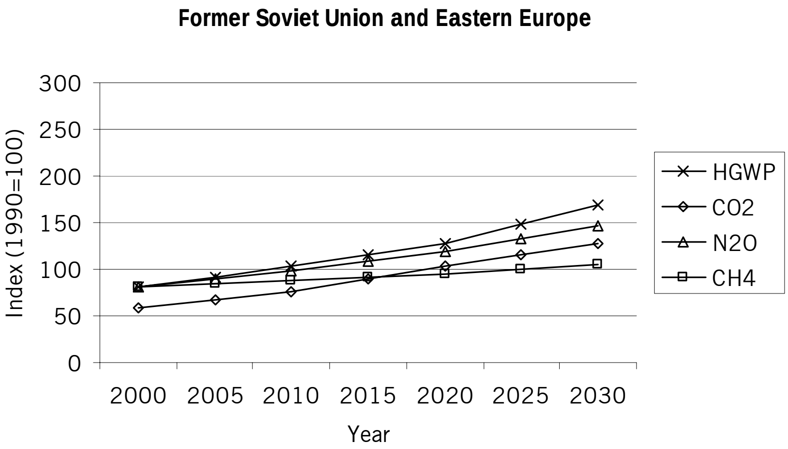
Figure 3. Baseline emissions of greenhouse gases











The international energy outlooks are typically based on global models of energy demand and supply.[3] This ensures some consistency in the outlooks across countries, for example with respect to international energy markets and methods for emissions accounting.

International outlooks with similar consistency are not available for non-CO_2 greenhouse gas emissions. We have therefore compiled a database with baseline non-CO_2 emissions based on the Annex B countries' ***individual*** communications to the UNFCCC.[4] The communications are not necessarily mutually consistent and in many cases, they furthermore include the anticipated effects of ***proposed*** policies. This makes it hard to identify a relevant baseline, i.e., the expected future emissions with no changes in ***current*** policies.

We therefore caution a too literal interpretation of the baseline emissions of non-CO_2 gases in Figure 3. The weak growth in most of the non-CO_2 emissions are consistent with Burniaux [2000], who also uses UNFCCC data to construct baseline emissions paths, but

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[3] See for example European Commission [1999] and Energy Information Administration [1999].

[4] See the appendix for further details on the data sources and the methods we employ.

different from Reilly ***et al.*** [2000], who report significant increases in most regions' emissions (also in Eastern Europe and the Former Soviet Union).[5]

Economic growth is one of the key drivers for the emissions increases in Reilly ***et al.*** [2000]. In our sensitivity analysis reported below, we adopt a similar assumption to illustrate the sensitivity with respect to the choice of baseline.

Abatement of emissions of non-CO_2 greenhouse gases

The key to lower emissions of CO_2 is reduced combustion of fossil fuels. In contrast, lower activity (use) is only one option with respect to emissions of non-CO_2 gases. For example, emissions of CH_4 from landfills can be combusted and provide energy, and the emissions of the HGWP industrial greenhouse gases can be recovered and recycled.

There typically exists a range of alternative abatement technologies for each source of non-CO_2 emissions, and a quickly growing literature analyses the potential emissions reductions and the associated costs and benefits. The studies typically summarize their results in a list, which shows estimates of costs for different levels of abatement. These estimates are effectively points on marginal abatement cost curves, which order the options for abating emissions from lowest cost to highest cost.

Using these points as inputs, we estimate continuous functional forms to incorporate the marginal abatement cost curves in the model. For CH_4 and HGWP, the functional form is

$$P = a + \frac{b}{Max - X}$$

where P is the marginal abatement costs in 95$/tCE, a, b, and Max are parameters and X is the percentage reduction in the country's emissions. Max can be interpreted as the maximum potential reduction. AEA [1998] and EPA [1999] list data for CH_4 for the European Union and the United States, respectively, and the data for the HGWP is listed in Harnisch and Hendriks [2000] for the European Union and EPA [2000] for the United States.

For N_2O, we use estimates from Burniaux [2000] based on

$$X = Max - Max * e^{c*P}$$

In this case, c and Max are parameters and P and X are as above. Table 2 summarizes the estimation results.

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[5] The baseline data reported in Manne and Richels [2000] do not make comparisons possible.

Table 2. Analyses of potential reductions in non-CO_2 emissions

Region	CH_4	N_2O [a]	HGWP
European Union	*a* =-104.25 *b* =32.206 *Max* =0.43	*c* =-0.01 *Max*=0.26	*a* =-50.203 *b* =37.859 *Max* =0.816
United States	*a* =-20.674 *b* =5.035 *Max* =0.4435	*c* =-0.01 *Max* =0.26	*a* =-6.7101 *b* =3.1205 *Max* =0.6522

[a] Estimation results from Burniaux [2000].

All the studies of CH_4 and N_2O abatement report "free" reductions, i.e., reductions with zero or negative costs. In the European Union, the "free" reductions amount to 40 $MtCO_2$ in 2010 or around 6% of total non-CO_2 emissions. In the United States, the corresponding figures are 139 $MtCO_2$ and 13%.

As noted above, the UNFCCC baselines often include the anticipated effects of ***proposed*** abatement policies. To minimize double counting of reductions, we therefore include the "free" reductions in the baseline in our policy analysis. This is an important assumption; the amount of "free" reductions is substantial and we illustrate the consequences in our sensitivity analysis reported below.

We have only found studies of the costs of non-CO_2 abatement for the European Union and the United States. We therefore make the simplifying assumption that all other regions have marginal abatement cost curves similar to the curves for the European Union. That is, the same percentage reduction in emissions has the same marginal costs in all Annex B countries, except the United States.

Figure 4 and Figure 5 compare marginal abatement costs across gases and across regions. We constructed the figures by first reducing CO_2 emissions in each region in steps of 1%-points from 1% to 20%.

Figure 4 shows that Japan and the European Union has the highest marginal abatement costs for CO_2 emissions, and that the Former Soviet Union and Eastern Europe has the lowest.

We then used the marginal abatement costs for CO_2 to calculate reductions in non-CO_2 emissions using our estimated marginal abatement cost curves. Figure 4 summarizes the costs all non-CO_2 gases and the Figure shows that the non-CO_2 gases offer a significant amount low costs abatement options.

Figure 5 finally shows the marginal abatement costs curves for the individual non-CO_2 gases. CH_4 dominates the abatement opportunities in the regions including the United States, New Zealand, Australia, Canada, the Former Soviet Union and Eastern Europe. The HGWPs dominate in Japan, following the large share of HGWPs in total non-CO_2 emissions, and in the European Union, the three types of gases offer an equal amount of abatement options.

Figure 4. Marginal abatement costs

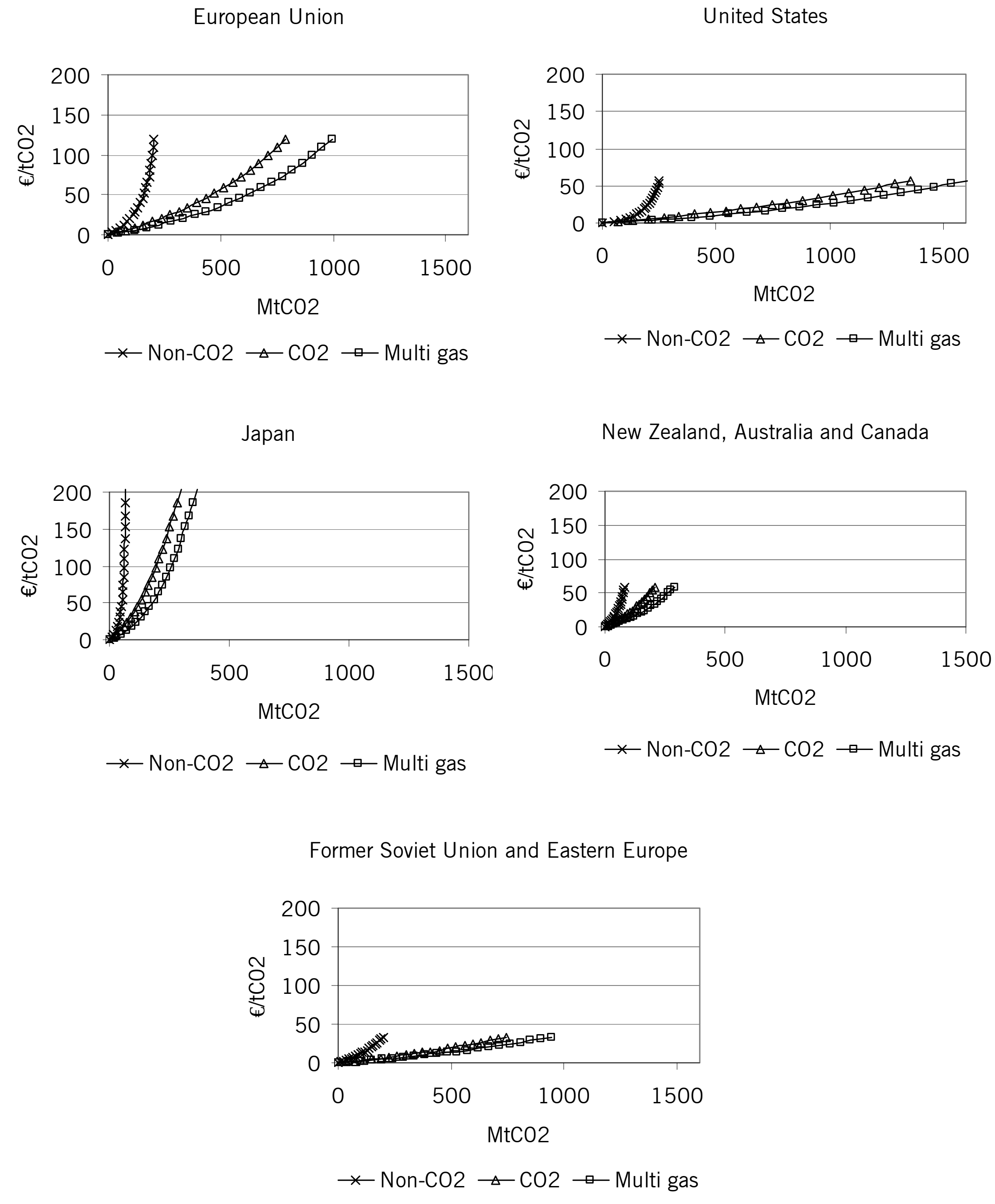
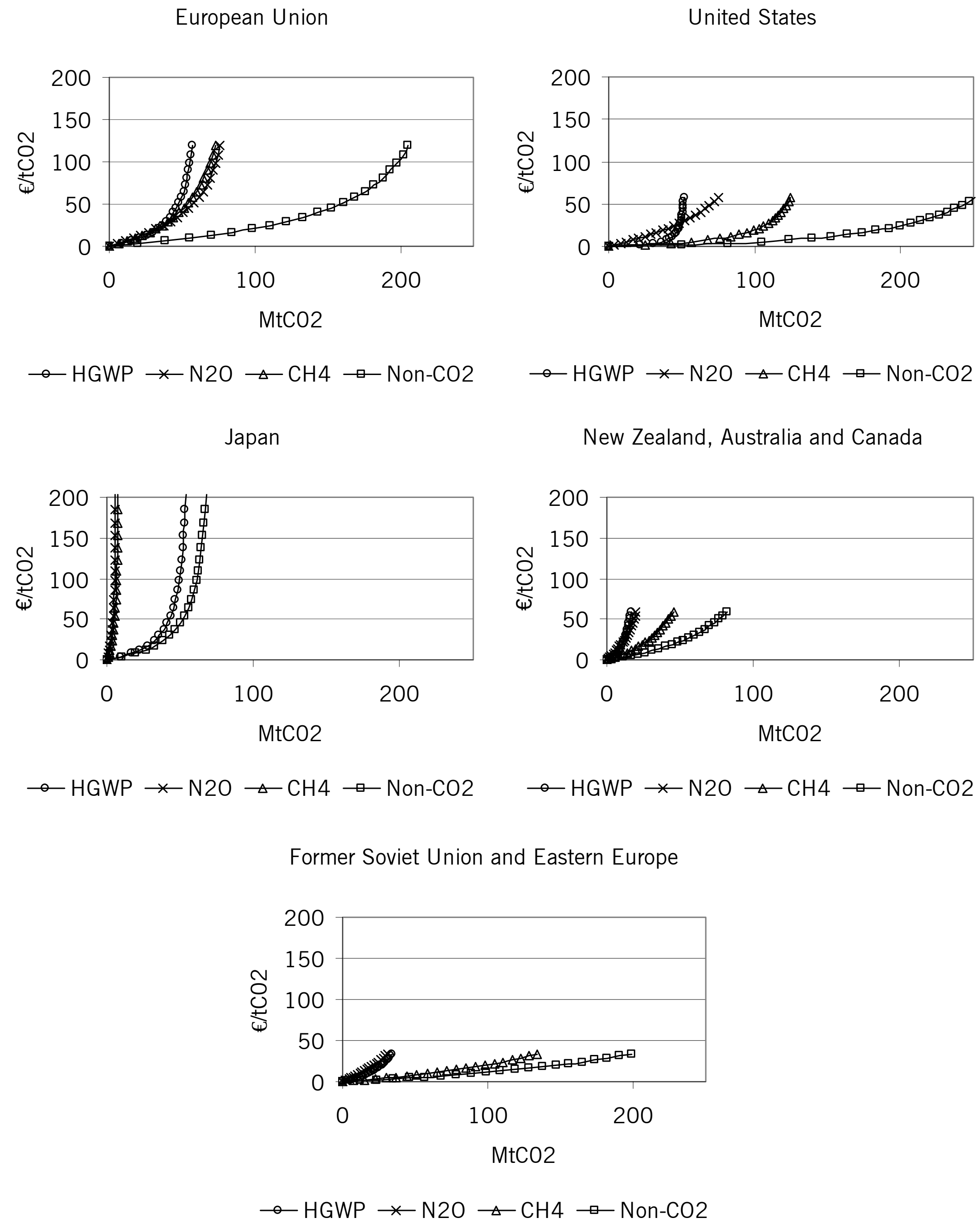


Figure 5. Marginal abatement costs for non-CO_2 gases



Sinks

The Kyoto Protocol allows net removals of greenhouse gases from land-use and forestry activities (hereafter referred to as sinks) to be counted towards the emissions limits. Several problems complicate the economic analysis of sinks.

First, it has been particularly difficult to reach agreement on the exact definitions of sinks as witnessed by the COP6 negotiations in November 2000. For example, what constitutes land management (including forest management) and how should the uncertainties related to emissions accounting be handled?

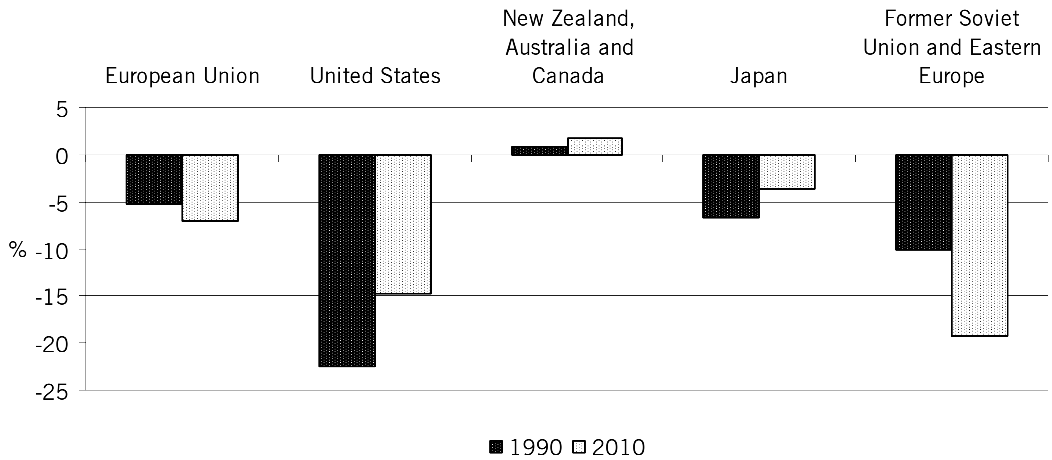
Second, we know very little about the costs of sinks projects. For example, what are the marginal costs per ton of removed CO_2 of converting agricultural land to a forest?

Finally, the removal of CO_2 by most forestry activities occurs over long periods and therefore requires discounting of both net removals of CO_2 and net revenues. To illustrate, plantation of a periodically harvested forest involves a cycle of both removal of CO_2 through the growth of the trees, the forest floor and soil, and release of CO_2 through material decay, harvesting, processing and manufacturing. Furthermore, the economics of forest plantation also depend on the opportunity costs of growing agricultural products and the value of harvested trees in a distant future.[6]

As a first step towards incorporating sinks, we therefore only incorporate baseline CO_2 removals and emissions from land use change and forestry using the Annex B countries' communications to the UNFCCC. We ignore any additional sinks projects.

Figure 6 illustrates the importance of sinks. Australia and the United Kingdom both have net emissions from sinks in 1990, but in all other countries, sinks reduce total emissions. Sinks are both absolutely and relatively most important in the United States, but sinks also make a large difference in Eastern Europe and the Former Soviet Union.

Figure 6. Sinks (share of total emissions including sinks).



[6] Stavins [1999] discusses these points and develops a methodological framework for estimating the marginal costs of CO_2 removal from land use, but his calculations are only illustrative.

3. The EDGE model

To analyse the economics of a multi-gas strategy towards the Kyoto commitments, we extend the EDGE model to incorporate removal of CO_2 via sinks and abatement of the five non-CO_2 gases. The model is an extension of Jensen ***et al.*** [2000a], which analyses the consequences of ceilings on international trade with emissions rights.

In the following, we outline the extensions necessary for multi-gas analysis. We refer the interested reader to Jensen ***et al.*** [2000a] for a non-technical summary of the model, and Jensen ***et al.*** [2000b] for a technical summary of the model.

Modelling greenhouse gas abatement

Abatement of CO_2 emissions effectively reduces to lower use of fossil fuels. Specifically, abatement may happen in the model through the following types of substitution: between the individual fossil fuels, between fossil fuels and non-fossil goods and services, and between non-fossil goods and services.

We model CO_2 abatement via a scheme for tradable emissions rights. All combustion of fossil fuels requires emissions rights according to the embodied CO_2 in the fuel. The government in each region sets the emissions limit, and firms and households can trade emissions rights on a perfectly competitive market.

In addition to lower use, abatement of non-CO_2 emissions also include options to recover gases, for example use recovered CH_4 from landfills to provide energy, and options to recycle gases. Including non-CO_2 abatement also raises the issue of interaction between abatement of the different gases. For example, lower use of coal may not only reduce CO_2 emissions but also reduce CH_4 emissions via lower mining activity.

Following Reilly ***et al.*** [2000] we ignore the interaction effect and focus on options for lower use, recovery and recycling. This allows us to employ directly our estimated marginal abatement cost curves and let the emissions be tradable on the market for CO_2 emissions.

4. Scenarios

All our scenarios share a number of common features. First, all countries and regions in the model have cost-effective national emissions trading. No transactions costs apply to any trade with emissions, and all markets for emissions rights are perfectly competitive.

Second, the scenarios reach the Kyoto emissions limits and imply the same absolute reduction in carbon-equivalent emissions (the same climate change effect). In other words, the scenarios provide the same public good, and we can therefore compare the scenarios without evaluating the costs and benefits of climate change.

Third, all emissions rights in a given country, corresponding to the country's Kyoto commitment, are grandfathered to the representative agent.[7] We therefore ignore any revenue recycling effects, for example if the government auctions the emissions rights and uses the revenue to reduce distortionary labour income taxes.[8]

Fourth, we assume Kyoto-forever. That is, the Kyoto commitments also apply in all commitment periods after 2012. This is important even if we are only interested in the results for 2008-2012, as the decisions of forward-looking agents in 2008-2012 also depend on the policies after 2012. The assumption is a convenient, but arbitrary point of departure, and we appreciate that the concentrations of greenhouse gases in the atmosphere will grow considerably under this assumption.

Fifth, we assume unlimited trade with emissions trading among the Annex B countries, including unlimited trade with hot air. We do not consider transfers of emissions via the Clean Development Mechanism.

Finally, we calibrate autonomous energy efficiency improvements and other technological changes to match the changes in baseline emissions and GDP. These changes are exogenous in the policy scenarios.[9]

Policy scenarios

We use acronyms to label the scenarios to facilitate the presentation of the results. The scenario **SingleGas** assumes control of CO_2 emissions only and no abatement of the non-CO_2 gases. This scenario corresponds to the least cost strategy across all sources of CO_2 emissions to reach the Kyoto emissions limits.

Policy makers can alternatively adopt a multi-gas strategy, which implies control of all emissions. We label this scenario **MultiGas**, and this scenario corresponds to the least cost strategy across all sources of emissions of all six greenhouse gases to reach the Kyoto emissions limits.

Both the scenarios **SingleGas** and **MultiGas** reach the same multi-gas target for aggregate carbon-equivalent emissions of all gases and both scenario include the same change in sinks. Figure 7 shows the percentage reduction requirements from the baseline emissions in 2010 necessary to reach the emissions limits in the Kyoto Protocol. Weak growth in baseline emissions implies a relatively low reduction requirement for the European Union. The emissions limits exceed the baseline emissions in the Former Soviet Union and Eastern Europe, and this region therefore has excess emissions (Hot Air).

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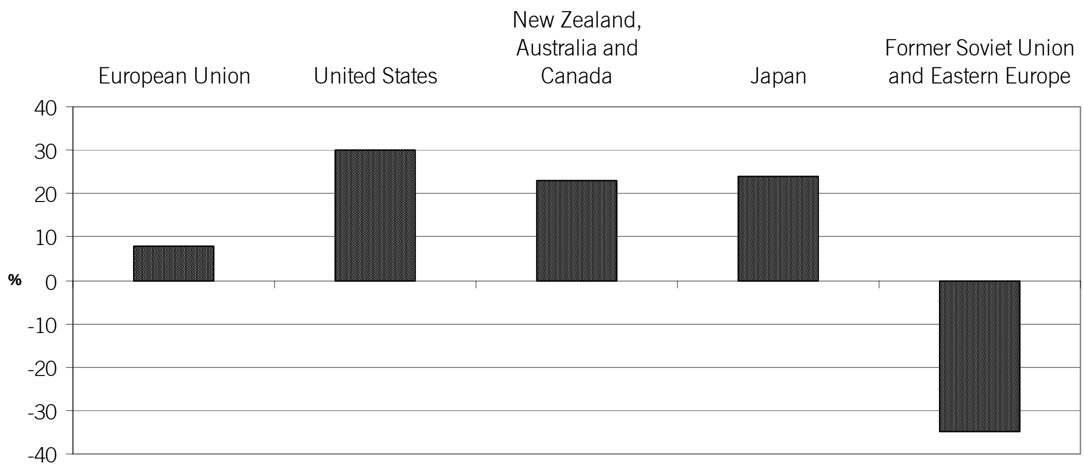
[7] See Jensen and Rasmussen [2000] for an analysis of alternative allocation rules and their distributive effects.
[8] Goulder [1995] provides an introduction to the "Double Dividend" literature.
[9] See Goulder and Schneider [1999] and Goulder and Mathai [2000] for analyses of technological change induced by climate policies.

Figure 7. Required reduction in emissions, 2010



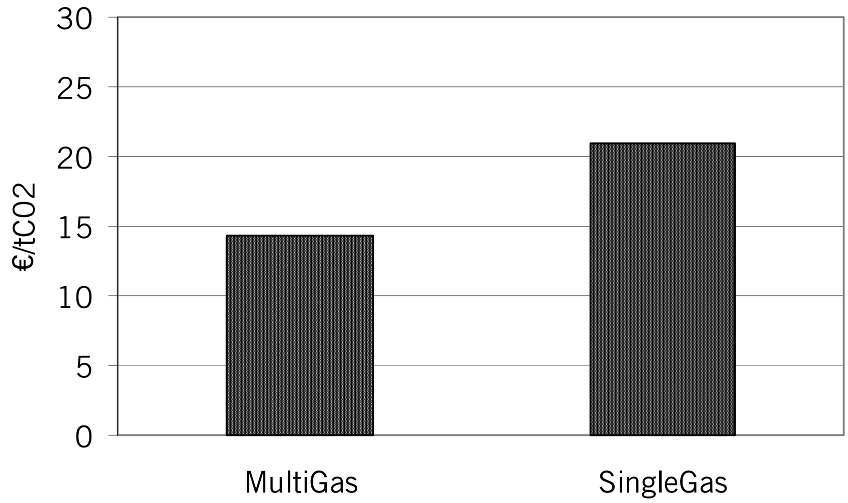
5. Results

The next sections present the numerical results from the analysis of the scenarios in the EDGE model. In all scenarios, we report marginal abatement costs, welfare costs, domestic action, and we furthermore decompose domestic action into CO_2 and non-CO_2 abatement. All economic results are reported in €2000. Our database is denominated in US$1995, and we assume that 1 US$1995 = 1.30 €1995, and that inflation implies that 1 €1995 = 1.11 €2000. Thus, 1 US$1995 = 1.44 €2000.

Economic results

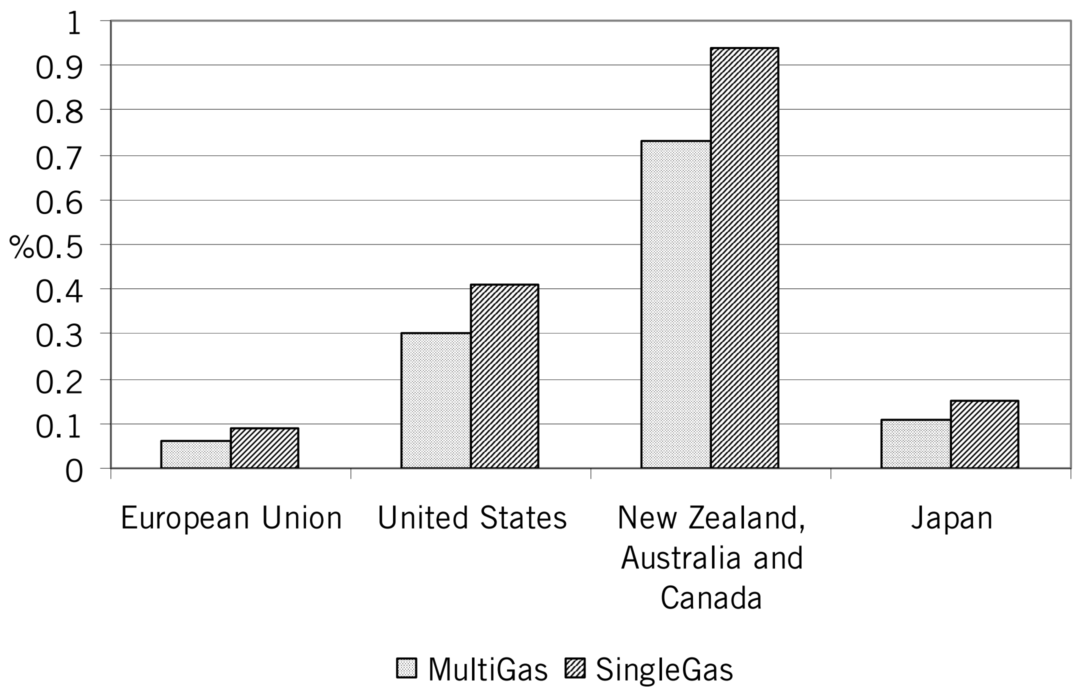
The marginal abatement costs in Figure 8 summarizes the economic impacts of the scenarios. A multi-gas control strategy lowers costs from 21 €/tCO_2 to 14 €/tCO_2 (or around 30%) when compared with a single-gas (CO_2) control strategy. Intuitively, non-CO_2 emissions offer many low cost opportunities, which can replace some of the high cost CO_2 abatement options.

Figure 8. Marginal abatement costs, 2010



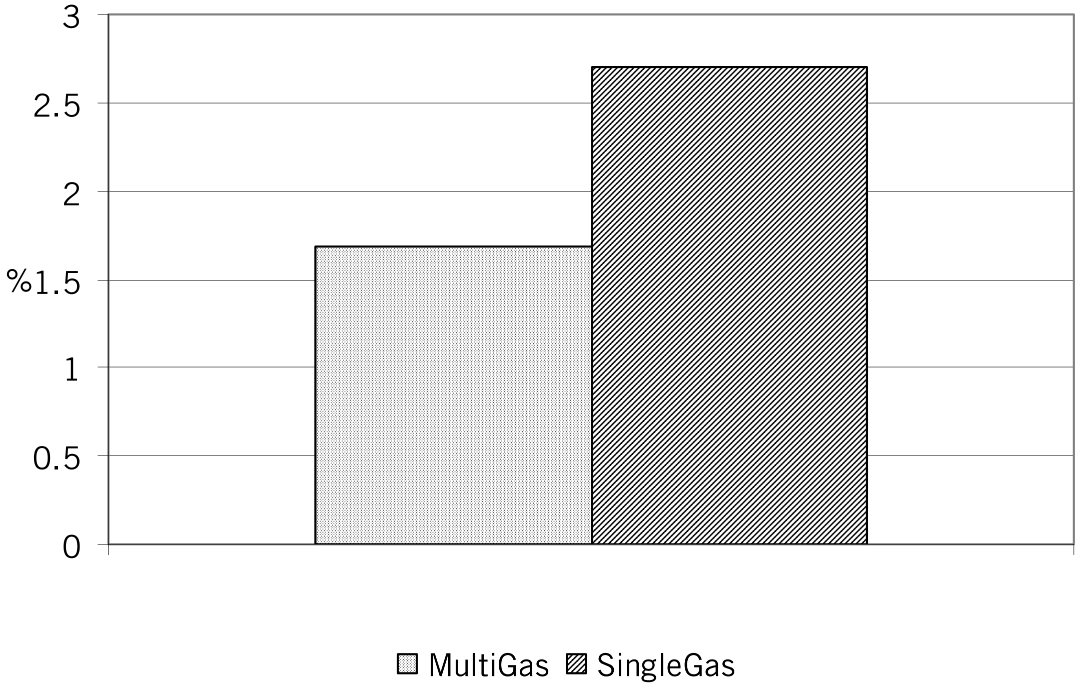
The reduction in marginal abatement costs reduces the welfare costs of the Kyoto Protocol in all Western Annex B countries (see Figure 9). The reductions in costs vary between 20% and 35%.

Figure 9. Welfare costs of the Kyoto Protocol



Exports of emissions, including Hot Air, are a major source of income for the Former Soviet Union and Eastern Europe. The reduction in the marginal abatement costs therefore reduces this region's welfare gain by almost 40% (see Figure 10).

Figure 10. Welfare gain in the Former Soviet Union and Eastern Europe

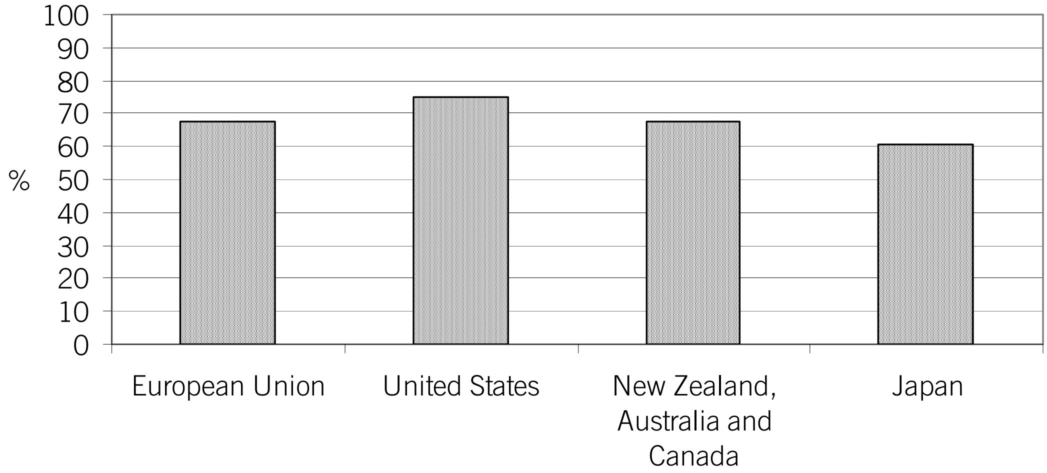


Environmental results

Abatement of CO_2 emissions will account for between 60% and 75% of the abatement in a multi-gas control strategy (see Figure 11). The large share is intuitive given CO_2's large share in total emissions. Nevertheless, in all regions, the share is smaller than the share of CO_2 emissions in total emissions as it is cost-effective to abate a relatively higher percentage of the non-CO_2 emissions.

The distribution of the reductions in non-CO_2 emissions follows the marginal abatement cost curves in Figure 5. That is, CH_4, N_2O, and the HGWP roughly account for one-third of total non-CO_2 abatement in the European Union, and in all other regions, except Japan, CH_4, also account for the majority of the reductions.

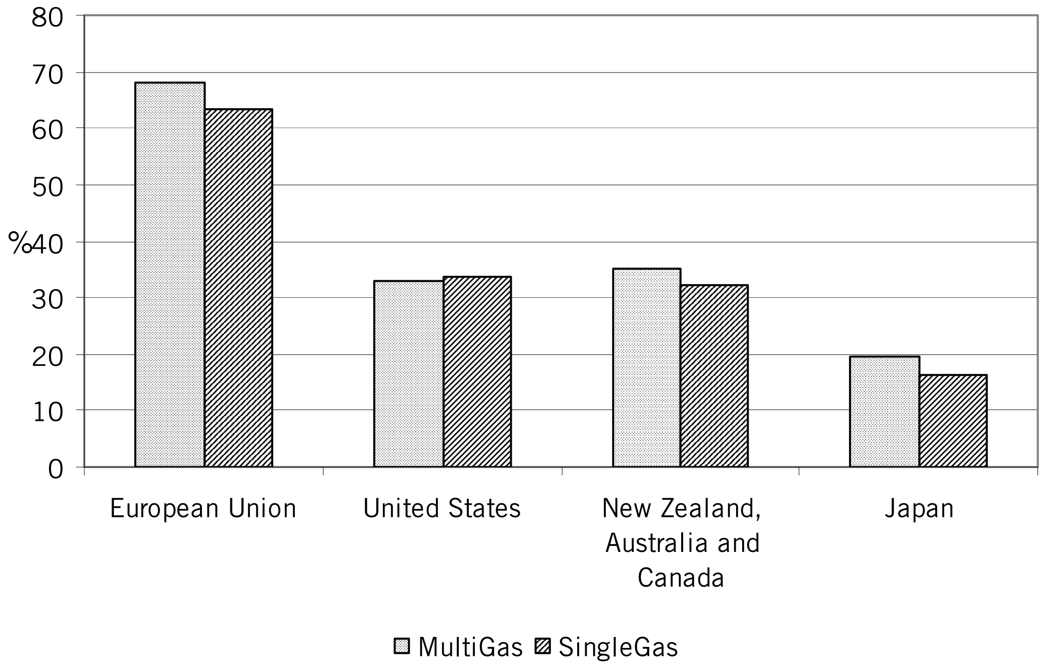
Figure 11. Share of CO_2 abatement in total domestic abatement, 2010



Finally, we report results for domestic action.[10] A multi-gas strategy increases domestic action slightly in most regions; lower marginal abatement costs increases imports of emissions rights and therefore lower domestic action, but more low cost abatement options increase domestic action and dominate the effect of cheaper emissions imports (see Figure 12). Domestic action decreases slightly in the United States, where the effects of cheaper emissions imports dominate.

[10] A set of current and prospective European Union member states underlined their concern for domestic action by proposing guidelines with concrete ceilings on emissions trading in 1999 (see Submission [1999]). See Ellerman and Wing [2000] and Jensen *et al.* [2000a] for analyses of the proposal.

Figure 12. Domestic action, 2010



6. Sensitivity analysis

How sensitive are the results to the assumptions we have made to extend the EDGE model to include sinks and non-CO_2 emissions? We address this question by analysing a second set of scenarios, which partly has been motivated by some of the uncertainties surrounding the limited data on sinks and non-CO_2 emissions.

Scenarios

First, we define the scenario **OnlyCO_2**, which assumes control of CO_2 emissions only and ignores both sinks and non-CO_2 emissions in setting the limits for emissions. This scenario shows the effects of all of the extensions of the model, and it also allows us to compare the EDGE model with most of the existing literature

The scenario **Growth** assumes that non-CO_2 emissions grow with the same percentage as CO_2 emissions in each region. This scenario illustrates the consequences of the generally optimistic baselines for future non-CO_2 emissions reported by the Annex B governments to the UNFCCC.

The scenario **NoRegrets** differs from the **MultiGas** scenario by including the "free" non-CO_2 abatement options in the analysis. That is, these options will be used as a response to the Kyoto requirements.

Finally, we define the scenario **FixedSinks**, which includes sinks in 1990 in setting the target (similar to the other scenarios) but ignores any subsequent removals or emissions of CO_2 from land use change and forestry. In other words, this scenario illustrates the importance of the changes in sinks embodied in the baselines.

Table 3 summarizes the scenarios in terms of emissions and Figure 13 shows the corresponding reduction requirements. The scenarios **MultiGas**, **SingleGas**, and **NoRegrets** imply the same baseline emissions and reduction requirements by definition, as they only differ by the available abatement options. Table 3 also shows that the scenario **OnlyCO2** does not provide the same environmental improvement as the other scenarios as it ignores sinks and non-CO_2 emissions.

Table 3. Scenario emissions ($MtCO_2$)

Region	Year	MultiGas SingleGas NoRegrets	OnlyCO2	Growth	FixedSinks
European Union	1990	4338	3641	4338	4338
	2010	4352	3945	4642	4433
	Kyoto	4000	3359	4000	4000
United States	1990	5170	5196	5170	5170
	2010	6838	6776	7245	6692
	Kyoto	4811	4833	4811	4811
New Zealand, Australia and Canada	1990	1118	766	1118	1118
	2010	1434	1030	1514	1415
	Kyoto	1107	759	1107	1107
Japan	1990	1261	1232	1261	1261
	2010	1562	1485	1566	1533
	Kyoto	1184	1159	1184	1184
Former Soviet Union and Eastern Europe	1990	5727	4928	5727	5727
	2010	4158	3725	3967	4393
	Kyoto	5621	4836	5621	5621

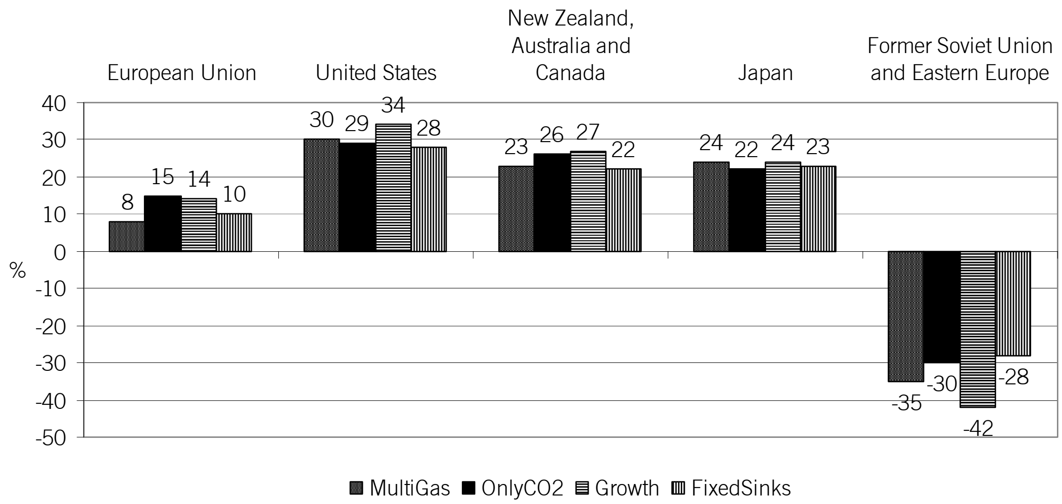
Two factors help explain the comparison with most of the existing literature (scenario **MultiGas** versus scenario **OnlyCO2**). First, baseline emissions of non-CO_2 gases grow slower than CO_2 emissions in all regions, except in Eastern Europe and the Former Soviet Union. The effect is particularly strong in the European Union, where the exclusion of the five non-CO_2 emissions implies a strong increase in the percentage reduction requirement. Second, emissions from sinks in the United States and Japan dominate the baseline decrease in non-CO_2 emissions and the reduction requirements therefore increase in these regions.

Alternatively, if the expected decreases in baseline non-CO_2 emissions fail to materialize (as in the scenario **Growth**), the reduction requirements increase significantly in most

Western regions. In particular, the reduction requirement in the European Union almost doubles if non-CO_2 emissions grow at the same yearly rate as CO_2 emissions. In addition, the amount of hot air in Eastern Europe and the Former Soviet Union increases significantly.

Finally, Figure 13 also shows that the increases in the reduction requirements in the scenario **FixedSinks** show that the changes in baseline sinks imply a net removal in the European Union, Eastern Europe and the Former Soviet Union, and vice-versa for the other regions.

Figure 13. Emissions reduction requirements, 2010



Economic results

The scenario **OnlyCO_2** implies marginal abatement costs of 28 €/tCO_2 or 71 $1995/tCE. (see Figure 14). This compares well with the results of the multi-model evaluation of the Kyoto Protocol in Weyant [1999]. The median carbon tax for Annex B trading is around 70 $1990/tCE and five out the thirteen models included report carbon taxes in the range 50-80 $1990/tCE.[11] The scenario also suggests that the narrow focus on CO_2, both with respect to abatement options and in setting the target, leads to a significant overestimate (almost 100%) of the costs of the of the Kyoto Protocol.

Comparing the same scenarios, Reilly ***et al.*** [1999] show narrow focus on CO_2 leads to an overestimate of the marginal abatement costs between 8% in Eastern Europe and 153% in some of the OECD countries. Assuming Annex B emissions trading and ignoring the

[11] Pp. xxxi-xxxii in Weyant [1999].

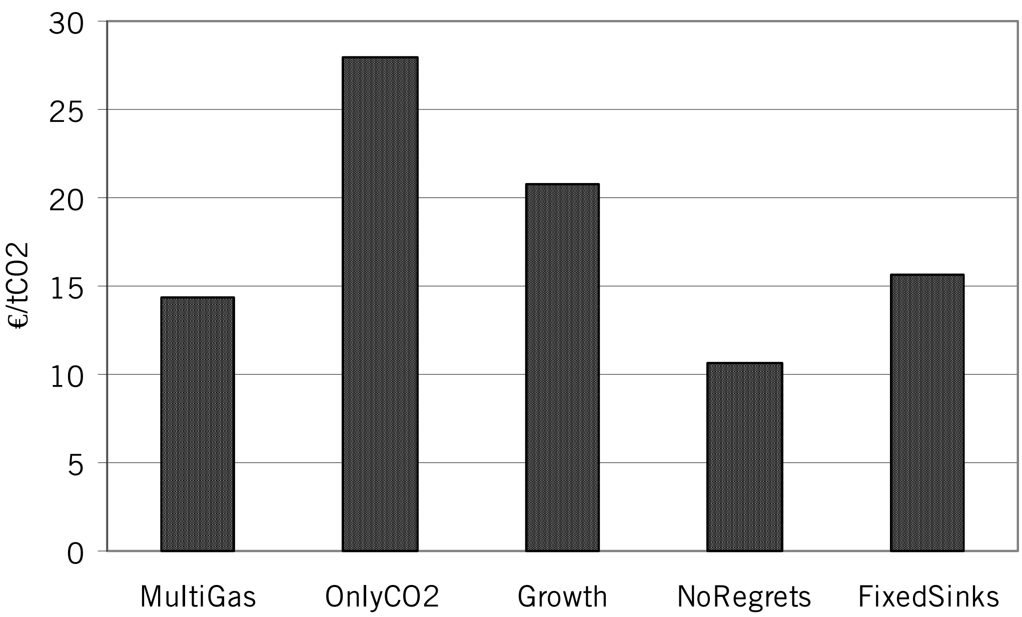
HGWPs, Burniaux [2000] and Manne and Richels [2000] show that the marginal abatement costs increases by around 50% and 100%, respectively.

The weak growth in the non-CO_2 baseline emissions, particularly in the European Union, reduces the reduction requirements significantly. If these baseline reductions fail to materialize and non-CO_2 emissions grow in line with CO_2 emissions, the scenario **Growth** shows that the marginal abatement costs increase almost 50%.

In contrast, marginal abatement costs decrease more than 25% if we include the "free" reductions in the analysis as part of the abatement options for new policies (scenario **NoRegrets**). Effectively, the "free" reductions shift the marginal abatement curves horizontally, and the same reduction requirements therefore imply lower costs.

Finally, the scenario **FixedSinks** illustrates the effects of eliminating the baseline changes in sinks. Specifically, all the previous scenarios, except the scenario **OnlyCO$_2$**, included a total net removal of 110 MtCO_2, or around 7% of the total emissions Annex B emissions reductions in 2010. In the scenario **FixedSinks**, we exclude this baseline effect and the marginal abatement costs therefore increases, as expected.

Figure 14. Marginal abatement costs, 2010



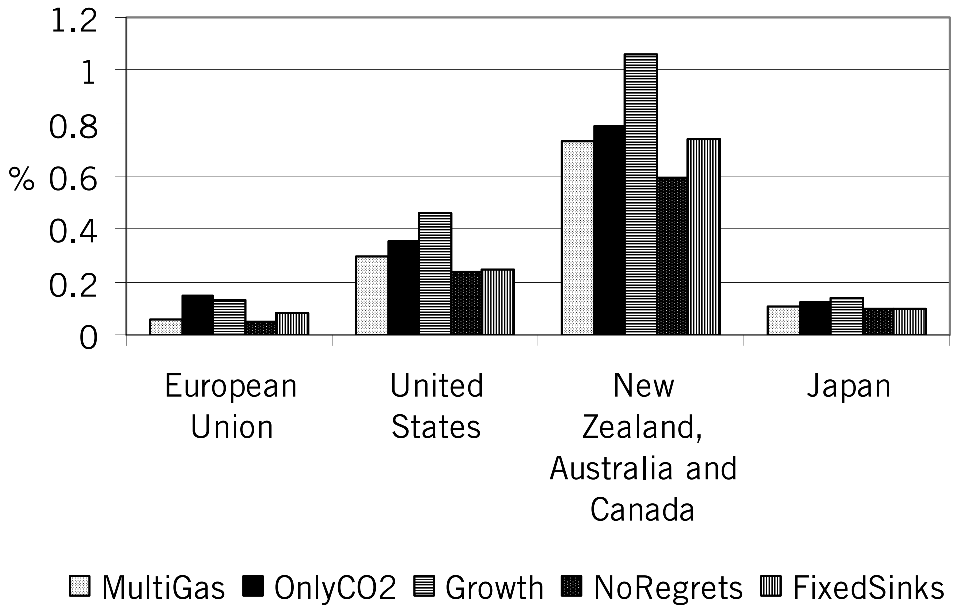
The changes in the marginal abatement costs and the reduction requirements help explain the changes in the welfare costs (Figure 15). In all regions, a narrow focus on CO_2 (scenario **OnlyCO$_2$**) leads to an overestimate of the costs of the Kyoto Protocol.

Stronger growth in the non-CO_2 baseline emissions increases the reduction requirements (scenario **Growth**). As expected, this increases the welfare costs in all regions. The Figure also shows that if non-CO_2 baseline emissions grow in line with CO_2 baseline emissions, then the costs of a multi-gas strategy may actually exceed the cost estimates focussing on CO_2 only (compare scenarios **MultiGas** and **OnlyCO$_2$**).

Our reference baseline for non-CO_2 emissions includes the effects of proposed policies, and we therefore include the "free" non-CO_2 abatement options in the baseline to minimize double counting of reductions. If we instead include the "free" reductions in the policy analysis (scenario **NoRegrets**), costs decrease in all regions as expected.

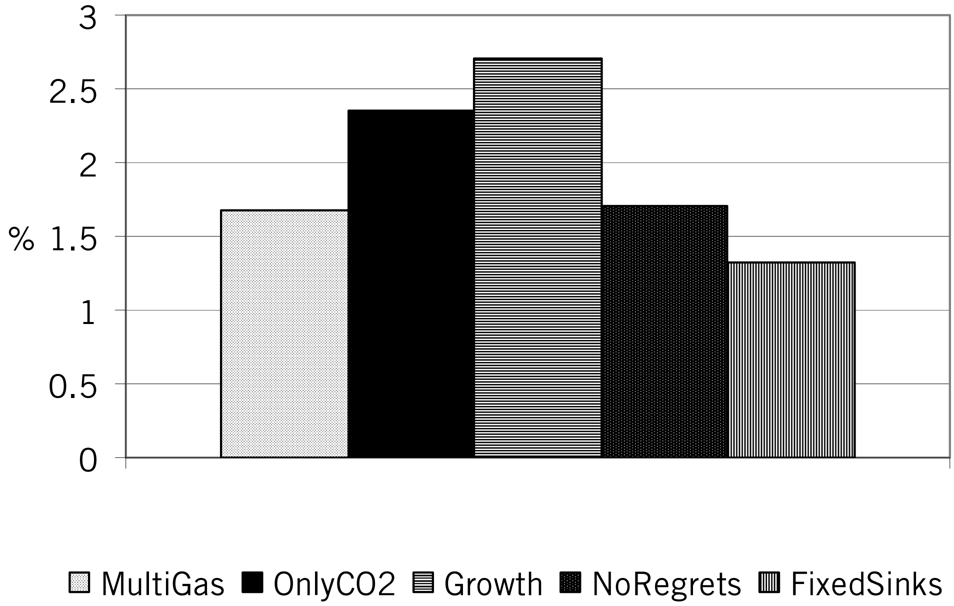
Finally, if sinks in 2010 equal sinks in 1990 (scenario **FixedSinks**), marginal abatement costs increases, but the reduction requirements decrease in all regions, except in the European Union. The changes in marginal abatement costs and in the reduction requirements unambiguously increase welfare costs in the European Union, but works in opposite directions in the other regions.

Figure 15. Welfare costs of the Kyoto Protocol



A multi-gas strategy reduces the gains to countries in the Former Soviet Union and Eastern Europe (Figure 16). A narrow focus on CO_2 (scenario **OnlyCO$_2$**) increases both the marginal abatement costs and the revenues from emissions exports.

Figure 16. Welfare gain in the Former Soviet Union and Eastern Europe



Stronger growth in the non-CO_2 baseline emissions (scenario **Growth**) leads to similar effects: higher marginal abatement costs and higher revenues from emissions exports, and both effects improve welfare. The opposite happens if we instead include the "free" reductions in the policy analysis (scenario **NoRegrets**). Finally, the scenario **FixedSinks** implies a welfare loss, if the net removal emissions in the baseline do not materialize.

Environmental results

Figure 17 shows that the CO_2 abatement share decreases in both the scenarios **Growth** and **NoRegrets**. Intuitively, both scenarios imply a larger abatement potential for non-CO_2 gases (because of higher baseline non-CO_2 emissions and "free" abatement options, respectively). The marginal abatement cost curves for non-CO_2 emissions are steeper than the curves for CO_2 emissions, and as the marginal abatement costs increases in the scenario **FixedSinks**, the share of CO_2 abatement increases.

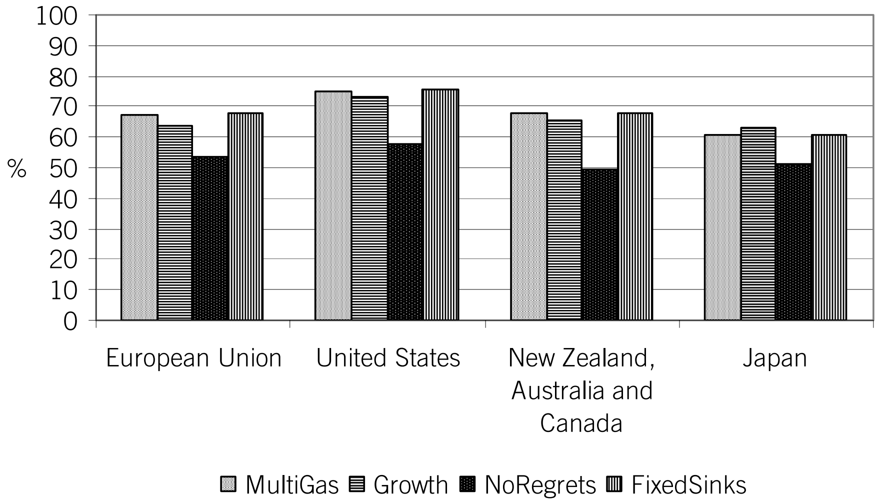


Figure 17. Share of CO_2 abatement in total domestic abatement, 2010

The narrow focus on CO_2 increases domestic action, except in the European Union (see scenario **OnlyCO₂** in Figure 18). Three factors drive this share. First, more low cost domestic abatement options increase domestic action. Second, domestic action increases as the marginal abatement costs increases (imports of emissions become more expensive). Third, domestic action decreases with the reduction requirement. The effect of higher marginal abatement dominates in all regions, except in the European Union, where the reduction requirements inflates emissions imports so much, that domestic action decreases.

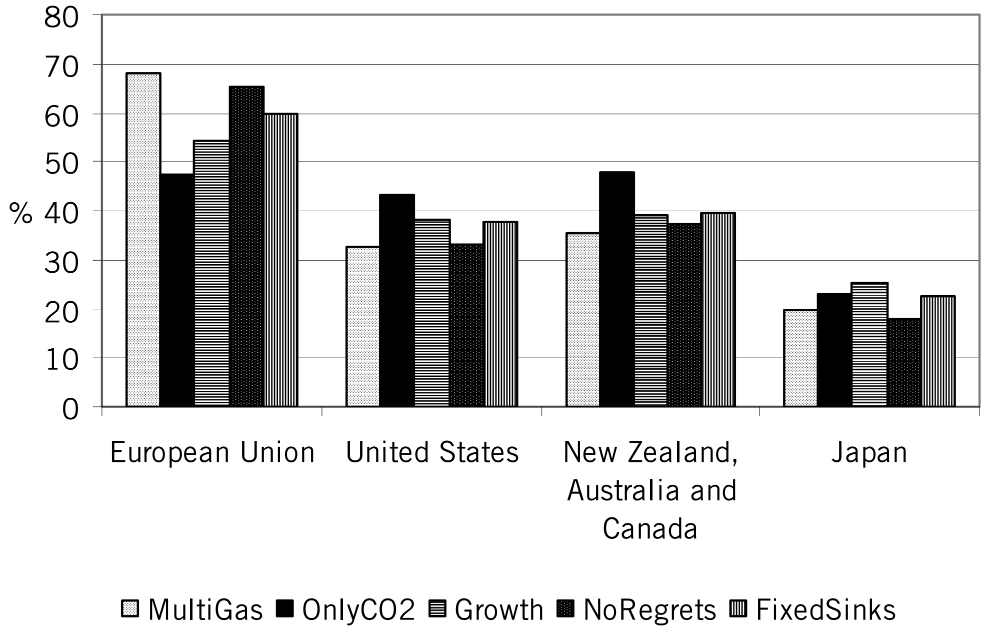
Ellerman and Wing [2000] also analyse the scenario **OnlyCO_2**. They report domestic action in the range 38% to 47% in all Western Annex B regions.

Stronger growth in the baseline non-CO_2 emissions (the scenario **Growth**) increases the abatement requirements and therefore the overall marginal abatement costs. The abatement requirement increases considerably in the European Union, and this reduces domestic action more than the increase following higher marginal abatement costs. In the other regions, the net effect is opposite: domestic action increases.

Marginal abatement costs decreases significantly, if we include the “free” reductions in the abatement options (the scenario **NoRegrets**). Most of the “free” reductions are available in the United States, which explains why domestic action increases in the United States. In the European Union and in Japan, the lower marginal abatement costs make imports of emissions rights more attractive, and domestic action therefore decreases.

Finally, the scenario **FixedSinks** illustrates the effects of the baseline changes in sinks: net removal in the European Union and emissions in the other regions. Marginal abatement costs change little, so if sinks in 2010 equal sinks in 1990, domestic action decreases in the European Union, but increases elsewhere.

Figure 18. Domestic action, 2010



7. Concluding remarks

The narrow focus on CO_2 in most economic analyses of the Kyoto Protocol captures the effects of abatement of the single-most important greenhouse gas. Our analysis shows, however, that policy makers may reduce costs significantly by exploiting the multi-gas flexibility in the Protocol. Specifically, the multi-gas flexibility implies more low costs abatement options and reductions in the abatement requirements. These effects may also increase domestic action, which together with costs, are some of the key issues in the policy debate.

We emphasize the preliminary nature of our results as many issues related to sinks and non-CO_2 abatement warrants more work. First, we only have studies of the marginal abatement costs of the non-CO_2 emissions in the European Union and the United States, and together these countries account for more than 50% of total Annex B emissions of non-CO_2. For the other Annex B regions, we use the marginal abatement cost curves for the European Union, but it would be useful to get estimates for these regions, particularly Eastern Europe and the Former Soviet Union, which together accounts for around 30% of total Annex B emissions.

Second, we developed our own baseline for non-CO_2 emissions based on the Annex B countries' communications to the UNFCCC. It is generally hard to identify consistent and relevant baselines in these data, so more and better emissions data could substantially improve the analysis.

Finally, additional sinks projects could be incorporated through a sector, which uses scarce land resources and receives emissions credit depending on the characteristics of the activities it undertakes (for example conversion of agricultural land to forests). Sales of the credits from this sector would then add to the regular sales revenues and thus provide an incentive to use the technologies with the highest potential for emissions removal. This approach would also capture the effects of changes in land rents and in product prices, but again, more analyses are needed, as we know little about the costs and benefits of additional sinks projects.

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9. Appendix: Database for sinks and non-CO_2 gases

Our model analysis requires data for historic and projected emissions of the six greenhouse gases covered by the Kyoto protocol. For CO_2, we combine consistent base year energy data from the International Energy Agency and carbon emissions coefficients to calculate historic CO_2 emissions. We derive projected CO_2 emissions based on model calculations reported in European Commission [1999].

Similar information is not available for sinks and non-CO_2 greenhouse gas emissions. We have therefore compiled a database with baseline sinks and non-CO_2 emissions based on the Annex B countries' communications to the UNFCCC.[12] The data sources include UNFCCC [1998], UNFCCC [2000], and World Bank [2000].[13]

Neither the data for historic nor projected emissions are complete. For historic emissions, we therefore make two assumptions: First, if only data for 1990 or 1995 is available, emissions in the two years are identical. Second, if no data for a given country is available, emissions equal GDP times the ratio of emissions to GDP in the EDGE region where the country belongs.

The data with projected emissions typically include data points for the years 1990, 2000, 2005, 2010 and 2020. To get data for 2030, we assume that the percentage growth from 2020 to 2030 equal the percentage growth in the period 2010-2020. Within the decades (2015 and 2025), we assume that emissions grow linearly. We can then compute emissions indices (1990=1) for each country and after aggregation also for each of the 45 GTAP regions and for each of eight regions in the model.

For countries without projected emissions, we use a three-step procedure. First, use the relevant GTAP index, if available. Second, if the relevant GTAP index is not available, use the index from the relevant model region. Third, if neither of the previous indices is available, use the index for global emissions.

Finally, we recalculate the emissions indices for the model regions based on the complete set of emissions projections.

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[12] Note that the communications are not necessarily mutually consistent and in some cases, they furthermore include the anticipated effects of proposed policies. This makes it hard to identify a relevant baseline, i.e., the expected future emissions with no changes in current policies.

[13] Very little data are available from the UNFCCC on developing countries (see http://ghg.unfccc.int). Alternative data sources include ALGAS and UNEP studies.

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