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A Multi-Gas Approach to Climate Policy

-- with and without GWPs

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April 2000

This paper was first presented at the EMF-19 Workshop in Washington, DC on March 22-23, 2000. We have benefited from discussions with Joe Aldy, Jae Edmonds, Larry Goulder, John Reilly, John Weyant, Tom Wigley, Larry Williams and Tom Wilson. We are indebted to Christopher Gerlach and Robert Parkin for research assistance. Funding was provided by EPRI. The views presented here are solely those of the individual authors. Comments should be sent to rrichels@epri.com.

Summary

When dealing with multiple greenhouse gases, we need some way to establish equivalence among gases. The Intergovernmental Panel on Climate Change (IPCC) has suggested the use of global warming potentials (GWPs) for making such trade-offs. We begin by examining the implications of such an approach for mitigation policy. We then discuss several significant limitations of GWPs. These include their failure to reflect damages, their sensitivity to the choice of time horizon, and their insensitivity to both the choice of and proximity to a prescribed target. We then explore an alternative approach where the relative price of each gas is an *endogenous output* rather than an *exogenous input* into the analysis. Our findings yield some important insights for those concerned with climate change policy making, particularly with regard to the role of each gas in accomplishing a long-term objective.

Non Technical Summary

This paper addresses four questions: (1) What are the implications of a multi-gas approach when designing policies for reducing greenhouse gas (GHG) emissions? (2) How sensitive is the optimal mix of mitigation options to the choice of global warming potentials (GWPs)? (3) Are there alternative approaches, which provide a more logical justification for action? (4) If so, what are their strengths and weaknesses?

We begin by adopting the 100-year GWPs recommended by the IPCC. In terms of carbon equivalence, incorporating the non-CO₂ greenhouse gases increases the absolute size of the reduction required by the Kyoto Protocol, but it also expands the portfolio of mitigation options. We find that a multi-gas approach benefits all Annex B regions with the exception of the economies in transition. It also turns out that the optimal mix of mitigation options is sensitive to the time horizon used to calculate the GWPs.

Given the lack of a rationale for choosing one set of GWPs over another, we examined two alternatives for establishing tradeoffs between gases. The first was based on cost-effectiveness analysis (minimizing the costs of limiting temperature change); the second was based on benefit-cost analysis. Both the cost-effectiveness analysis and the benefit-cost analysis highlight the shortcomings of GWPs for establishing equivalence among gases. Not only do the relative prices vary over time, but they also are sensitive to the ultimate goal.

Ideally, the price ratios would be the product of an analysis which minimized the discounted present value of damages and mitigation costs. Unfortunately, given the current state of knowledge regarding potential damages, such an approach may be premature. If indeed this is the case, focusing on temperature change may have distinct advantages over GWPs. It could serve as a temporary surrogate for benefit-cost analysis.

1. Introduction

Although the Kyoto Protocol (Conference of the Parties, 1997) encompasses a number of radiatively active gases, assessment of compliance costs have focused almost exclusively on the costs of reducing carbon dioxide (CO₂) emissions.^a There are a number of reasons why this is the case: CO₂ is by far the most important man-made gas (IPCC, 1996); until recently, few economic models have had the capability to conduct comprehensive multi-gas analyses;^b and, the quality of data pertaining to other greenhouse gases (GHGs) is poor (both spatially and intertemporally). Nevertheless, focusing exclusively on CO₂ may bias mitigation cost estimates and lead to policies that are unnecessarily costly. In this paper, we examine the implications of a multi-gas approach for both short- and long-term climate policy.

At the present time, a number of gases have been identified as having a positive effect on radiative forcing (IPCC, 1996). We consider the three thought to be the most important: carbon dioxide, methane (CH₄) and nitrous oxide (N₂O).^c We also consider the cooling effect of sulfate aerosols. We, however, exclude the so-called “second basket” of greenhouse gases included in the Kyoto Protocol. These are the hydrofluorocarbons (HFCs), the perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). This omission is not believed to alter the major insights of the analysis.

When dealing with multiple gases, we need some way to establish equivalence among gases. The problem arises because the gases are not comparable. Each gas has its own lifetime and specific radiative forcing. The IPCC (1996) has suggested the use of global warming potentials (GWPs) to represent the relative contribution of different greenhouse gases to the radiative forcing of the atmosphere. However, a number of studies have pointed out the limitations of this approach, noting that in order to derive optimal control policies, we must consider the discounted damages of emissions from each gas.^d GWPs do not address the impacts of climate change and therefore do not represent an adequate basis for decision making. In this paper, we examine the implications of using GWPs and explore alternatives that may provide a more logical basis for action.

^a See the Special Issue of *The Energy Journal* “On the Costs of the Kyoto Protocol: A Multi Model Evaluation” (1999) for numerous examples.

^b See Reilly *et al.* (1999) for an example of a multi-gas analysis of the costs of complying with the Kyoto protocol.

^c According to the IPCC (1996), the direct radiative forcing of the long-lived greenhouse gases is due primarily to increases in the concentrations of these gases.

^d See, for example, Reilly and Richards (1993), Schmalensee (1993), Fankhauser (1995), Hammitt, J. *et al.* (1995), Kandlikar (1995), Tol (1999), and Reilly *et al.* (1999). Also see Wigley (1998) for a discussion of GWPs and their shortcomings.

2. The model

The analysis is based on the MERGE model (a model for evaluating the regional and global effects of greenhouse gas reduction policies). MERGE is an intertemporal general equilibrium model. Like its predecessors, the current version (MERGE 4.0) is designed to be sufficiently transparent so that one can explore the implications of alternative viewpoints in the greenhouse debate. It integrates submodels that provide a reduced-form description of the energy sector, the economy, emissions, concentrations, temperature change and damage assessment. (See Figure 1.)

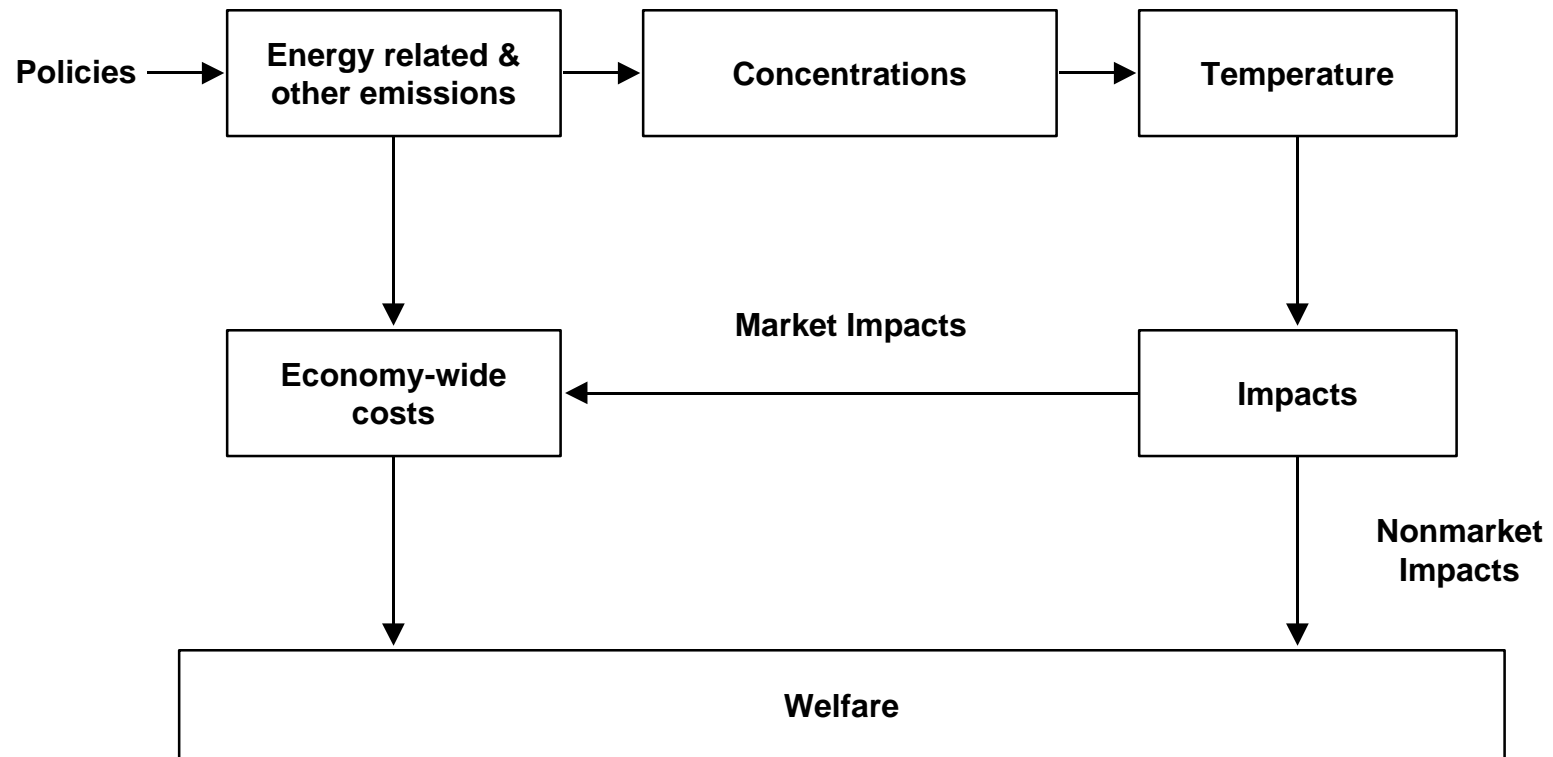
MERGE combines a bottom-up representation of the energy supply sector together with a top-down perspective on the remainder of the economy. For a particular scenario, a choice is made among specific activities for the generation of electricity and for the production of non-electric energy. Oil, gas and coal are viewed as exhaustible resources. There are introduction constraints on new technologies and decline constraints on existing technologies. MERGE also provides for endogenous technology diffusion. That is, the near-term adoption of high-cost carbon-free technologies in the electricity sector leads to accelerated future introduction of lower cost versions of these technologies.

Outside the energy sector, the economy is modeled through nested constant elasticity production functions. The production functions determine how aggregate economic output depends upon the inputs of capital, labor, electric and non-electric energy. In this way, the model allows for both price-induced and autonomous (non-price) energy conservation and for interfuel substitution. It also allows for macroeconomic feedbacks. Higher energy and/or environmental costs will lead to fewer resources available for current consumption and for investment in the accumulation of capital stocks. Economic values are reported in US dollars of constant 1990 purchasing power.

The world is divided into nine regions: 1) the USA, 2) OECDE (Western Europe), 3) Japan, 4) CANZ (Canada, Australia and New Zealand), 5) EEFSU (Eastern Europe and the Former Soviet Union), 6) China, 7) India, 8) MOPEC (Mexico and OPEC) and, 9) ROW (the rest of world). Note that the countries belonging to the Organisation for Economic Co-operation and Development (OECD) (Regions 1 through 4) together with the economies in transition (Region 5) constitute Annex B of the Kyoto Protocol.

Each of the model's regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region's wealth includes not only capital, labor and exhaustible resources, but also its negotiated international share in emission rights. Particularly relevant for the present calculations, MERGE provides a general equilibrium formulation of the global economy. We

Figure 1. MERGE 4.0



model international trade in emission rights, allowing regions with high marginal abatement costs to purchase emission rights from regions with low marginal abatement costs. There is also trade in oil, gas and energy-intensive goods. International capital flows are endogenous.

MERGE is designed to be used for either cost-effectiveness or cost-benefit analysis. For the latter purpose, the model translates global warming into its market and nonmarket impacts. Market effects are intended to measure direct impacts on the GDP, e.g., agriculture, timber and fisheries. Nonmarket effects refer to those not traditionally included in the national income accounts, e.g., impacts on biodiversity, environmental quality and human health. These effects are even more difficult to measure than market effects.

For Pareto-optimal outcomes, i.e., those scenarios in which the costs of abatement are balanced against the impacts of global climate change, each region evaluates its future welfare by adjusting the value of its consumption for both the market and nonmarket impacts of climate change. The market impacts represent a direct claim on gross economic output -- along with energy costs, aggregate consumption and investment. Nonmarket impacts enter into each region's intertemporal utility function, and are viewed as an adjustment to the conventional value of macroeconomic consumption.

For more on the model, see our web site:

<http://www.stanford.edu/group/MERGE/>

3. The treatment of greenhouse gases and carbon sinks

MERGE requires information on the sources of the gases under consideration, their geographical distribution, how they are likely to change over time, and the marginal costs of emissions abatement. Unfortunately, the quality of the data is uneven, particularly for the non-CO₂ greenhouse gases. In many instances, we have had to rely on a great deal of judgement to arrive at globally disaggregated time series. Similarly, there is a paucity of data related to the potential for carbon sinks. In this section, we will identify the main sources for our estimates. However, we stress that in many instances, the cited data required some interpretation to meet the demands of the present analysis. Again, for details, see the computer program shown on our web site.

For purposes of the present analysis, greenhouse gas emissions are divided into two categories: energy related and non-energy related. MERGE tracks energy related releases of both CO₂ and CH₄. For the reference case, the model is calibrated so that global CO₂ emissions approximate the IPCC (1994) central case "no policy" scenario (IS92a). This has been done through the adjustment of

Table 1. Methane Emissions in 1990 -- millions of tons

Regions	USA	OECD	JAPAN	CANZ	EEFSU	CHINA	INDIA	MOPEC	ROW	WORLD
Non-energy:										
Enteric fermentation	7.8					5.2	12.0		60.0	85.0
Rice paddies	0.0					18.0	18.0		24.0	60.0
Biomass burning	0.0					10.0	10.0		20.0	40.0
Landfills	8.0	8.0		2.0	4.0	4.0	2.0		12.0	40.0
Animal waste	5.0	2.0		2.0	2.0	5.0	3.0		6.0	25.0
Domestic sewage	5.0	5.0	1.0	1.0	1.0	1.0	1.0		10.0	25.0
Subtotal	25.8	15.0	1.0	5.0	7.0	43.2	46.0	0.0	132.0	275.0
Energy-related:										
Gas	3.5	3.3	0.4	1.2	29.2	0.6	0.2	12.0	4.7	55.0
Coal	7.1	2.6	0.0	1.0	10.0	20.8	0.5	0.0	2.9	45.0
Subtotal	10.7	5.9	0.4	2.2	39.2	21.4	0.7	12.0	7.6	100.0
Anthropogenic	36.5	20.9	1.4	7.2	46.2	64.6	46.7	12.0	139.6	375.0
Natural										160.0
Total										535.0

Sources: IPCC (1994) and IEA (1998).

several key supply- and demand-side parameters in the energy-economy submodel. Table 1 presents estimates of energy and non-energy related CH₄ emissions for 1990. When a constraint is placed on GHG emissions, the choice of technologies for the energy sector is influenced by the emission characteristics of those technologies.

We next turn to non-energy related emissions. In the case of CO₂, we must account for “other industrial releases” (primarily cement production) and the net changes associated with land use. According to IPCC (1994), other industrial emissions are relatively small. These are exogenous inputs into MERGE. With regard to land use, we assume that, in the absence of policy, the mass of carbon in the terrestrial biosphere remains constant.

This brings us to the issue of carbon sink enhancement. The Protocol states that Annex B commitments can be met by “the net changes in greenhouse gas emissions from sources and removal by sinks resulting from direct human-induced land use change and forestry activities limited to afforestation, reforestation, and deforestation since 1990, measured as verifiable changes in stocks in each commitment period” (Conference of the Parties, 1997). There is some confusion, however, regarding the treatment of soil carbon. This issue has been flagged for further study in the Protocol. For the present analysis, we have adopted the values shown in Table 2 for 2010. We suppose that marginal sink enhancement costs are proportional to the quantity of enhancement. We also assume that the potential for sink enhancement increases over time.

**Table 2. Potential Sink Enhancement in 2010 at a
Marginal Cost of \$100 per ton of carbon
(million tons of carbon)**

USA	50
OECD	17
Japan	0
CANZ	50
EEFSU	34
China	25
India	13
MOPEC	25
ROW	250
World	464

Source: IPCC (1996).

Table 1 also includes non-energy related CH₄ emissions. Reductions from the reference path are determined by a set of time-dependent marginal abatement cost curves. In 2010, the curve is calibrated based on Reilly *et al.* (1999).^a For later years, the marginal cost of emissions abatement declines as a result of technical progress.

N₂O emissions are treated in a manner similar to non-energy sector CH₄ emissions. Table 3 reports estimates for 1990. A marginal abatement cost curve for each region is constructed for each commitment period. For 2010, we again rely on the work of Reilly *et al.* (1999). Similarly, for latter years, we assume that the marginal cost of emission abatement declines with technical progress.

Table 3. Anthropogenic Nitrous Oxide Emissions in 1990 -- millions of tons

USA	1.1
OECD	0.8
Japan	0.1
CANZ	0.3
EEFSU	0.3
China	0.7
India	0.5
MOPEC	0.2
ROW	1.7
World	5.7

Source: IPCC (1994).

The modification of the model to include multiple gases raises the issue of tradeoffs between gases. We begin by employing the global warming potentials (GWPs) established by the IPCC (1996). They represent the cumulative radiative forcing between the present and an arbitrary future date caused by a unit mass of gas emitted, expressed relative to CO₂.

Table 4 shows alternative global warming potentials for the three gases under consideration. For the initial set of calculations, we utilize the 100-year GWPs

^a In contrast to Reilly *et al.* (1999), we use linear marginal abatement cost curves. Both coincide at \$100 per ton. For discussions of the potential for CH₄ abatement, see Kruger (1999) and USEPA (1999) and IPCC (1996). The latter also contains a discussions of the potential for N₂O abatement.

adopted at the third meeting of the Conference of the Parties (1997) to the Framework Convention.

Table 4. GWPs as a Function of Alternative Time Horizons

Species	Chemical Formula	Lifetime (years)	Global Warming Potential		
			20 years	100 years	500 years
Carbon Dioxide	CO ₂	50-200	1	1	1
Methane	CH ₄	12	56	21	6.5
Nitrous Oxide	N ₂ O	120	280	310	170

Source: IPCC (1996), p. 22.

4. Single gas vs. multi-gas analysis

The Kyoto Protocol imposes emission limits on Annex B countries for the first commitment period (2008-2012). The aim is to reduce their aggregate emissions by approximately 5% below 1990 levels. For our initial set of calculations, we assume that these constraints will continue to be imposed on Annex B countries after 2010 and that no limits are imposed outside of Annex B.

Numerous economic analyses have attempted to assess the costs of complying with the prescribed targets. However, in most instances the studies have focused exclusively on CO₂. The analyses were conducted as if CO₂ were the only greenhouse gas. Mitigation costs were calculated accordingly. For purposes of exposition, we refer to the earlier approach as a “CO₂ emissions only” approach. Alternatively, we describe the incorporation of multiple gases *and* the potential for sink enhancement as a “multi-gas” approach. In this section, we explore the implications of choosing one approach over the other.

Figure 2 shows our projections for US carbon and carbon equivalent emissions for 2010. In the case of CO₂ emissions only, the cap is 1.250 billion tons of carbon (93% of 1990 carbon emissions). Since unabated emissions are projected to rise to 1.825 billion tons in 2010, the required reduction is 0.575 billion tons in that year. When we take a multi-gas approach, we deal in carbon equivalents rather than carbon emissions. For our initial set of calculations, equivalence is based on 100-year GWPs. The inclusion of CH₄ and N₂O raises reference case emissions to a total of 2.150 billion tons and the cap to 1.530 billion tons (93% of 1990 carbon

Figure 2. US Emissions in 2010 under Single-gas and Multi-gas Scenarios

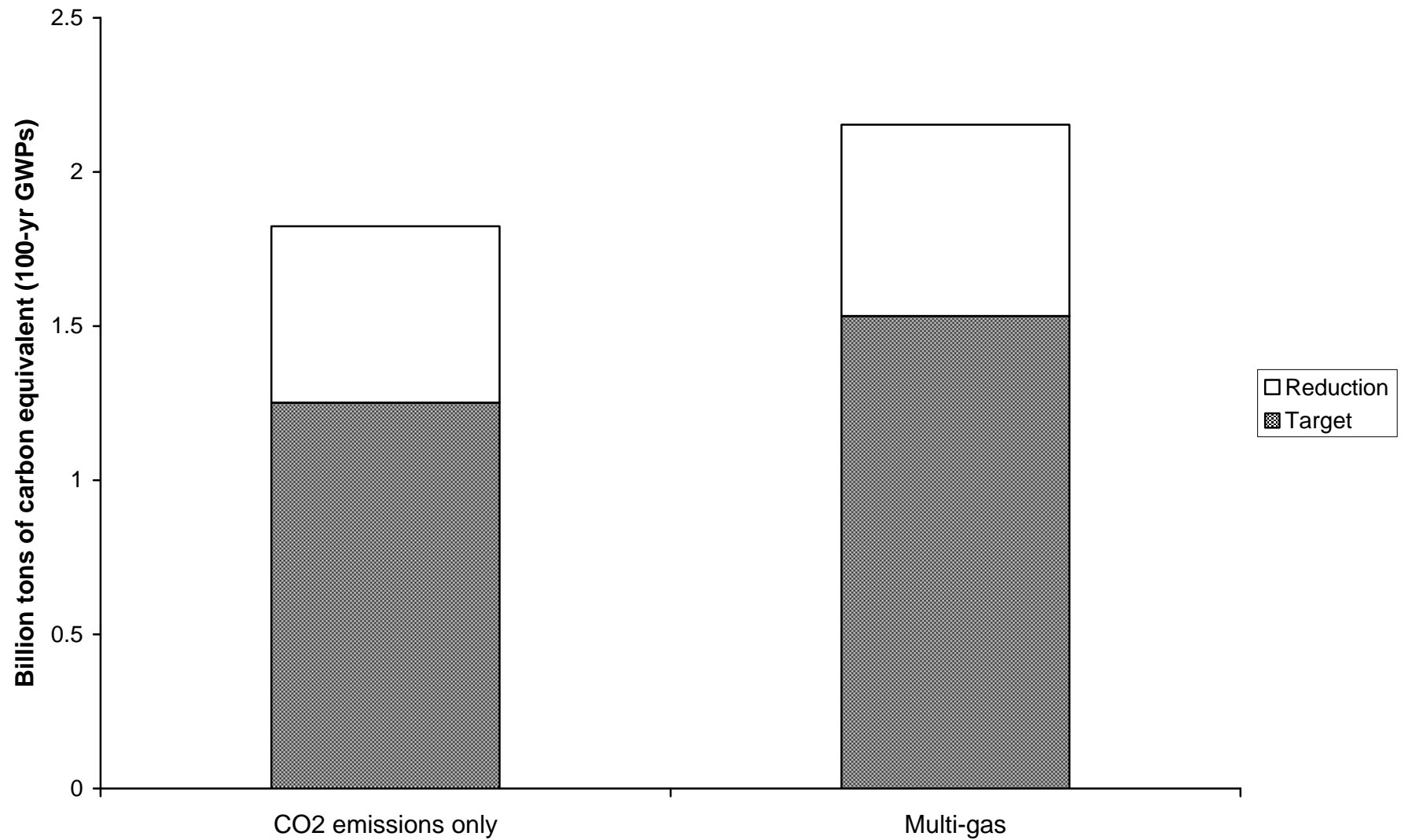
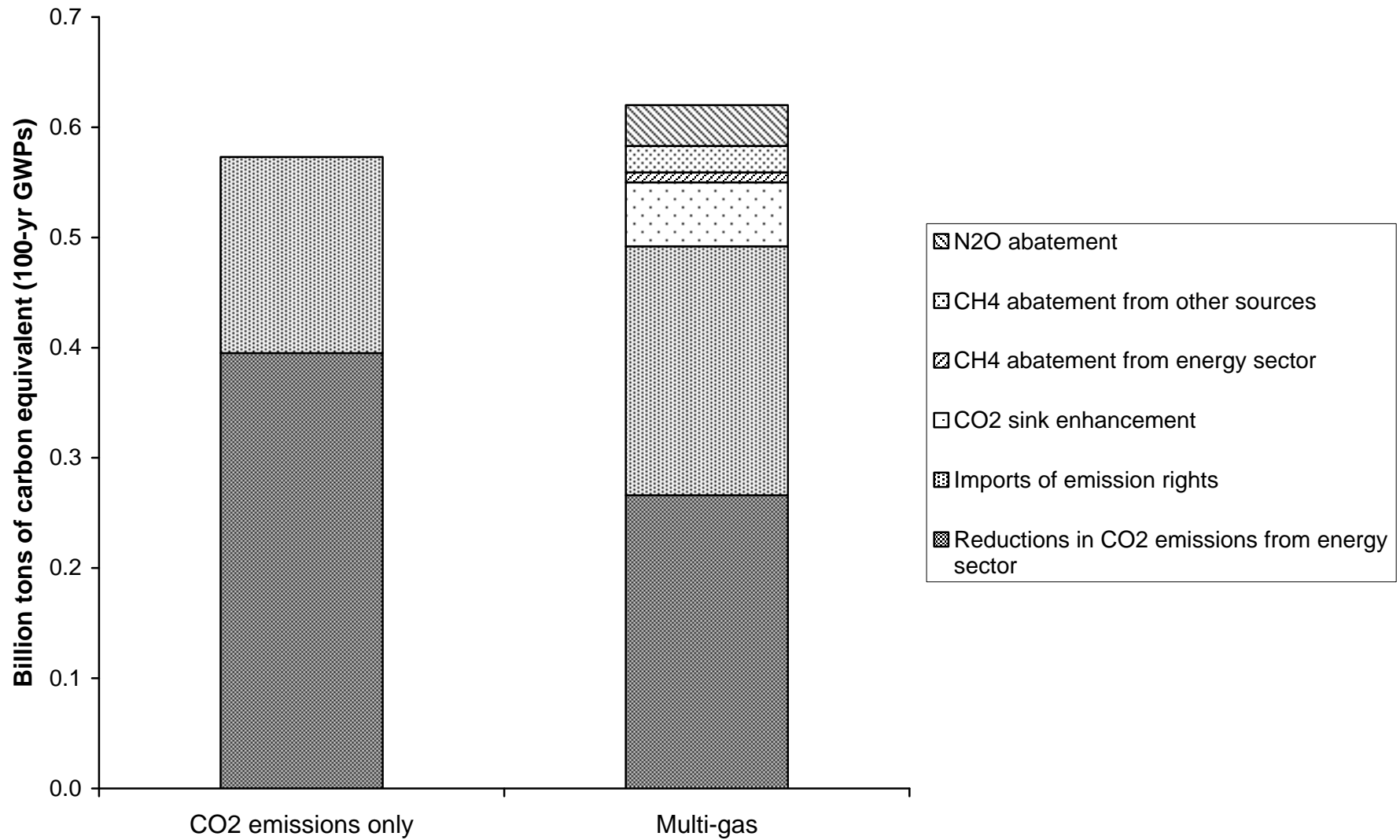


Figure 3. US in 2010 -- Optimal Mix of Options for Reductions



**Figure 4. Incremental Value of Carbon (Equivalent) Emission Rights in 2010 --
Annex B Trading**

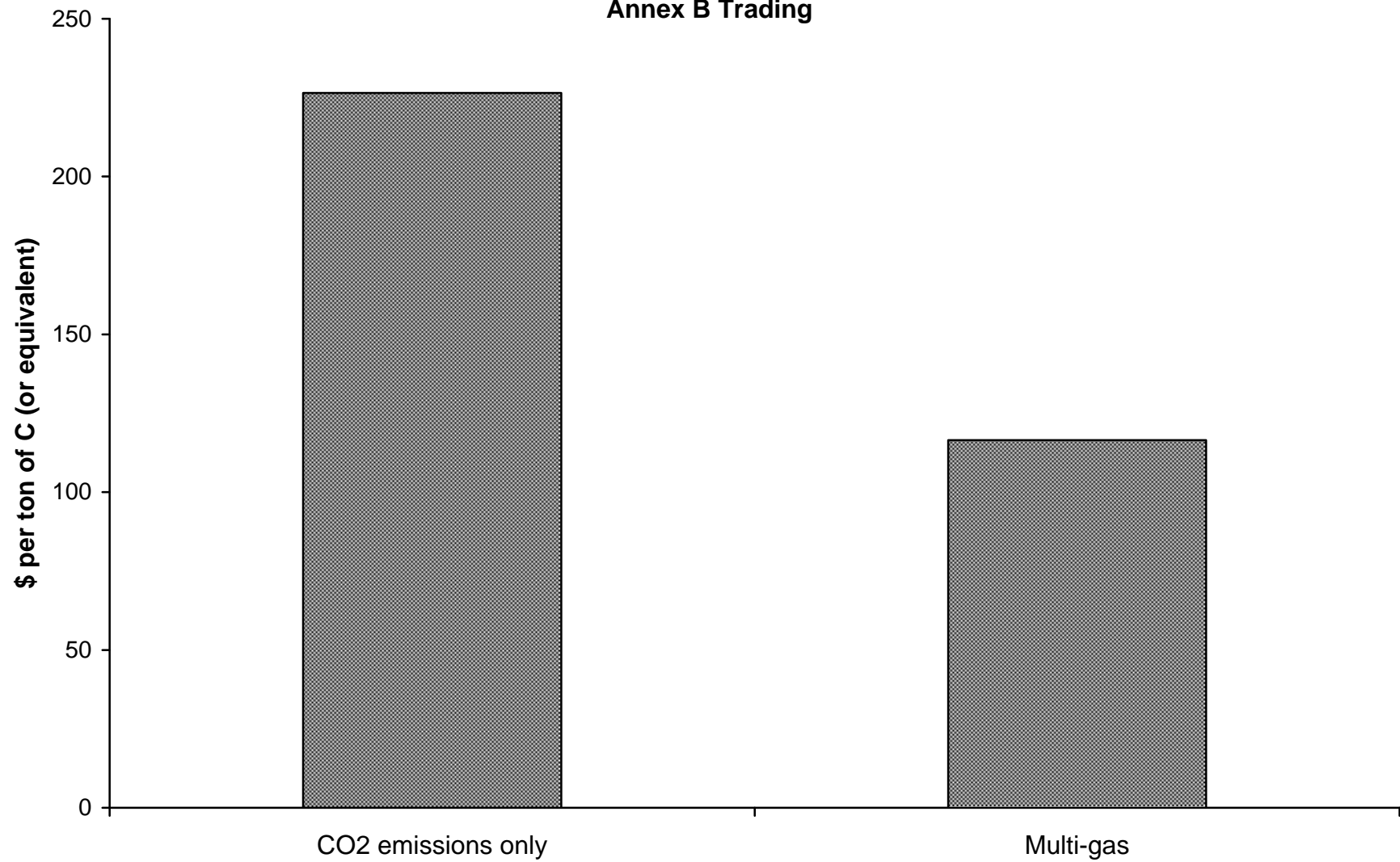
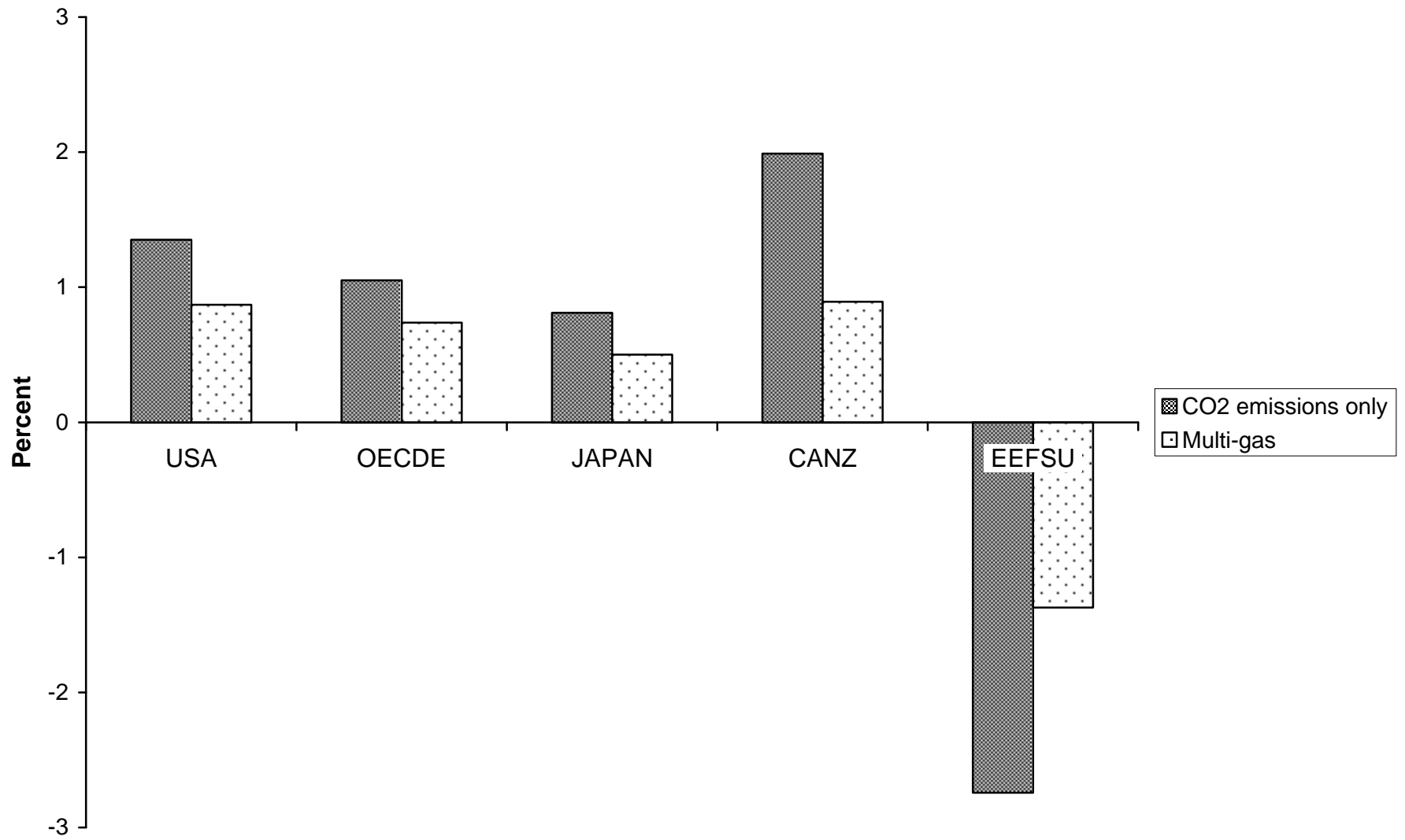


Figure 5. Percentage GDP Losses in 2010



equivalent emissions). The net result is to increase the required reduction to 0.620 billion tons.

Figure 3 shows how the respective targets might be met. For the “CO₂ emissions only” case, there are but two options: purchasing emission rights from abroad or reducing domestic CO₂ emissions.^a Approximately one-third of the reduction is provided by imports. The remaining two-thirds is the result of fuel switching and price-induced conservation.

For the multi-gas case, the number of options is increased. There is now the opportunity for CH₄ and N₂O abatement and carbon sink enhancement. Figure 3 shows the optimal mix. Notice that the need for domestic CO₂ reductions declines in the multi-gas case. Not only do the additional low-cost abatement options more than offset the increase in the required reduction. They also drive down the international price of emission rights (Figure 4), making imports more attractive relative to reducing domestic emissions in the OECD.

Figure 5 shows GDP losses for the various Annex B regions resulting from the implementation of the Kyoto Protocol.^b Losses are presented as a percent of overall GDP. Notice that the four OECD regions benefit from a multi-gas approach at the expense of Eastern Europe and the former Soviet Union (EEFSU). The decline in GDP in EEFSU during the past decade has led to a decrease in their greenhouse gas emissions. Although this trend is eventually expected to reverse, emissions are projected to lie below the constraint imposed by the Protocol for the first commitment period (2008-2012). If this does occur, the region will have excess emission rights. In the parlance of the climate debate, this is described as “hot air” or “Russian hot air” denoting the country expected to receive the largest number of excess emission rights. At present, the Protocol permits these rights to be sold to countries in search of low-cost options for meeting their own targets. In addition, as it undergoes restructuring, EEFSU will have opportunities for low-cost emission reductions that are unavailable to the OECD countries. According to Figure 4, the value of these rights (both zero- and low-cost) falls substantially in the multi-gas case.

5. The effect of the choice of time horizon for calculating GWPs

Among the arguments against using GWPs is their dependence on the choice of time horizon. Unfortunately, as a number of studies have pointed out, the choice is totally arbitrary. Indeed, Schmalensee (1993) reviews arguments for adopting

^a Emission trading is allowed within Annex B only. Opportunities under the Clean Developed Mechanism are not considered in the present analysis.

^b For the case of “carbon emissions only”, the prescribed reduction is calculated as if CO₂ were the only greenhouse gas. For the multi-gas case, the prescribed reductions are in terms of carbon equivalence.

Figure 6. US Reference Case Emissions in 2010 under Alternative GWPs

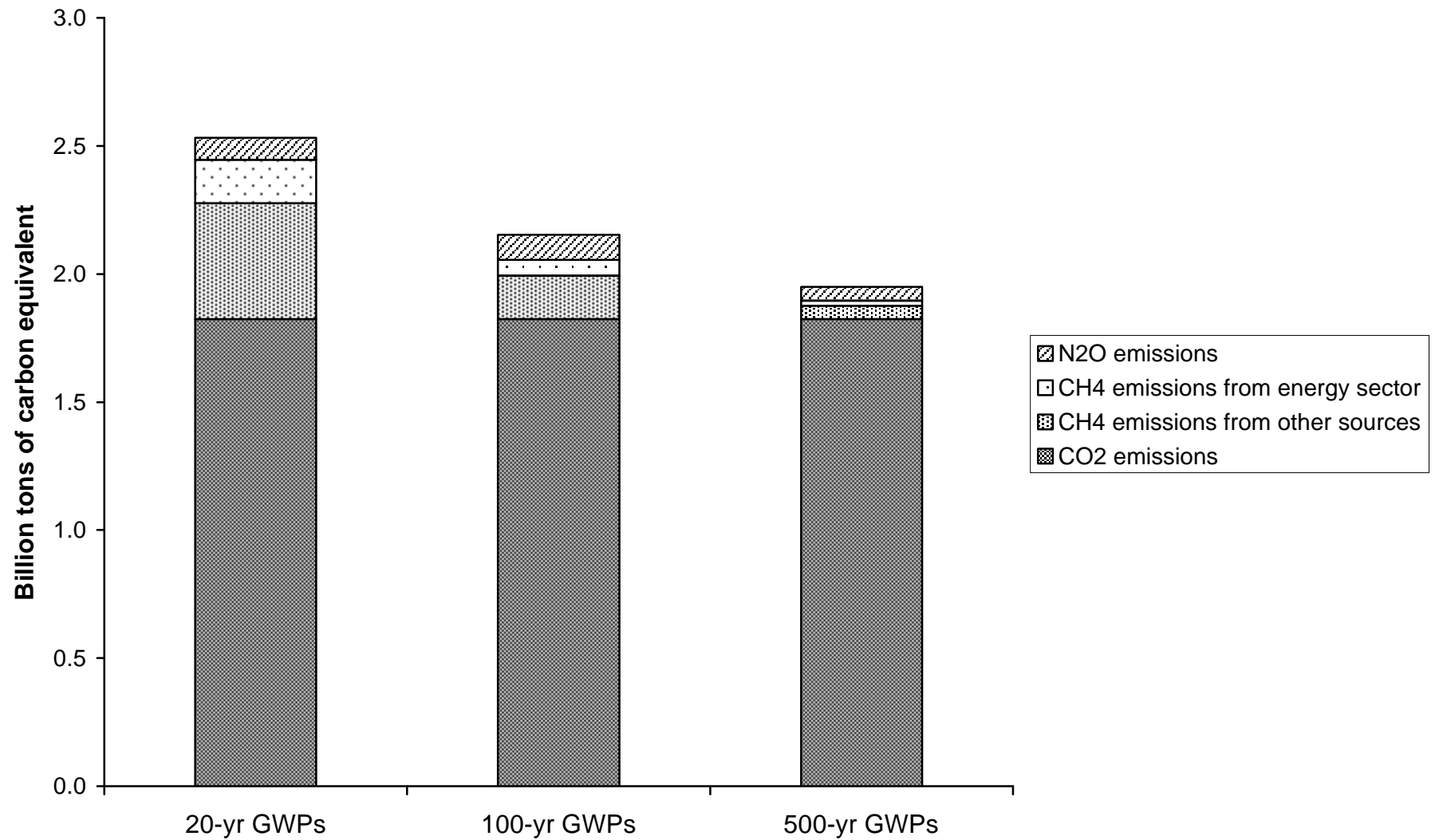


Figure 7. US Reductions in GHG Emissions in 2010 Under Alternative GWPs

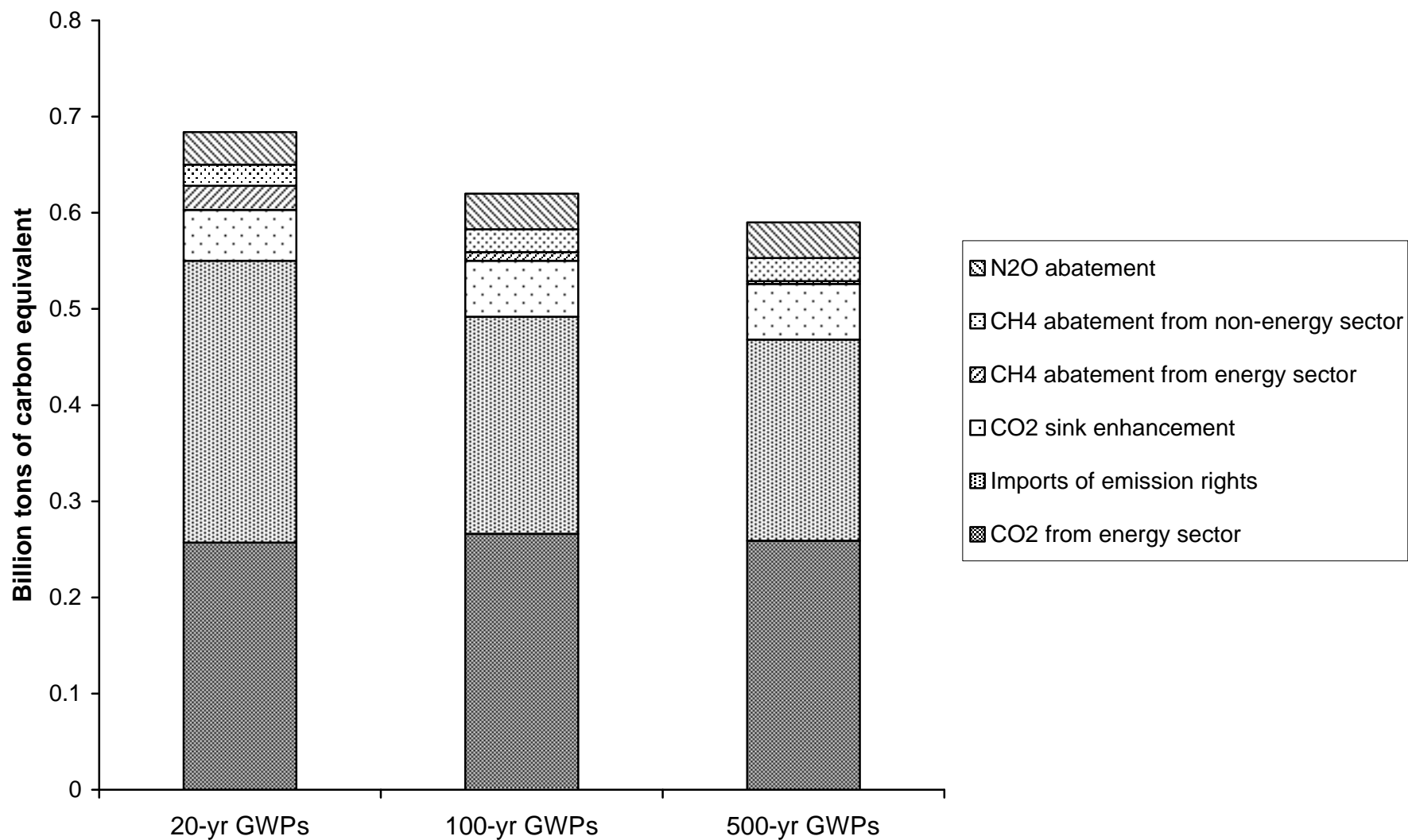


Figure 8. Sources of EEFSU "Hot Air" in 2010

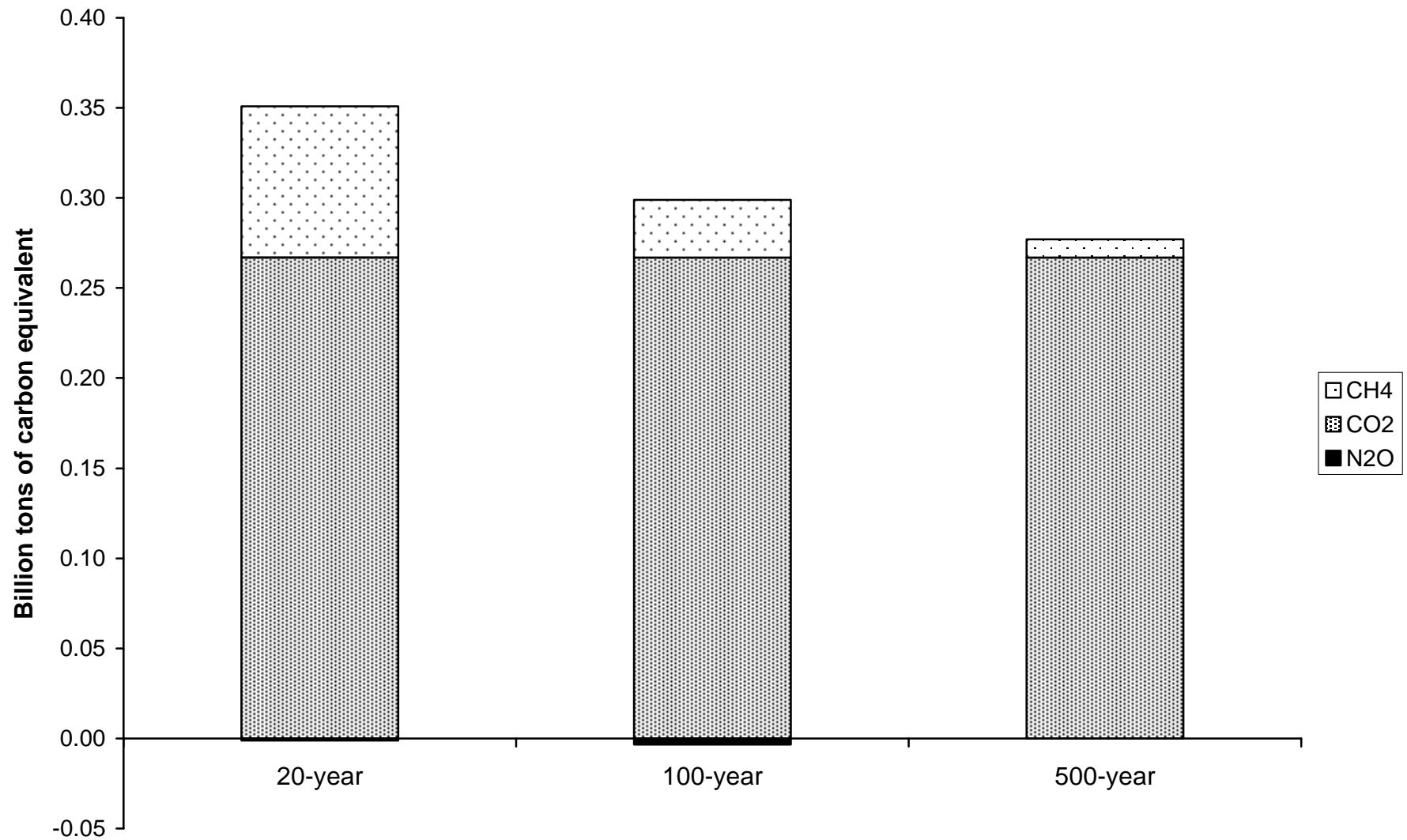
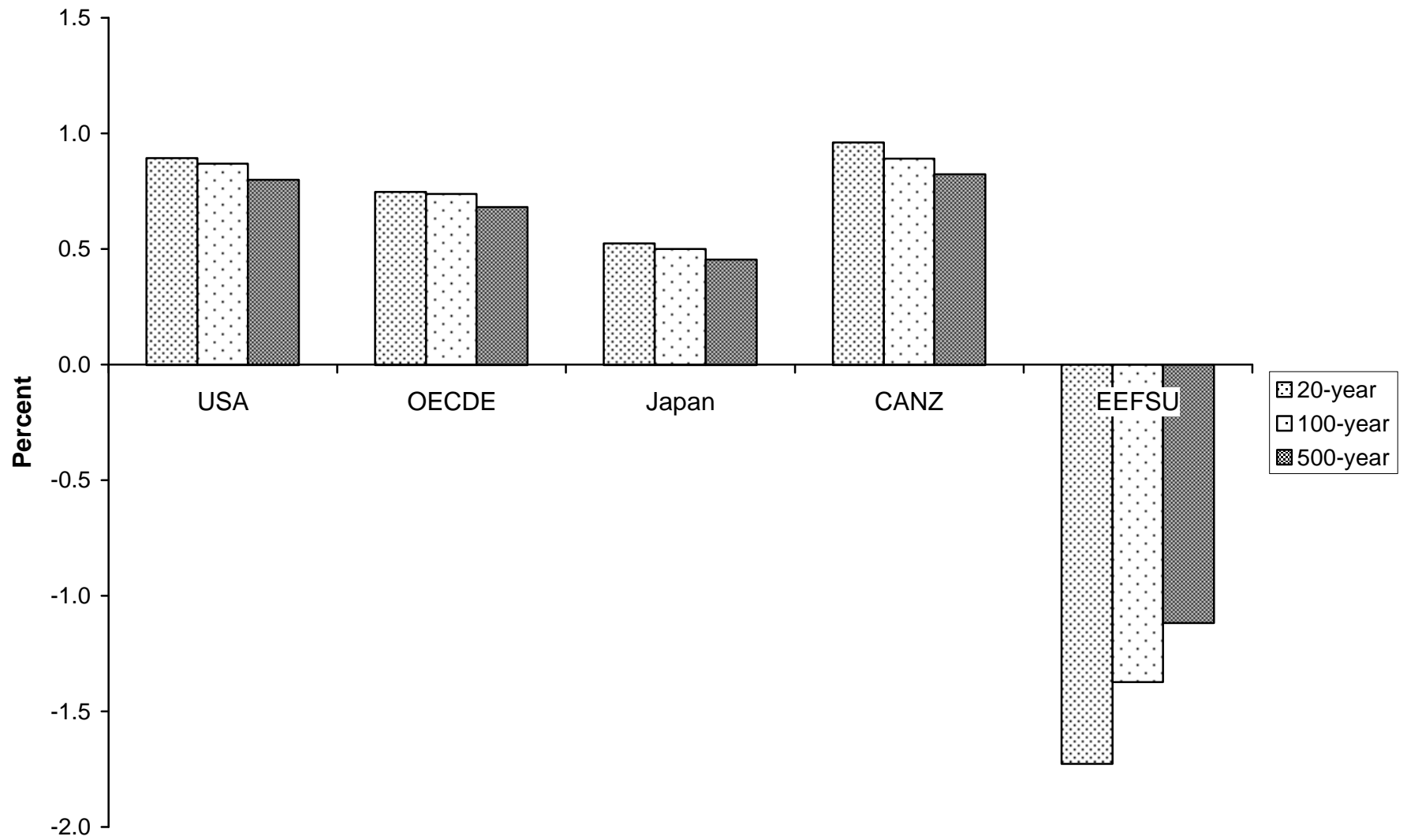


Figure 9. Percentage GDP Losses in 2010



extreme values at either end and notes that there is no sound economic reason for selecting one time horizon over another. From Table 4, recall that CH₄ is particularly sensitive to the time horizon. This is because of its relatively short lifetime. With a 20-year time horizon its weight nearly triples (relative to the IPCC's recommended 100-year time horizon). With a 500-year time horizon, it is reduced by nearly two-thirds. In this section, we examine how the choice of time horizon influences reference case emissions, the required reduction, and how the reduction is achieved.

Figure 6 shows US reference case emissions in 2010 under alternative sets of GWPs. Since the indices are established relative to CO₂, carbon emissions remain constant as we vary the time horizon. Carbon equivalent emissions of the other gases do change, however, with the choice of GWPs. As one would expect, CH₄ is the most sensitive.

Figure 7 shows the impact of the time horizon on the magnitude of the required reduction and on how the reduction is to be achieved. Note that US dependence on imports of emission rights would increase by approximately 50% for a 20-year time horizon relative to a 500-year time horizon. This is due to the increases in both zero-cost ("hot air") and low-cost emission rights available for sale by EEFSU.

From Table 1, note that in 1990, EEFSU released large amounts of CH₄ through energy-related activities. Much of this is due to fugitive emissions from the region's natural gas pipelines. These fugitive emissions are assumed to decline gradually over time. As a result, EEFSU's CH₄ emissions are projected to be below 1990 levels in 2010. Figure 8 shows how the magnitude of the "hot air" changes with the choice of time horizon. The shorter time horizon also increases the amount of low-cost emission rights available for sale by EEFSU.

Figure 9 shows GDP losses in 2010 as a percentage of total GDP for each of the 5 regions constituting Annex B. The OECD countries lose with a shorter time horizon. The increase in "hot air" and low-cost emission rights is offset by the larger emission reductions required to meet the prescribed target. EEFSU, on the other hand, would prefer the 20-year time horizon since it benefits from increased sales of its emission rights.

6. An alternative approach to GWPs

We now turn to alternatives to GWPs for guiding climate policy. In doing so, we shift from a near-term focus on the first compliance period (i.e., 2008 to 2012) to the longer-term goals of climate policy. Such a shift is useful independent of the

Figure 10. Reference Case vs. Ceilings of 2° and 3° C
(temperature increase from 2000, °C)

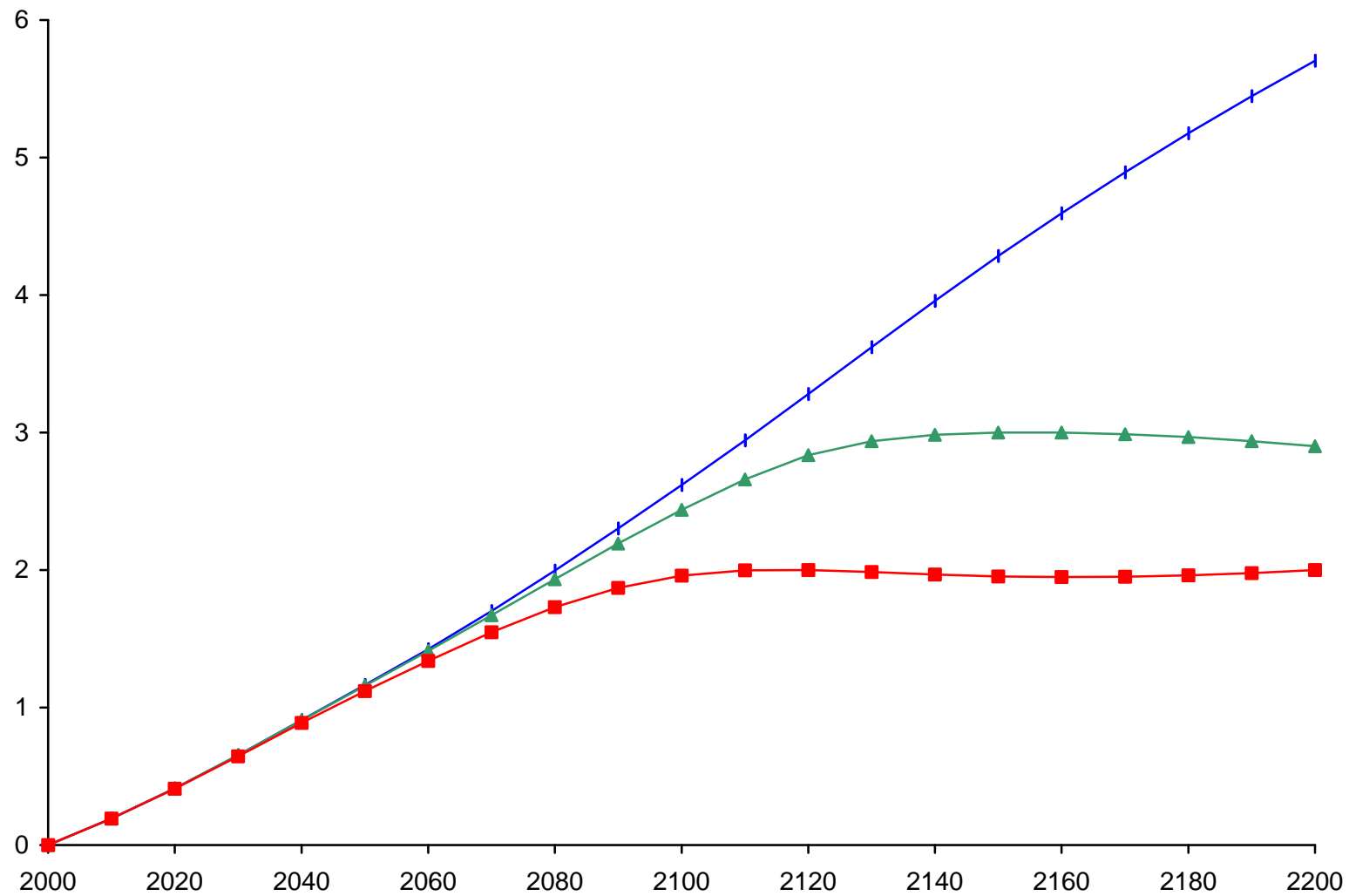
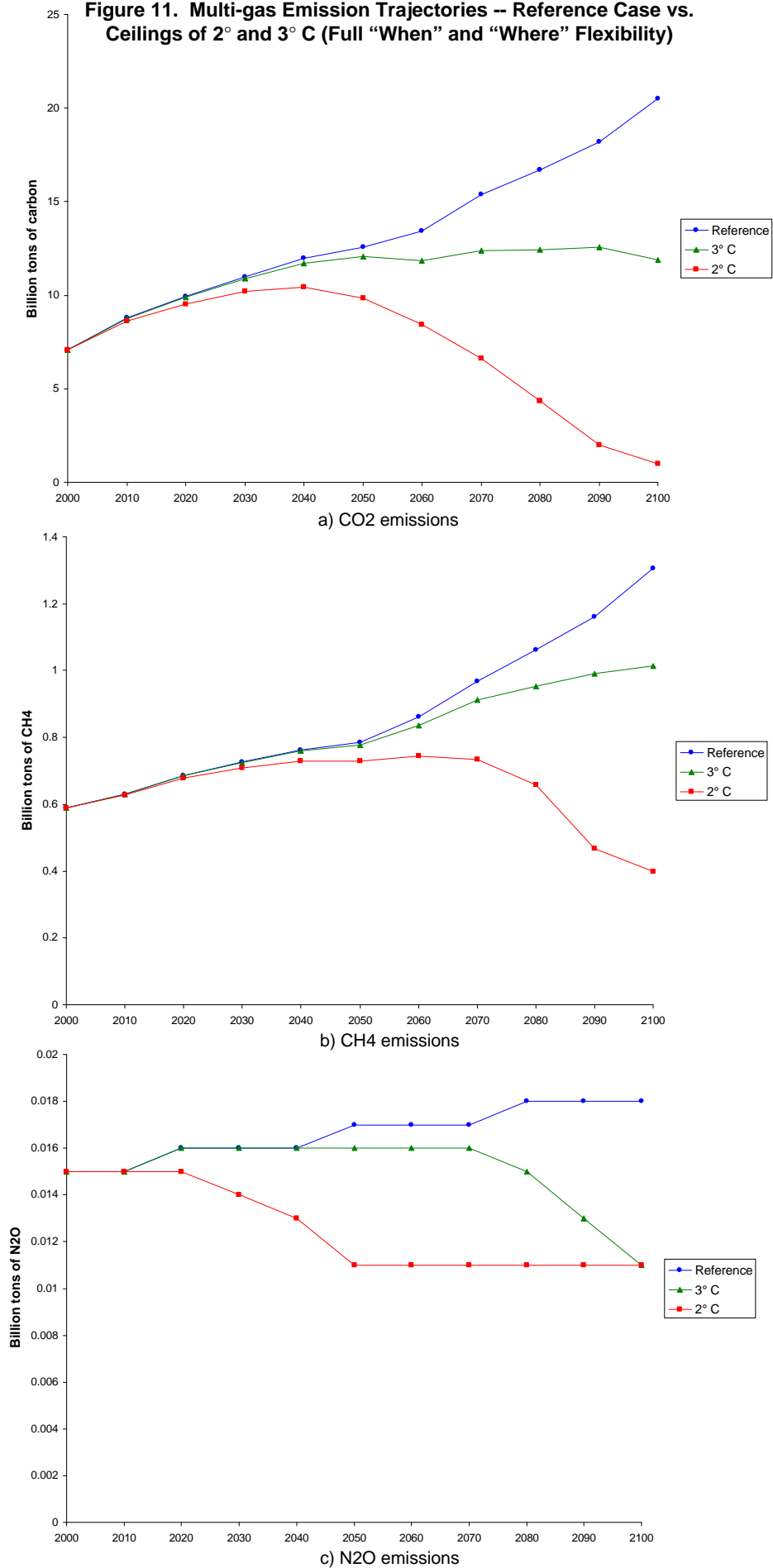
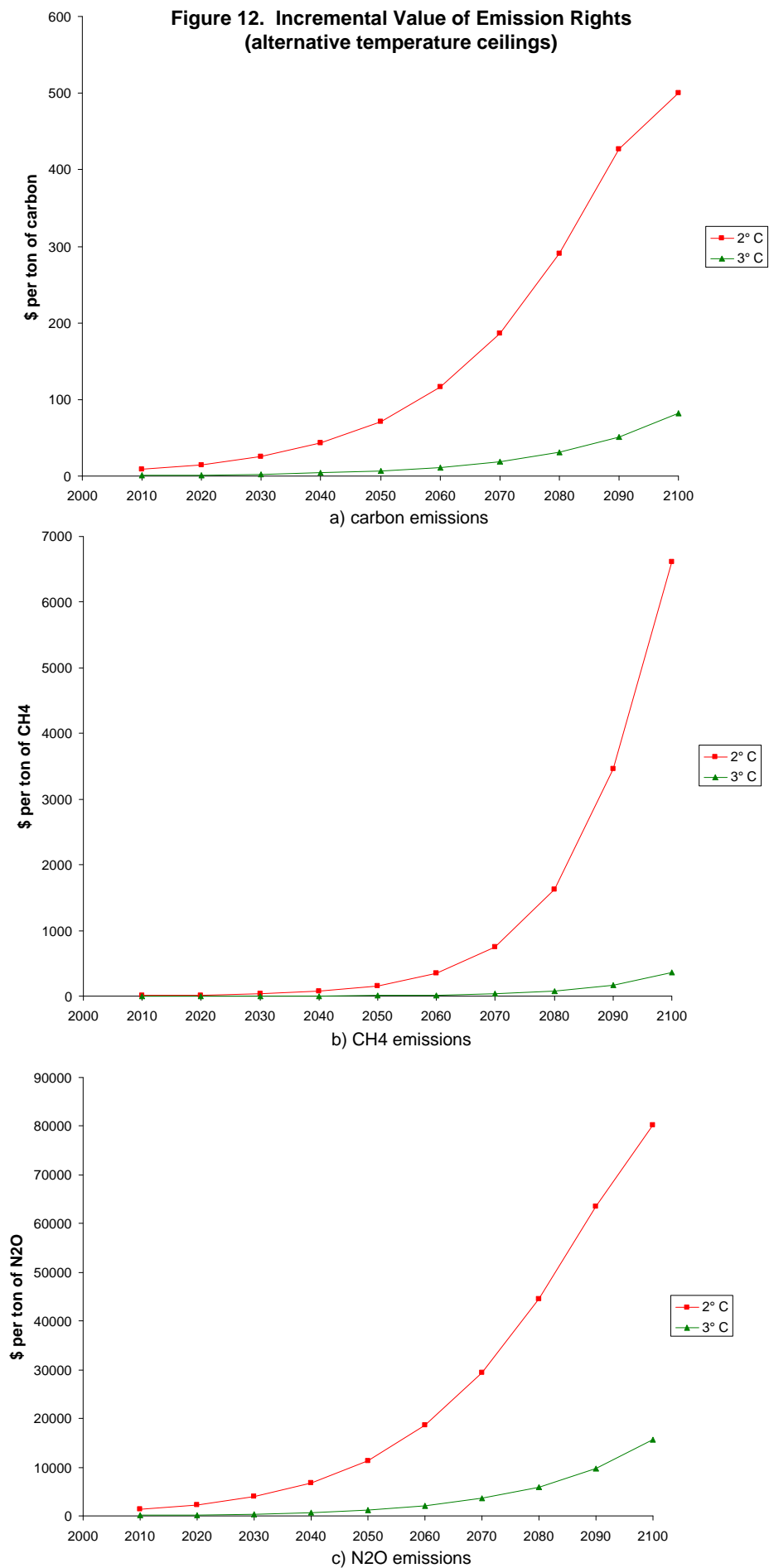


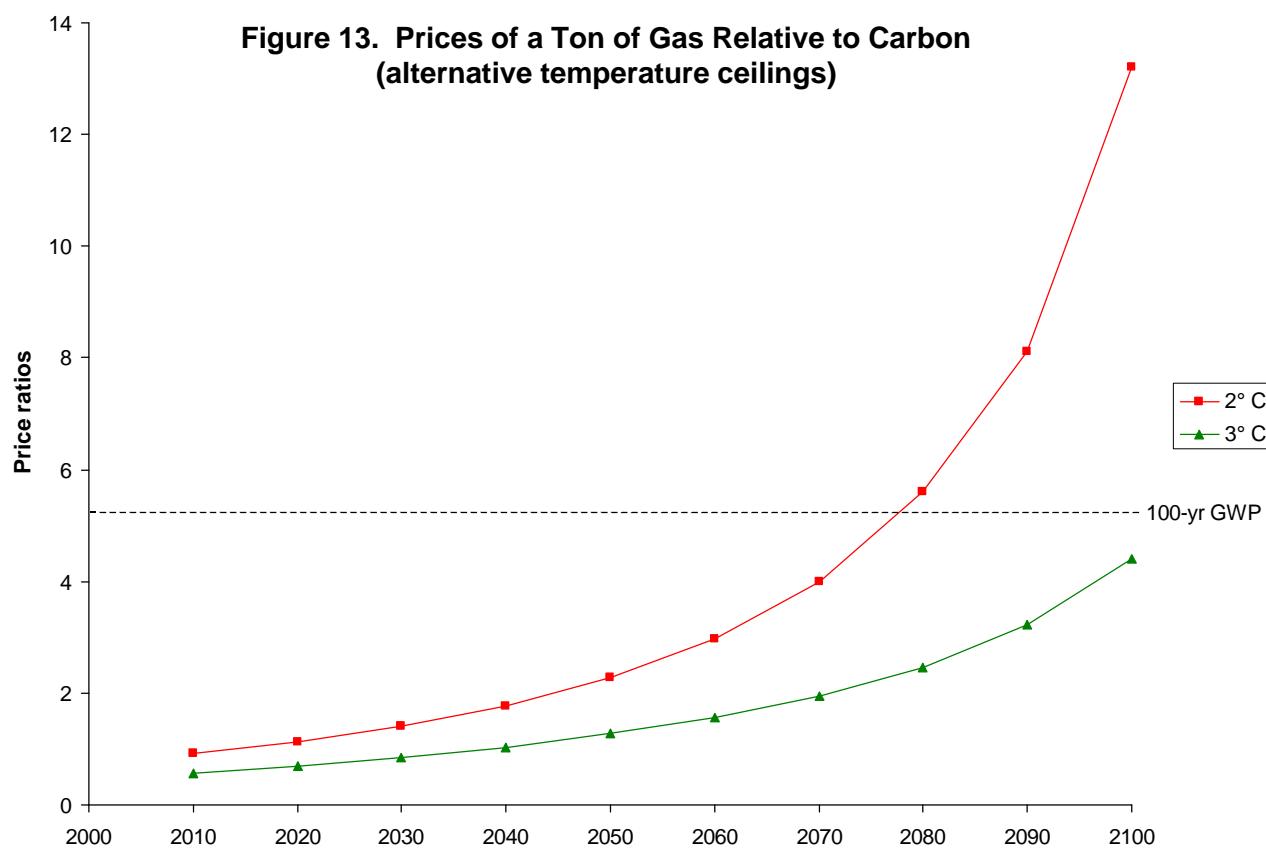
Figure 11. Multi-gas Emission Trajectories -- Reference Case vs. Ceilings of 2° and 3° C (Full “When” and “Where” Flexibility)



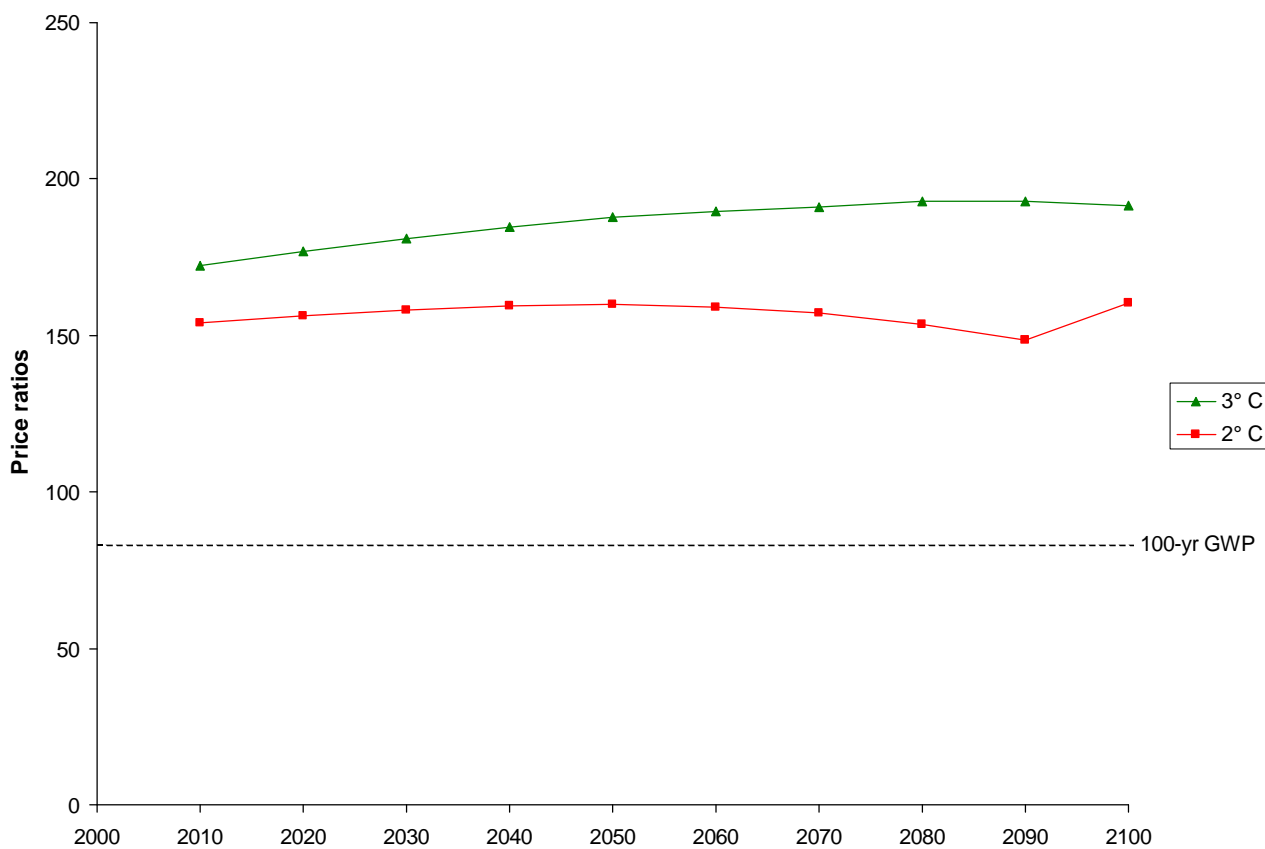
**Figure 12. Incremental Value of Emission Rights
(alternative temperature ceilings)**



**Figure 13. Prices of a Ton of Gas Relative to Carbon
(alternative temperature ceilings)**



a) Price of CH₄



b) Price of N₂O

debate over GWPs. It is important to examine the robustness of near-term decisions in light of the ultimate objectives.

We will explore two approaches -- one based on cost effectiveness and the other based on the balancing of costs and benefits. In each case, the relative contribution of each gas to achieving the goal is an endogenous output rather than an exogenous input. That is, we make an endogenous calculation of the incremental value of emission rights for CH₄ and N₂O relative to CO₂ and examine how the relationships might change over time.

In a cost-effectiveness analysis, the goal is to minimize the cost of achieving a particular objective. In the area of climate policy, objectives have included: limits on emissions, cumulative emissions, atmospheric concentrations, the rate of temperature change, absolute temperature change and damages.

For purposes of illustration, we begin by assuming that the goal of climate policy is to limit the increase in mean global temperature. Using MERGE, we identify the least-cost strategy for staying within the prescribed ceiling. Figure 10 shows the temperature trajectory for the reference case scenario and for ceilings of 2° and 3° C. These trajectories incorporate the cooling effects of sulfate aerosols. Sulfate emissions are assumed to depend largely on local and regional air quality considerations and to be independent of global climate policy.

Associated with each temperature trajectory, there are emission pathways for each of the three greenhouse gases (see Figure 11). The top line in each of the three panels represents the reference case emission trajectory. The other two lines represent optimal pathways for staying within the prescribed temperature ceilings of 2° or 3° C above the level in 2000.

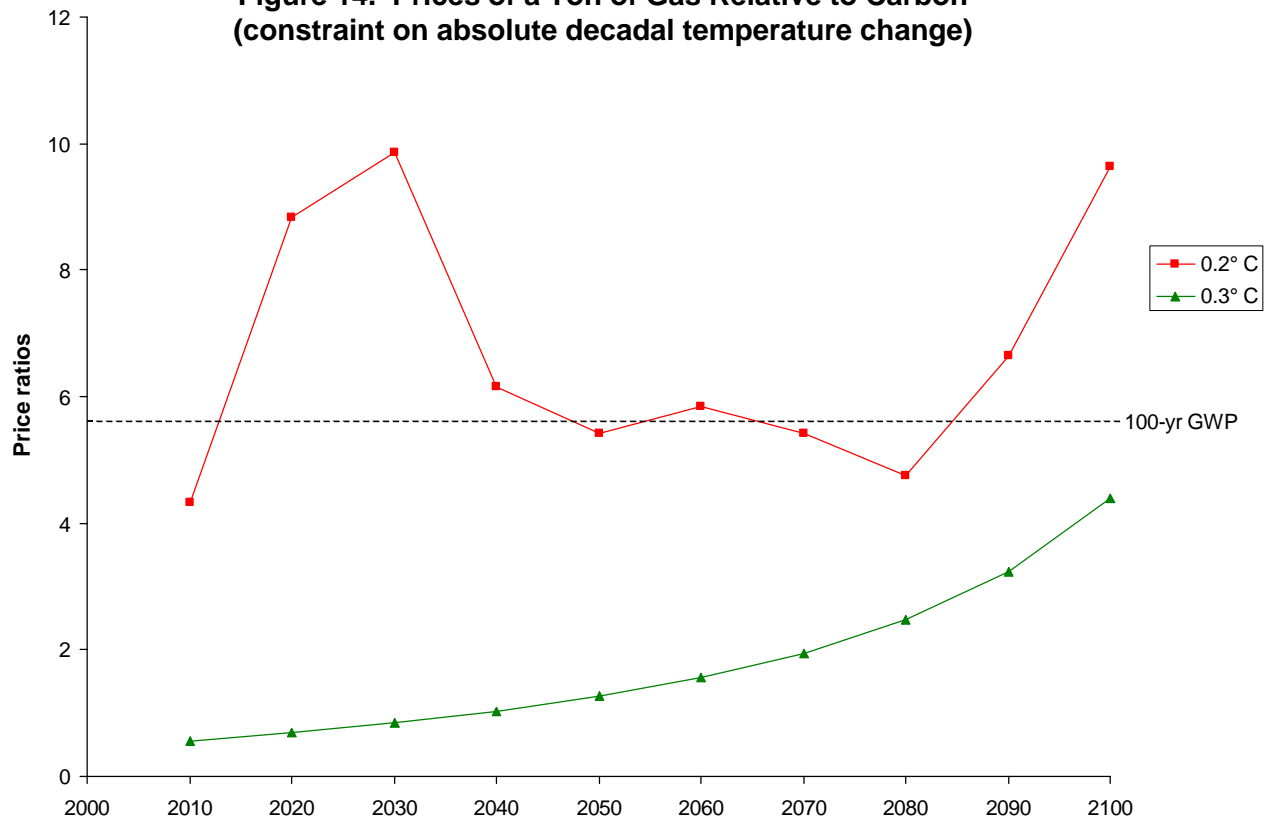
In addition, the model calculates the incremental value of emission rights for each of the three gases (see Figure 12). Not surprisingly, the rate of increase is greater with the more stringent target. The calculations are made under the assumption of full “where” and “when” flexibility. With the first, reductions take place where it is cheapest to do so regardless of the geographical location. With the second, reductions take place when it is cheapest to do so.^a

Figure 13 shows the price of the other two gases relative to that of carbon. It also shows the 100-year GWPs for each gas.^b Notice that the relative prices vary over time. This is particularly so for CH₄. With a relatively short lifetime, a ton emitted in the early decades of the 21st century will have a negligible effect on temperature in the late 21st century. As we approach the temperature ceiling,

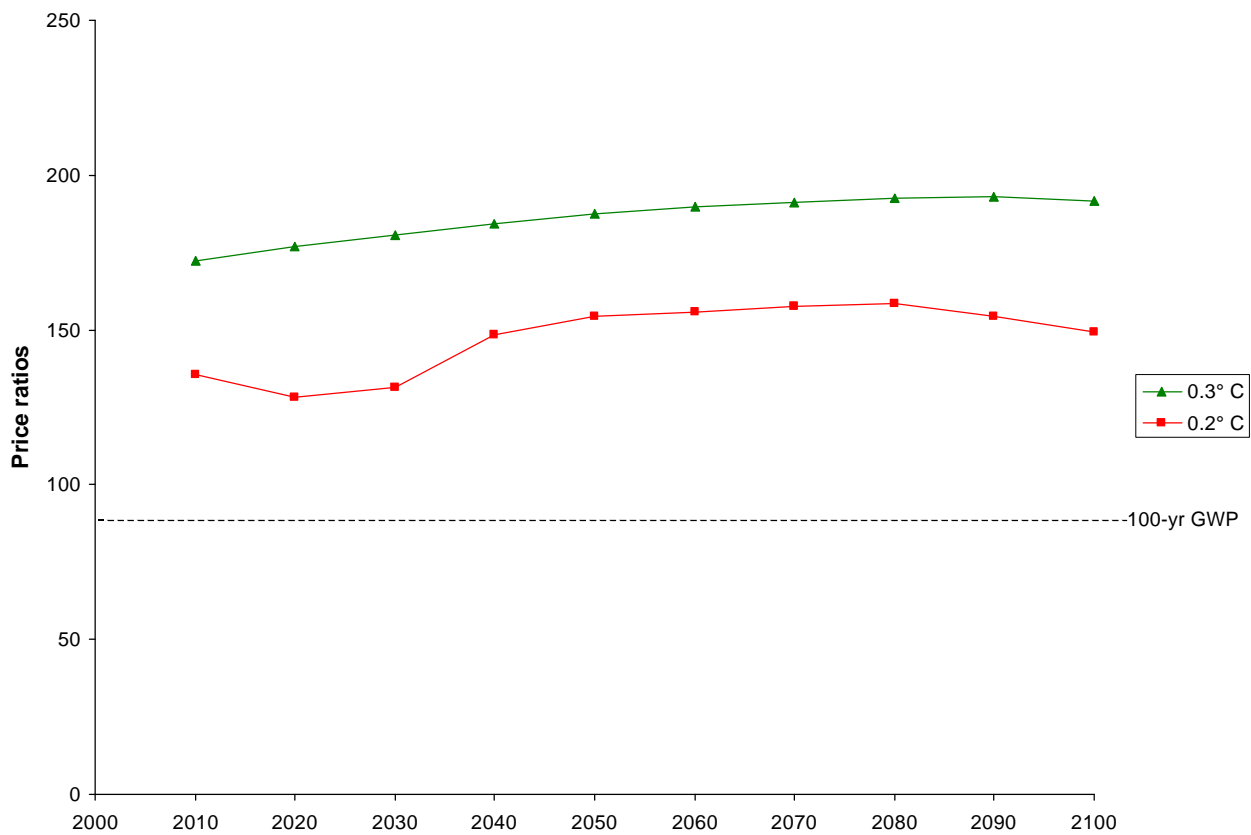
^a Equity need not be sacrificed in order to achieve efficiency. There are alternative ways to make side-payments between regions.

^b Note that we have converted the GWPs from carbon dioxide equivalents to carbon equivalents.

**Figure 14. Prices of a Ton of Gas Relative to Carbon
(constraint on absolute decadal temperature change)**



a) Price of CH₄



b) Price of N₂O

however, emitting CH₄ becomes increasingly problematic. Conversely, N₂O has a lifetime more commensurate with that of CO₂. Hence, its price ratio is less volatile. The price ratios are sensitive not only to the proximity to the ceiling but also to the ceiling itself. Limiting the temperature increase to 2° rather than 3° C produces an entirely different set of weights.

Some have suggested that damages may be sensitive both to absolute temperature change and the *rate* of temperature change. (See for example, Peck and Teisberg, 1994; Toth *et al.*, 1997; Petschel-Held *et al.*, 1999; Alcamo and Kreileman, 1996.) To explore this possibility, we impose an additional constraint on the two temperature scenarios. We limit the allowable increase during a single decade to 10 percent of the total allowable increase. That is, decadal temperature change is limited to 0.2° and 0.3° C, respectively.

With a 2° C ceiling on absolute temperature change, there are decades during the 21st century where the limit on the rate of temperature change would be binding. From Figure 14, note that the price ratios for CH₄ reflect what we observed earlier -- the closer we are to the temperature constraint, the more valuable CH₄ becomes. This appears to be true whether the constraint is on absolute temperature change or on the decadal rate of temperature change.

7. When the objective is balancing costs and benefits

Thus far, we have assumed that the objective is cost-effectiveness. That is, it is to minimize the cost of meeting a specified target. In this section, we illustrate how the model can be used to identify relative prices when the goal is to balance the costs of abatement against what such reductions might achieve in terms of reducing environmental damages.^a

Before proceeding, however, a major caveat is in order. Given the rudimentary state of the existing knowledge base, it would be unwise to place too much weight on any particular set of damage estimates. The primary purpose of this section is to illustrate how such an analysis might proceed. Nevertheless, we find that even an illustrative analysis can yield some useful insights into the nature of the price ratios.

We begin by dividing impacts into two categories -- market and nonmarket. Smith (1996) reviewed several studies of the potential impacts of climate change on the US. With regard to market impacts, these studies showed considerable disagreement at the sectoral level. Based upon our reading of the literature, we assume that a 2.5° C

^a With a cost-effectiveness analysis, one ensures that the marginal cost of emission reductions is the same for all greenhouse gases. With a benefit-cost analysis, one also ensures that these marginal costs are equal to the marginal benefits of emission reductions.

Figure 15. Temperature Change, °C -- Reference vs. Two Pareto Optimal Cases

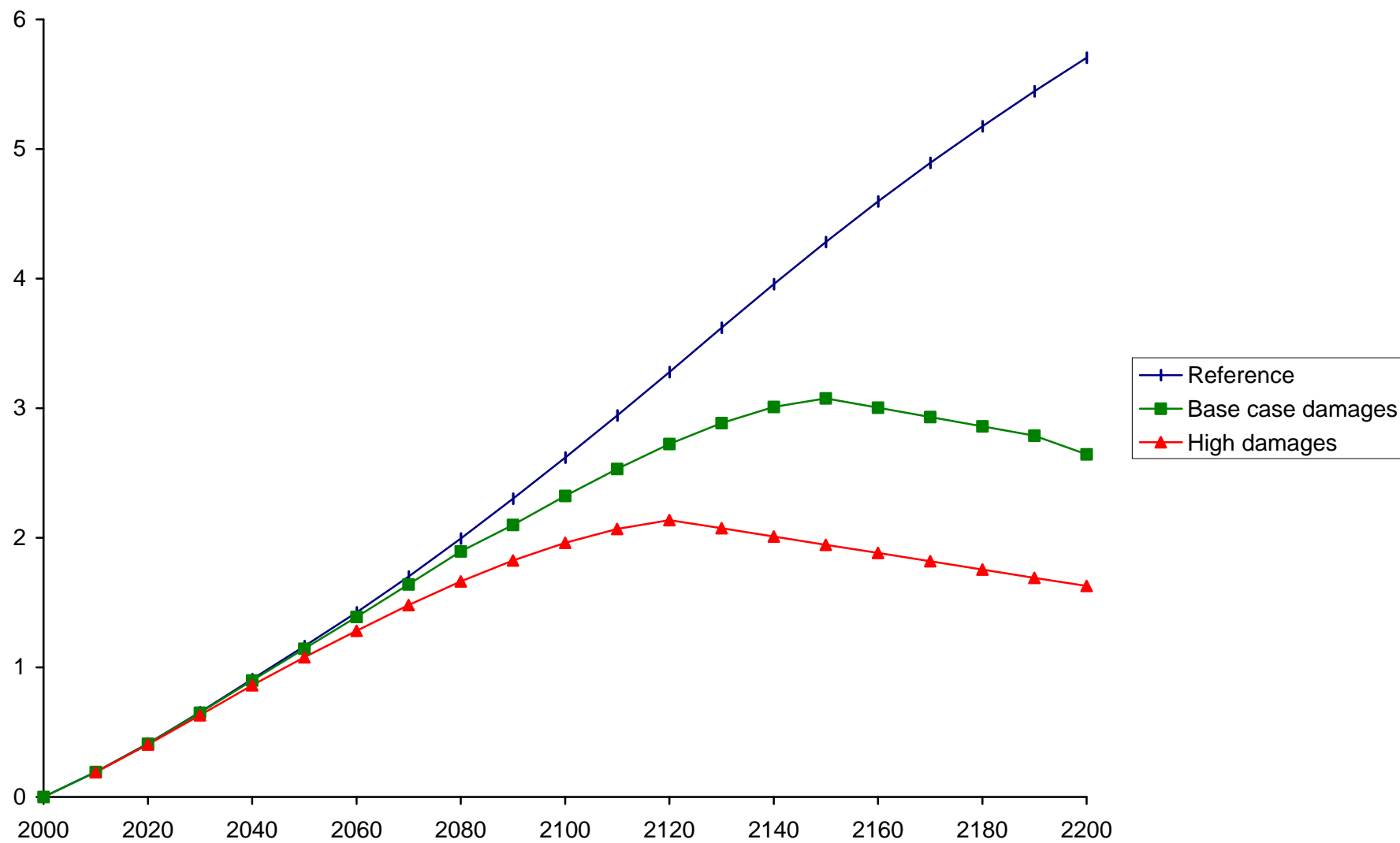
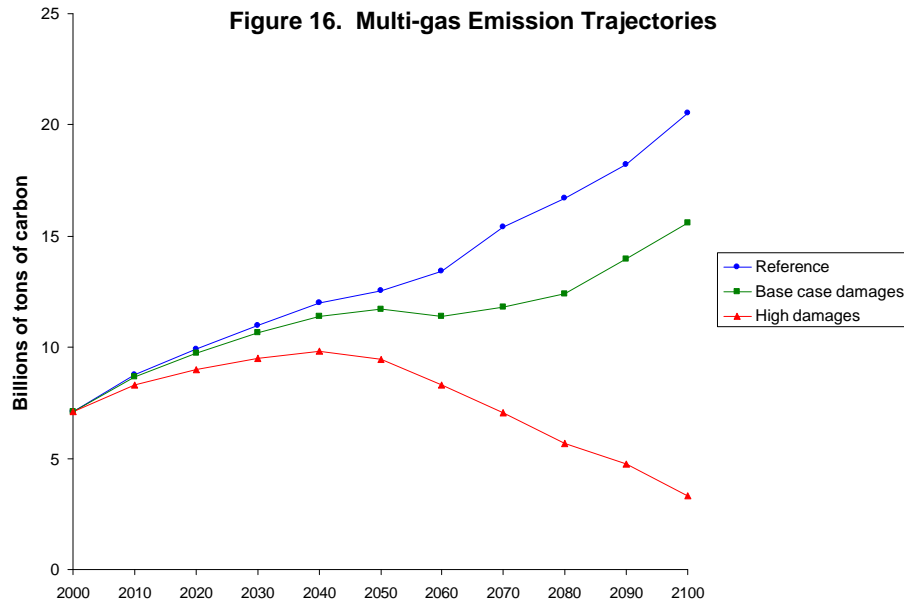
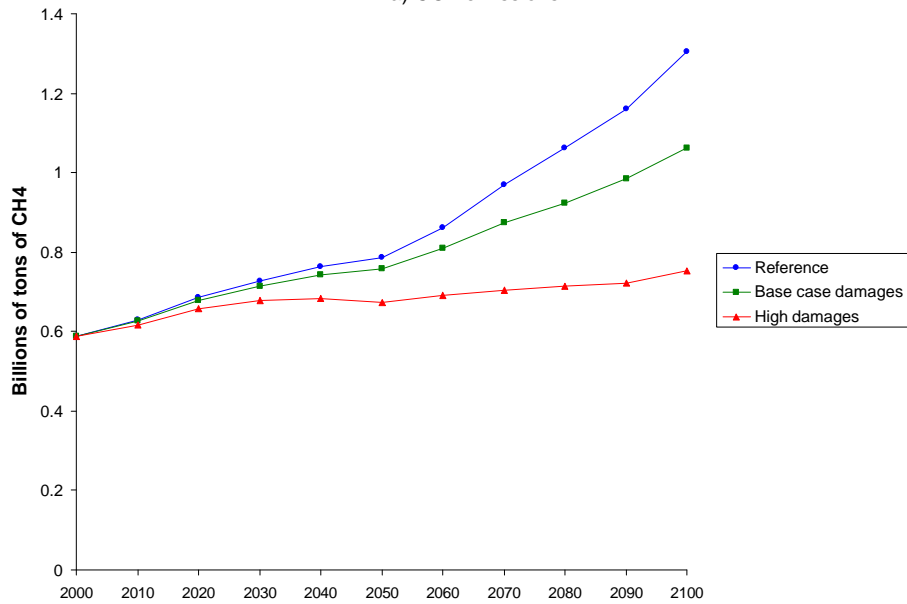


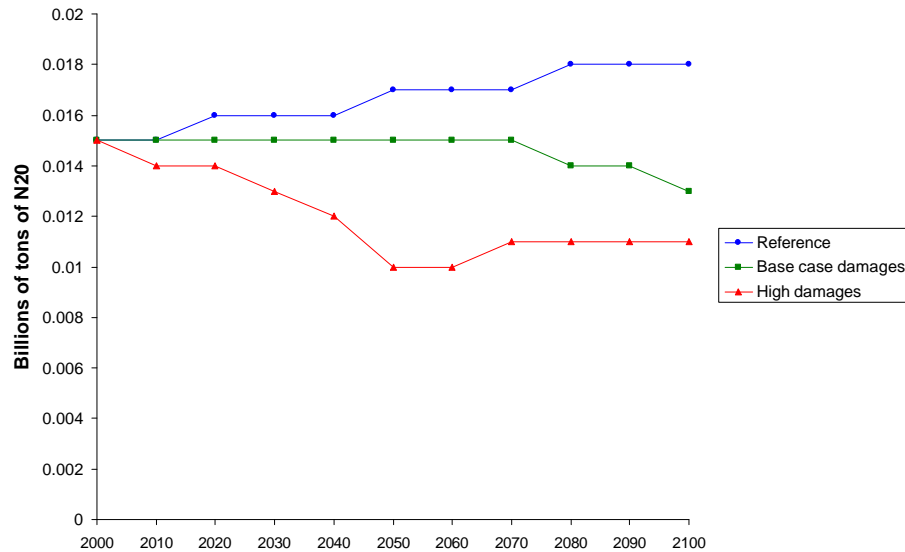
Figure 16. Multi-gas Emission Trajectories



a) CO2 emissions



b) CH4 emissions



c) N2O emissions

Figure 17. Incremental Value of Emission Rights

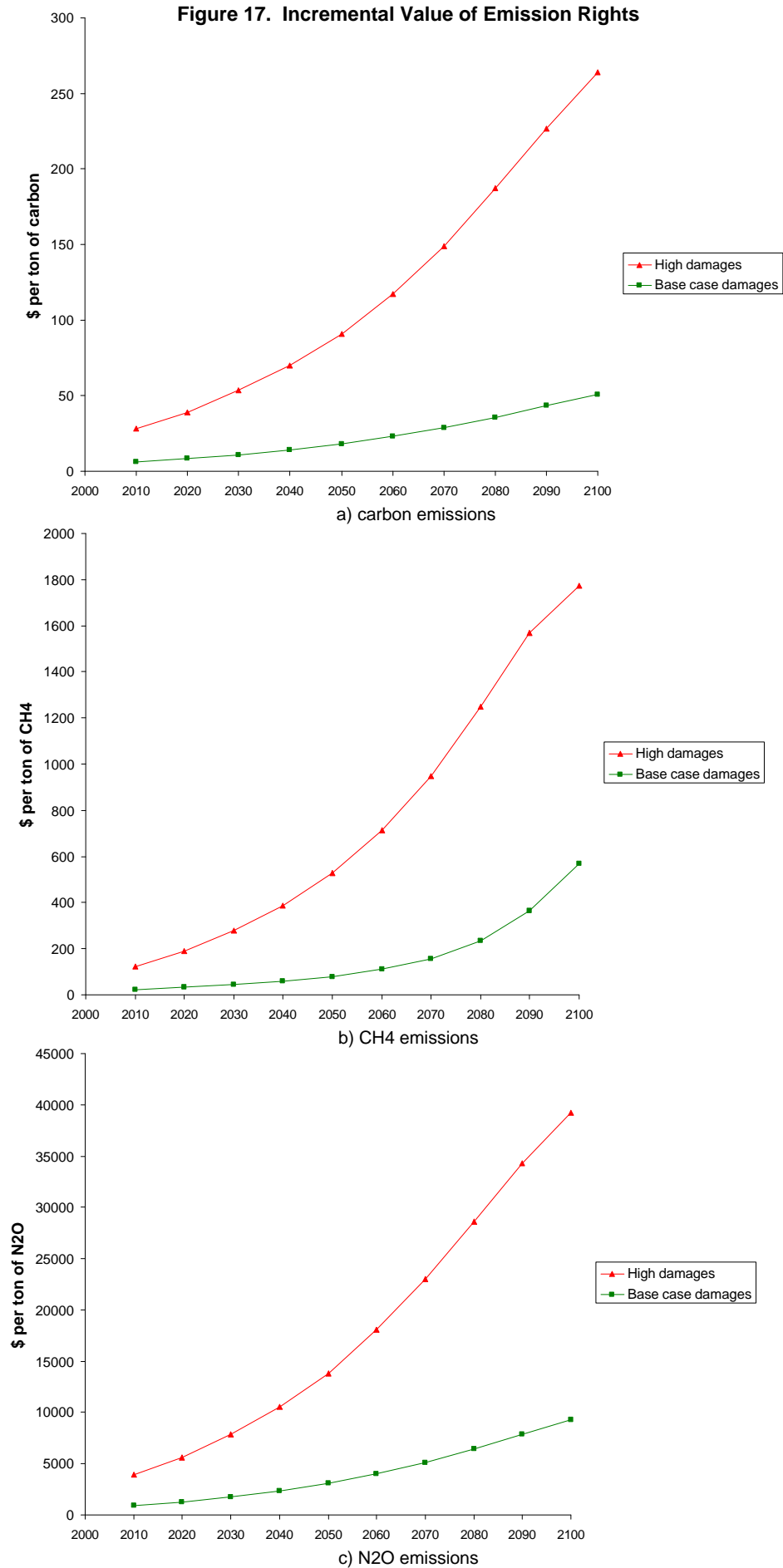
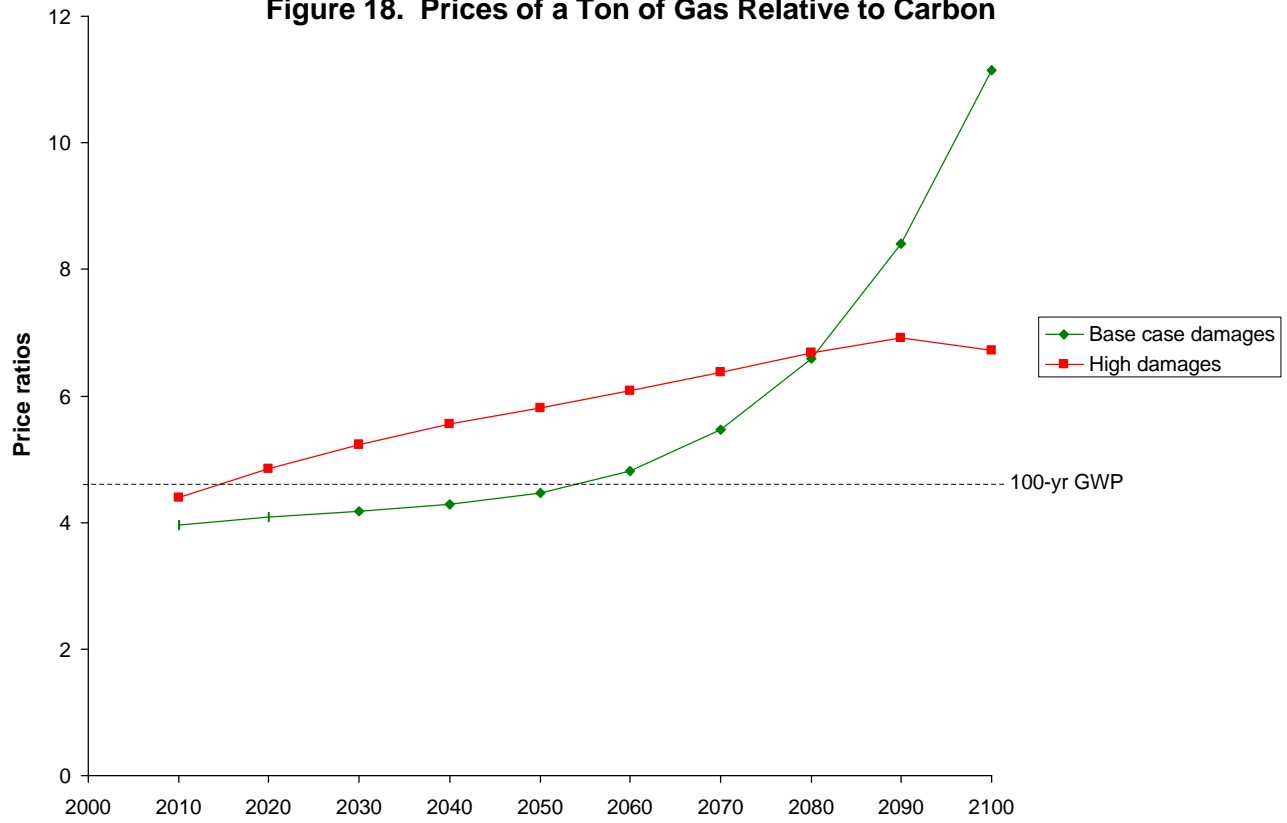
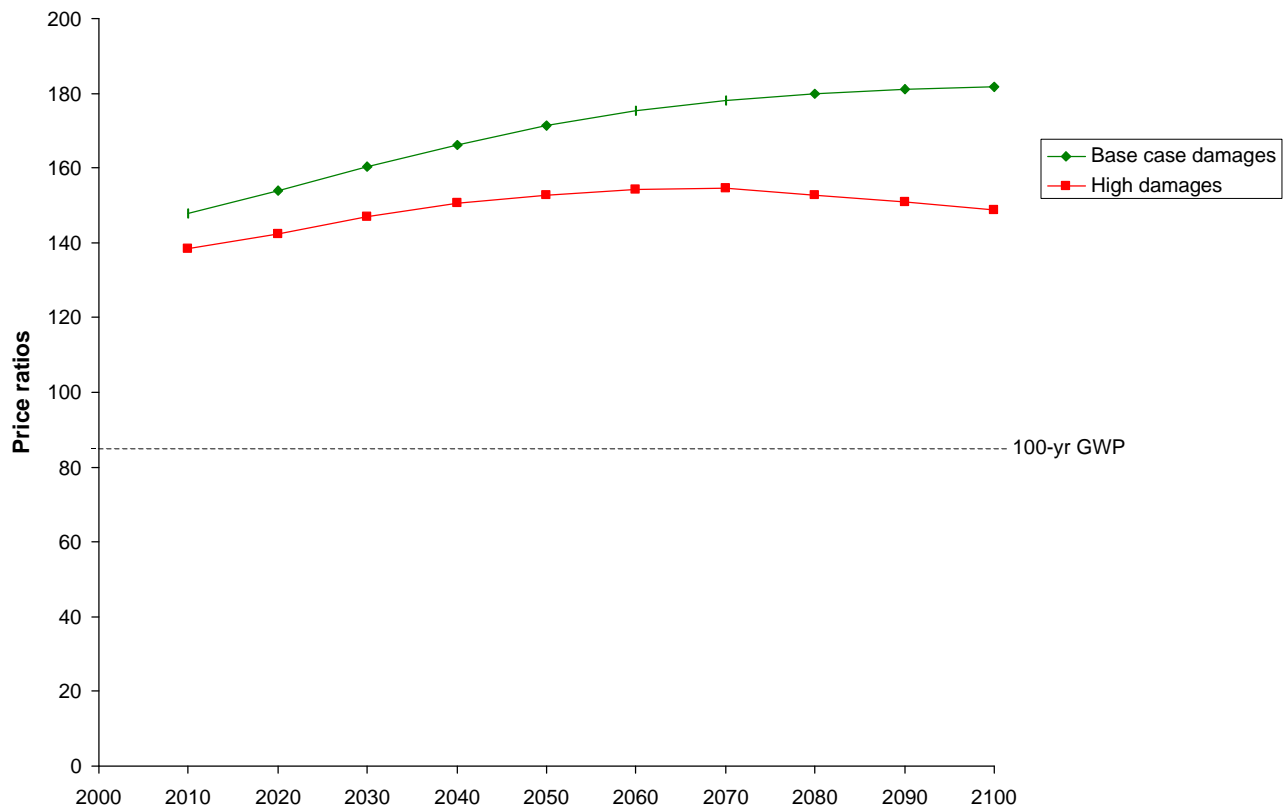


Figure 18. Prices of a Ton of Gas Relative to Carbon



a) Price of CH₄



b) Price of N₂O

increase in temperature (beyond current levels) would result in market damages of the order of 0.25% of GDP to Annex B countries.

Unfortunately, there has been relatively little analysis of the potential impacts of climate change on developing countries. Because they tend to have a larger share of their economies concentrated in climate sensitive sectors, we assume that market damages are apt to be a higher percentage of GDP. Specifically, we assume that a 2.5° C increase in temperature would result in market damages of 0.50% of GDP in developing countries. For all regions, market damages are projected as proportional to the amount of temperature change.

For our base case estimates of *nonmarket* damages, we assume that when per capita incomes approach \$40 thousand (about twice the 1990 level in the OECD nations), consumers would be willing to pay 2% of their incomes to avoid a 2.5° C increase in temperature. (As a point of reference, the US today spends about 2% of its GDP on all forms of environmental protection.) For high income countries, we assume that damages would increase quadratically with increases in the mean global temperature. For example, consumers would be willing to pay 8% of their incomes to avoid a 5° C increase. Of all the parameters in our model, this is perhaps the most uncertain. For purposes of sensitivity analysis, we explore a much more pessimistic scenario, one in which consumers are willing to pay 2% of their incomes to avoid just a 1° C increase in temperature and 8% of their incomes to avoid a 2° C increase.

Figure 15 shows the Pareto optimal temperature paths for the base case damage and high damage scenarios. With the base case damage estimates, temperature peaks at approximately 3° C above current levels. Conversely, under the high damage scenario, the maximum increase is only about 2° C. Figure 16 shows the Pareto optimal emission trajectories associated with the two damage scenarios and compares them with that of the reference case. As one would expect, the most aggressive reductions are associated with the high damage scenario. Here, the emission trajectories depart from the baseline in 2010. With the base case damage scenario, the departure from the baseline is delayed by at least a decade. Figure 17 compares the incremental value of emission rights for the two damage scenarios. Not surprisingly, they are much higher for the more pessimistic scenario. Finally, Figure 18 compares the prices of CH₄ and N₂O relative to that of carbon.

The above results are similar in many respects to that of the cost-effectiveness analysis with a constraint on absolute temperature change. With a temperature ceiling, we are in essence adopting an L-shaped damage function. That is, we are assuming that damages are zero below the ceiling and infinite thereafter. With the aggregate damage function employed in our benefit-cost analysis, we have damages rising slowly in the early years and more rapidly later on. While not exactly an L-shaped damage function, it nevertheless produces *qualitatively*

similar results. That is, we again find the value of the non-CO₂ gases relative to CO₂ to vary over time. We also find the value of CH₄ to increase significantly as we approach the *bend* in the damage function. Finally, we find the price ratios to be extremely sensitive to the damage functions chosen for the analysis.

8. Some concluding thoughts

Until recently, climate policy analyses have focused almost exclusively on CO₂ emissions abatement. This is not surprising, given the importance of CO₂ relative to other greenhouse gases, the capabilities of existing models, and the paucity of data related to the non-CO₂ gases. Nevertheless, a “CO₂ emissions only” focus can lead to significant biases in the estimation of compliance costs. Accordingly, existing models are being modified to account for a broader array of greenhouse gases.

This paper documents one such modeling effort. Before summarizing our conclusions, we again stress the preliminary nature of the results. Calculating the long-term implications of CO₂ emissions abatement has always been a daunting task. The problem is compounded with the addition of other gases. Still, we believe that the present analysis, although illustrative in nature, highlights some important considerations for policy makers.

We address four questions: (1) What are the implications of a multi-gas approach when designing policies for complying with the Kyoto Protocol? (2) How sensitive is the optimal mix of mitigation options to the choice of GWPs? (3) Are there alternative approaches, which provide a more logical justification for action? (4) if so, what are their strengths and weaknesses?

We begin by adopting the 100-year GWPs recommended by the IPCC. It is not obvious, *a priori*, whether a multi-gas approach will increase or decrease the immediate costs of complying with the Protocol. In terms of carbon equivalence, incorporating the non-CO₂ greenhouse gases increases the size of the required reduction, but it also expands the portfolio of mitigation options. Based on what we believe to be plausible assumptions regarding the marginal costs of emissions abatement, we find that a multi-gas approach benefits all Annex B regions with the exception of Eastern Europe and the former Soviet Union (EEFSU).

EEFSU is a major seller of emission rights -- whether we adopt a CO₂ emissions only or a multi-gas approach. The inclusion of the non-CO₂ gases and carbon sinks expands the available mitigation options. In doing so, it reduces the incremental value of emission rights. Although the demand for emission rights increases, the increase is insufficient to offset the decline in price. Hence, EEFSU experiences a fall in revenue. Conversely, the four OECD regions benefit from a

multi-gas approach. The fall in the price of emission rights reduces the need for costly domestic reductions. For example, in the US, there is a 30% decline in domestic CO₂ abatement as we move from a CO₂ emissions only to a multi-gas approach.

The optimal mix of mitigation options is sensitive to the time horizon used to calculate the GWPs. For CH₄, the GWP for a 20-year time horizon is approximately eight times that of the GWP for a 500-year time horizon. This has important implications for the amount of zero-cost (“hot air”) and low-cost emission rights available for sale by EEFSU. Both increase with the shorter time horizon.

Given the lack of a rationale for choosing one set of GWPs over another, we examined two alternatives for establishing tradeoffs between gases. The first was based on cost-effectiveness analysis, the second on benefit-cost analysis. In the former, we imposed a ceiling on the mean global temperature increase. We then identified the least-cost strategy for not exceeding the ceiling. We found that the price of the non-CO₂ gases relative to that of carbon tended to vary over time. This was particularly so in the case of CH₄. With its relatively short lifetime, its value increased as we approached the temperature ceiling. The tighter the ceiling, the more rapid the increase in value. We observed a similar phenomenon when we added a constraint on the rate of temperature change in any one decade. The incremental value of CH₄ was particularly high when the rate of temperature change approached the prescribed limit.

A number of studies have noted that in order to derive optimal control policies, we must consider the discounted damages of emissions from each gas. Here, the goal is to balance the cost of abatement with what such reductions might achieve in reducing environmental damages. Although this approach provides a more rational basis for climate policy, we currently lack the necessary knowledge base for specifying the shape of the damage functions and for valuing undesirable impacts. Nevertheless, through sensitivity analysis we were able to develop some insights as to the relative weights of the various gases.

Both the cost-effectiveness analysis and the benefit-cost analysis highlight the shortcomings of GWPs for establishing equivalence among gases. Not only do the price ratios vary over time, but they also are sensitive to the ultimate goal. Ideally, the price ratios would be the product of an analysis which minimized the discounted present value of damages and mitigation costs. Unfortunately, given the current state of knowledge regarding potential damages, such an approach may be premature. If indeed this is the case, focusing on temperature change may have distinct advantages over GWPs. It could serve as a temporary surrogate for benefit-cost analysis.

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