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(MERGE)

**On Stabilizing CO₂ Concentrations -
Cost-Effective Emission Reduction Strategies**

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1. Introduction

In recent years, global climate change has become one of the most contentious environmental issues facing the international community. The UN Framework Convention calls for the "stabilization of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."¹ Yet the issue of what constitutes "dangerous anthropogenic interference" is likely to remain the subject of intense scientific and political debate for some time. For the present, international negotiations must remain an ongoing process -- with ample opportunities for learning and for midcourse corrections.

We are currently in the midst of one such review cycle. When initially put forward at the "Earth Summit" in 1992, the Framework Convention called upon developed countries to aim to return emissions to 1990 levels by the year 2000. At the first meeting of the Conference of the Parties in 1995, these commitments were deemed inadequate. As a result, the so-called "Berlin Mandate" was adopted. This called upon developed countries to set "quantified limitation and reduction objectives" for the post-2000 time frame.²

Although the Berlin Mandate is explicit in its call for additional reductions, it does not specify how large the reductions should be. Rather it specifies an "analysis and assessment" phase to help inform the decision making process. The deadline for new commitments is December 1997. A wide variety of proposals have been put forward in anticipation of this deadline. These proposals range from sharp cuts in near-term emissions to a more gradual transition away from carbon-intensive fuels. The international research community is actively engaged in trying to understand the environmental and economic implications of these policy proposals.

This paper is intended to contribute to the process of analysis and assessment. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO₂ concentrations to alternative levels. We then explore the implications for near-term mitigation decisions and for long-term participation by the developing countries.

There are several reasons why a broader perspective is desirable. The Intergovernmental Panel on Climate Change (IPCC) has demonstrated that if CO₂ concentrations were to be stabilized at any of the levels it examined, this would require an eventual and sustained reduction in emissions to

substantially below current levels.³ Developed countries cannot do the job by themselves. Nor can the transition be accomplished overnight. Cost-effective strategies will require both a global and a long-term perspective.

Any analysis of stabilization must confront the divisive issue of burden sharing. With trade in carbon emission rights, emission reductions can be made where it is cheapest to do so, regardless of their geographical location. The allocation of permits will have little impact on the least-cost global strategy.⁴ It will, however, have profound affects on who pays. Consistent with the Framework Convention, we adopt a burden sharing scheme that initially places the onus on developed countries. We then discuss the implications for international negotiations.

Economic analysis can play an important role in the climate debate. It can help policy makers identify least-cost mitigation strategies from a global perspective. In doing so, this helps to minimize the size of the overall burden. It can shed light on the implications of alternative burden sharing schemes at the regional level. Economic analysis, however, cannot tell us how a given burden *should* be allocated. Fairness and equity issues must necessarily be left to the international negotiation process.

Finally, we emphasize that our analysis is confined to mitigation costs. We recognize that this is not the whole story, but it is an important part. Article 3 of the Framework Convention states that "policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible costs."⁵ Identifying least-cost mitigation strategies can free up valuable resources for addressing alternative uses.

2. The model

The analysis is based on MERGE – a model for evaluating the regional and global effects of greenhouse gas reduction policies. MERGE provides a bottom-up representation of the energy supply system. For a given scenario, a least-cost choice is made among specific technologies for the generation of electricity and for the production of nonelectric energy. As fossil fuels (coal, oil and gas) are exhausted, their prices rise and carbon-free alternatives become more competitive. To allow for inertia in the energy supply system, decline and expansion constraints are placed on existing and new technologies, respectively.

A top-down perspective is taken for the balance of the economy. These sectors are modeled through nested constant elasticity of substitution production functions. The production functions determine how aggregate output depends upon the inputs of capital, labor, electric and nonelectric energy. In

this way, the model allows for both price-induced and autonomous (non-price) energy conservation and also for interfuel substitution. A "putty-clay" formulation is used to allow for the lags in adapting to changes in energy prices.

In MERGE, the savings and investment process is affected by intertemporal and interregional forces. Each region is represented as though it maximizes discounted utility (the logarithm of consumption) subject to an intertemporal budget constraint. Its wealth includes not only capital, labor, and exhaustible resources, but also its negotiated share in global carbon emission rights. With this objective function, the costs of abatement are defined as the losses in the discounted value of consumption associated with alternative carbon constraints.

In previous versions of MERGE, the world was subdivided into five geopolitical regions.^{6,7} The present version of the model, known as MERGE 3.0, divides the world into nine regions: 1) the USA, 2) OECD (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). The further disaggregation provides better alignment with the Annex 1/non-Annex 1 structure of the Framework Convention. It provides more details concerning winners and losers under alternative burden sharing schemes, and it distinguishes between the major oil importing and exporting regions.

Population trends for each region are taken as exogenous. Per capita incomes are determined primarily by the rate of labor force productivity. Between 1990 and 2020, our projections are consistent with the conventional wisdom median values of the International Energy Workshop poll.⁸ For the world as a whole, GDP growth is projected at an average annual rate of 2.5% between 1990 and 2100. It is assumed that there are ultimate limits to economic growth, and that there will eventually be convergence between the per capita incomes in the OECD countries and those in the rest of the world. Figure 2.1 shows our specific projections of per capita GDP in each of the nine regions.

MERGE is based on a general equilibrium formulation of the global energy-economic system. This enables us to model trade in oil, gas and carbon emission rights. The model does not, however, account for the effect of an economic slowdown in one region on the full range of exports of another. It may therefore be ignoring some important "spillover" effects. MERGE is not designed to address short-run macroeconomic issues such as unemployment and inflation. The employment level is exogenous, and there are instantaneous adjustments to policy shocks. As a result, the model may overlook some costly short-term dislocations.

When we assume that reductions take place wherever it is cheapest to do so (regardless of the geographical location), we refer to this as "interregional" or "where" flexibility. When there is a choice in the timing of emission reductions, we refer to this as "intertemporal" or "when" flexibility.

The burden sharing rule. Region-specific mitigation costs will also depend upon how emission reductions are allocated among regions. Consistent with the Berlin Mandate, we assume that the burden will fall on Annex 1 countries during the initial decades of an agreement. During this period, Annex 1 countries would be required to limit their emissions to amounts proportional to their 1990 levels.

Even if the Annex 1 countries were to reduce their emissions to zero, this would not be sufficient to limit global concentrations. Eventually, the non-Annex 1 countries will also have to limit their emissions. The ultimate concentration target will affect the date at which these non-Annex 1 countries must begin to participate in a global agreement. The more ambitious the target, the sooner they will have to participate in such an agreement. Once the non-Annex 1 countries do agree to a constraint, however, it is plausible to assume that there will be a gradual transition to equal per capita emission rights. (For one such scheme, see Table 3.1.)

Table 3.1 Structure of Burden Sharing Scheme

Concentration target (ppmv)	Date at which non-Annex 1 countries must begin to limit emissions	Date by which transition to equal per capita emission rights is achieved
450	2020	2040
550	2030	2050
650	2040	2060
750	2050	2070

With "where" flexibility, global mitigation costs are independent of the burden sharing scheme. That is, reductions will take place wherever it is cheapest to do so regardless of the geographical location. This is not the case, however, when emission reductions are restricted to the region of origin. With this type of restriction, the burden sharing scheme will affect both the global and the regional costs.

Shifting emission reductions into the future provides valuable time for: 1) adapting the energy using and energy producing capital stock, 2) developing low cost substitutes to carbon intensive fuels, and 3) removing carbon from the atmosphere via the carbon cycle. In addition, with the economy yielding a positive return on capital, future reductions can be made with a smaller commitment of today's resources. For a more detailed discussion of these factors, see ref. (11).

Figure 4.2 also estimates the benefits from international cooperation. Without "where" flexibility, the immediate emission reductions are confined directly to the Annex 1. The more countries that participate in an international agreement, the greater become the opportunities for cost-effective trades. It then becomes possible for countries with high marginal abatement costs to purchase emission rights from countries with low marginal abatement costs.

From a global perspective, combining "where" flexibility with a more gradual transition away from fossil fuels substantially reduces the present value of mitigation costs. It turns out that there can be cost reductions as high as 90% when we combine both types of flexibility. (Compare the leftmost to the rightmost bar in Figure 4.2.) The discounted cost savings to the international community appear to be of the order of trillions of dollars over the 21st century. This is consistent with earlier studies which focused exclusively on near-term targets and timetables.^{18,19}

Table 3.1 describes a burden sharing rule that is particularly favorable to the non-Annex 1 countries during the early decades of the next century. This is why the mitigation costs are lowest for non-Annex 1 countries under the WG1 pathway when we allow for "where" flexibility. Indeed, the WG1 emission constraints creates a sufficiently high price for emission rights and high wealth transfers during the early decades of the coming century so that the non-Annex 1 countries are actually better off in the presence of a carbon constraint than in its absence. This particular result should not, however, obscure the fact that from a global perspective, costs are far lower under the WRE pathway.

5. Annual losses when stabilizing concentrations at 550ppmv

Figure 4.2 summarizes abatement costs in terms of discounted present value – summing over all time periods. Additional insights can be gained by looking at how losses might evolve over time. In MERGE, we adopt consumption as our welfare measure. Relative impacts are more apparent when we measure annual losses in percentage rather than absolute dollar terms.

CO2 mitigation costs are determined by 1) the emissions baseline – i.e., how emissions are apt to grow in the absence of policy interventions, 2) the cost and availability of alternative supply and demand-side options, and 3) the magnitude of the CO2 constraint. For the present analysis, several supply and demand parameters of the energy-economy submodel have been adjusted so that the baseline tracks the IPCC IS92a⁹ scenario through the year 2100. Figure 2.2 shows carbon emissions for the OECD, EEFSU and non-Annex 1. Figure 2.3 shows the corresponding total primary energy use by fuel type.

Some observers have suggested that the exogenous specification of technical change will overstate the costs of a carbon constraint. They argue that an international carbon abatement agreement will automatically induce innovations in carbon-saving technologies. We do not share their optimism on the automatic nature of such innovations. (Consider, for example, the history of both fission and fusion technologies.) We do believe, however, that carbon constraints might speed up the process of technology diffusion.

MERGE 3.0 incorporates the notion of “endogenous technology diffusion”. Specifically, in the electric power sector, the near-term adoption of high cost carbon-free substitutes makes it possible to introduce low-cost alternatives more rapidly in the future. Upon request, the authors will supply computer files that fully document the assumptions underlying the model.¹

3. Scenario design

We focus on three factors critical to determining the costs of stabilizing concentrations at a particular level: the choice of global emissions pathway, the degree of international cooperation and the burden sharing scheme. In this section, we describe our assumptions with regard to each.

The global emissions path to stabilization. In 1994, Working Group I (WG1) of the Intergovernmental Panel on Climate Change (IPCC) published a set of concentration profiles for stabilizing atmospheric CO2 at 350, 450, 550, 650 and 750ppmv.¹⁰ The purpose of their estimates was to illustrate what might be required in terms of global CO2 emissions reductions in order to stabilize concentrations at these different levels. Subsequently, Wigley, Richels and Edmonds (WRE) published an alternative set of emission profiles for achieving the WG1 concentration targets.¹¹ Although WG1 and WRE are identical in terms of the prescribed stabilization levels and attainment dates, they differ in the routes to stabilization (Figure 3.1a). The IPCC, while not taking a position on the desirability of one set over another, published both in their 1995 scientific assessment.¹²

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Figure 3.1b shows the emission rates required to achieve stabilization via the WG1 concentration profiles (the dashed lines) and the WRE concentration profiles (the solid lines). The calculations were made using the Wigley carbon cycle model. The WRE curves were constructed so that they would follow the central IPCC "existing policies" or "baseline" emissions scenario (IS92a) in the early years. The higher the stabilization target, the longer the adherence to IS92a. In contrast, the WG1 curves depart from IS92a immediately.

WRE assert that concentration pathways with higher near-term emissions are apt to have lower mitigation costs. They cite several economic studies that have examined how mitigation costs might vary with the timing of emission reductions.^{13,14,15,16} These studies suggest that the time path to stabilization may be as important as the concentration target itself in determining the overall discounted costs. They conclude that emission pathways that provide for a gradual transition away from fossil fuels are apt to be less expensive in terms of mitigation costs.

The WRE analysis is primarily qualitative. While drawing upon other studies to make their points, no explicit analysis is made of the mitigation costs associated with either the WG1 or WRE pathways. This is the issue to which we now turn. In this paper, we examine the costs of stabilizing concentrations at 450, 550, 650, and 750ppmv, first following the WG1 emissions pathway and then those suggested by WRE. In each case, we examine the costs to Annex 1 and non-Annex 1 countries under alternative burden sharing schemes.

The extent of international cooperation. A number of studies have shown that the marginal costs of emissions abatement might vary considerably among regions.¹⁷ This will be particularly the case in those periods when emission reductions are confined to Annex 1 countries. Clearly, it is inefficient to incur high marginal domestic abatement costs in Annex 1 countries when the marginal cost of emissions abatement is lower in non-Annex 1 countries. It is equally clear that it would be unrealistic to expect the non-Annex 1 countries to bear the burden of domestic reductions so as to achieve a globally cost-effective result.

This suggests opportunities for efficiency gains through various forms of "joint implementation". This could be done on a bilateral project-by-project basis during the earlier years of an international agreement. Over the long term, however, it is more promising to explore market mechanisms such as a system of international allocations of tradable carbon emission rights. Here we first examine mitigation costs when emission reductions are confined to the region of origin. We then calculate the benefits from international cooperation using trade in emission rights as a proxy for other forms of cooperative mechanisms with side payments.

4. Global costs of stabilization at 550ppmv

Mitigation costs are incurred when the imposition of a carbon constraint leads to a reallocation of resources from the pattern that would be preferred in the absence of the constraint. A carbon constraint will lead to more expensive conservation activities and to fuel switching. There are changes in both domestic and international prices. In most cases, these forced adjustments lead to a reduction in economic performance. The tighter the constraint, the greater the effect.

With MERGE, we can calculate how mitigation costs vary with the choice of concentration profile. At the present time, there is little consensus on what constitutes an appropriate concentration target. There is even less consensus on the choice of a pathway to stabilization. We shall begin by focusing on a concentrations target of 550ppmv – approximately twice the preindustrial level. Later, we will explore the implications of adopting alternative concentration targets.

Figure 3.1b shows two sets of emission pathways for stabilizing concentrations at 550ppmv. The burden sharing rule (Table 3.1) will determine how emissions might be apportioned between regions. The results are summarized for three broad groups of countries: 1) the OECD (USA, Western Europe, Japan, Canada, Australia and New Zealand), 2) EEFSU (Eastern Europe and the former Soviet Union) and 3) developing countries. In the language of the Framework Convention, the first two groups are described as Annex 1 countries. All others (the developing countries) are non-Annex 1 countries.

Figure 4.1 shows the implications of the burden sharing rule for these three regional groupings. The figure provides some insight into both global and regional costs. Under the WRE scenario, Annex 1 countries have some room for emissions growth, at least during the early decades of the 21st century. This is not the case, however, under the WG1 scenario. Here, Annex 1 emission reductions must begin immediately. This decline would be inconsistent with post-1990 trends in all but a few countries.

Figure 4.2 compares mitigation costs over the 21st century. Consumption losses are expressed in constant dollars, discounted to 1990 at 5% per year. Notice that costs are considerably lower for the WRE pathway. There are several reasons why this turns out to be the case. A concentration target defines an emissions budget, i.e., an allowable amount of carbon to be released between now and the date at which the target is to be achieved. A cost-effectiveness analysis is focused upon how this global budget might be allocated over time.

In order to explain the pattern of annual losses, it is first necessary to say something about the impact of a carbon constraint on world oil prices. A carbon constraint would have roughly the same consequence as monopsonistic cartel behavior on the part of oil importing nations.

Figure 5.1 shows the international price of oil for the reference case and under the alternative pathways for stabilizing concentrations at 550ppmv. Note that oil prices are quite sensitive to the pathway to stabilization. With a tight near-term constraint, there is a drop in the international demand for crude oil. This has a dramatic effect on oil prices. There can be a differential of as much as \$20 per barrel between the reference and the WG1 cases. This has important implications for the costs of a carbon constraint to both oil exporting and oil importing countries.

Figure 5.2 compares annual welfare losses across scenarios for each of the three broad regional groupings. Under WG1, the Annex-1 countries must begin reducing emission immediately. Losses are highest when there is no opportunity for trading emission rights. Losses rise to more than 3% and 6% of annual consumption for the OECD and EEFSU, respectively. As a major importer of oil, the OECD benefits from the decline in world oil prices. Hence, its losses are partially mitigated. EEFSU, on the other hand, is a substantial exporter. As a result, it will be adversely affected by a drop in world oil prices, and this compounds its losses from a near-term carbon constraint.

The non-Annex 1 region consists of both oil exporting and oil importing countries. Under the burden sharing scheme described in Table 3.1, the WG1 proposal leads to substantial net benefits in the early years, particularly with "where" flexibility. A tight near-term global emissions constraint would create a large demand for emission rights in Annex 1 countries. Since non-Annex 1 countries have carbon allocations up to their baseline emissions, it is in their interest to engage in domestic abatement, and to sell some of their rights to Annex 1 countries.

With the parameters employed in this version of MERGE, there is a net benefit to the non-Annex 1 countries, even without "where" flexibility. The oil importers gain more than the oil exporters lose from the decline in world oil prices. Eventually, however, the region will become a net loser unless it is able to sell emission rights to Annex 1 countries.

6. The least-cost mitigation pathway – 550ppmv

The WG1 emission pathways were meant to be purely illustrative. No attempt was made to determine whether they represented an efficient transition away from fossil fuels. WRE, on the other hand, drew upon the insights of earlier studies in constructing their emission pathways. They

argued that allowing more time for the transition would lower mitigation costs. They did not attempt to quantify the savings from choosing one path over another. Nor did they try to identify the least-cost mitigation pathway.

In the preceding sections, we analyzed the mitigation costs associated with the WG1 and WRE pathways. We now turn to the question of what might constitute a least-cost mitigation pathway for stabilizing concentrations at 550ppmv. For these calculations, we use MERGE 3.0. Rather than apply a carbon constraint derived through inverse calculations with the Wigley carbon cycle model, we now place a constraint on atmospheric concentrations and use the model to identify the least-cost mitigation pathway.

Note from Figure 6.1 that the least-cost and WRE pathways for stabilizing concentrations at 550ppmv lie fairly close together, at least in the early years. That is, they tend to follow the emissions baseline during the first decade of the next century and then depart gradually. Figure 6.2 shows the results in terms of discounted present value. In each case, we assume trade among all regions. As would be expected from the previous figure, the WRE and least-cost cases are also close in terms of costs.

The cases differ dramatically, however, in terms of the value of carbon emission rights. From Figure 6.3, we see that the least-cost path starts off at a low price (approximately \$2/ton of carbon) and rises gradually over time. The WRE case leads to an erratic time path of carbon prices. Indeed, in some years there is an excess of emission rights. As a result, their value falls to zero. In other years, their value exceeds that of the least-cost optimal emissions reduction path.

7. The costs of stabilizing concentrations at alternative levels

The selection of the 550ppmv target was purely arbitrary and not meant to imply an optimal concentration level. Given the present lack of consensus on what constitutes "dangerous" interference with the climate system, it is important to understand how mitigation costs might vary with alternative concentration targets.

Figure 7.1 summarizes the results of the MERGE analysis. As would be expected, mitigation costs are a declining function of the stabilization target. Recall that a concentration target places an upper limit on the amount of CO₂ to be released into the atmosphere between now and the date at which the target is to be achieved. This in effect defines an emissions budget. The lower the target, the smaller the emissions budget.

Figure 7.2a shows the constraint on Annex 1 emissions during the initial decades of the next century under the WG1 scenario. In the absence of

“where” flexibility, this becomes an effective upper bound on emissions. The figure provides useful insights into the shape of the abatement cost curve. Relative to higher targets, 450ppmv implies that: 1) more carbon must be removed from the energy system, 2) there is greater need to reconfigure the existing energy using and energy producing capital stock, 3) low-cost substitutes are likely to be available in a less timely manner, and 4) there is less opportunity for discounting to reduce the present value of mitigation costs. As the concentration constraint is relaxed, each of these factors acts to lower costs.

The costs of complying with WG1 are substantially reduced when we allow for “where” flexibility. Annex 1 countries are able to purchase lower marginal cost abatement alternatives from non-Annex 1 countries. As a result, the need is not as intense for early reductions.

WRE produces the lowest mitigation cost possibilities. The asymmetry in the cost function between 450 and 550ppmv suggests that even with WRE, the low target will provide insufficient time to adapt the existing capital stock. From Figure 7.2b, note that a 450ppmv target would require a departure from the baseline during the first decade of the next century, and there would be an even more rapid departure thereafter. With targets of 550ppmv and above, there is time for a more gradual transition away from carbon-intensive fuels.

8. The choice of near-term mitigation strategy

Figure 7.2b provides some useful guidance for the design of near-term emission strategies. If it is certain that the target is 550ppmv or above, the near-term emissions path appears to be quite robust. That is, it adheres fairly closely to the emissions baseline through 2010. It should be noted, however, that even in this case, there is some transition away from the world’s current heavy dependence on carbon-intensive technologies prior to 2010. That is, inexpensive alternatives (e.g., renewables and cost-effective conservation) are introduced in increasing amounts - both on the supply and demand sides of the energy sector. However, if these alternatives are economically attractive in their own right, they will be adopted in the absence of climate policy.

Suppose, on the other hand, that one believes there is some probability that the target is in the 450 to 550ppmv range. A more aggressive departure from the emissions baseline will be required. The degree of hedging depends upon the probabilities and the relative costs of two types of errors in the design of future capital stocks. That is, one must balance the risks of investing in capital stocks that lead to carbon emissions that are either too high or too low.

Of course, the choice of emission pathway for meeting a prescribed concentration target must also involve consideration of the environmental

consequences of adopting one emission trajectory over another. The WRE emission pathways result in higher concentrations in the years preceding the date by which the target is to be achieved. For the 550ppmv case, the higher concentrations lead to pathway related differentials of up to .2 degrees C in global mean temperature and 4cm in global mean sea level change (ref. 11). To the extent that this leads to higher environmental damages, these need to be balanced against the benefits from reduced mitigation cost.

9. Some concluding comments

The above analysis suggests that a more gradual transition away from fossil fuels is likely to be less expensive in terms of mitigation costs. This should not be interpreted as suggesting a "do nothing" or "wait and see" strategy. Mitigation may mean action, but action does not necessarily mean mitigation. As pointed out in the IPCC 1995 Report²⁰, climate policy requires a portfolio of responses. The challenge facing today's policy makers is to arrive at a prudent hedging strategy in the face of climate-related uncertainties. Among the options are

- immediate reductions of greenhouse gas emissions,
- investments in actions to assist human and natural systems adapt to climate change should it occur,
- continued research to reduce uncertainties about how much change will occur and what effects it will have, and
- R&D on energy supply and end-use technologies to reduce the costs of limiting greenhouse gas emissions.

The issue is not one of either-or but one of finding the right blend of options. Policy makers must decide how to divide greenhouse insurance dollars among these competing needs.

The present analysis has provided some useful insights bearing on this decision. Deep near-term reductions are apt to be costly. They provide less time to adapt the existing capital stock. There will be more opportunities for reducing emissions cheaply as the current capital equipment turns over. Indeed, the 1995 IPCC report states that "implementing emission reductions at rates that can be absorbed in the course of normal capital stock turnover is likely to be cheaper than forcing premature retirement now."²¹

Fortunately, with regard to carbon dioxide, the issue is one of cumulative rather than year-by-year emissions. This means that we can allow for an economical turnover of the existing capital stock if we are prepared to make sharper reductions in the future.

This brings us to the issue of R&D. Sharper reductions in the future will be less problematic if we can lower the costs of fuel switching and conservation. Indeed, studies by Stanford University's Energy Modeling Forum suggest that the development of economically competitive alternatives to conventional fossil fuels could substantially reduce the costs of a carbon constraint.²²

Although virtually all parties in the debate recognize the value of R&D, we have yet to develop a technology strategy for dealing with global climate change. How much should we be investing today to ensure ample supplies of low-cost alternatives in the future? What should be the nature of these investments, who would make them, and how would they be managed? Given the size of the stakes, surprisingly little attention has been devoted to these questions.

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Figure 2.1 Per Capita GDP

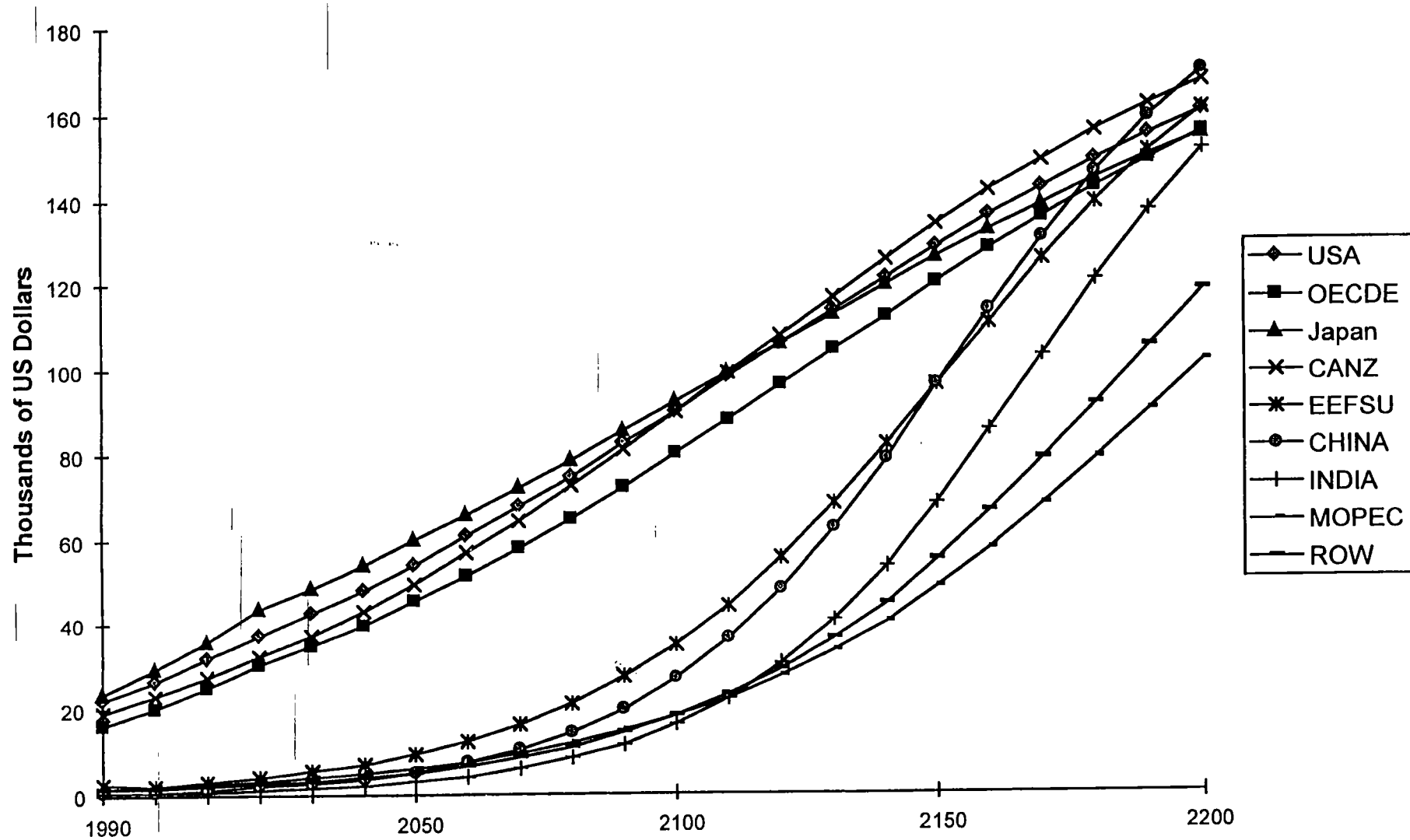


Figure 2.2 Regional Carbon Emissions

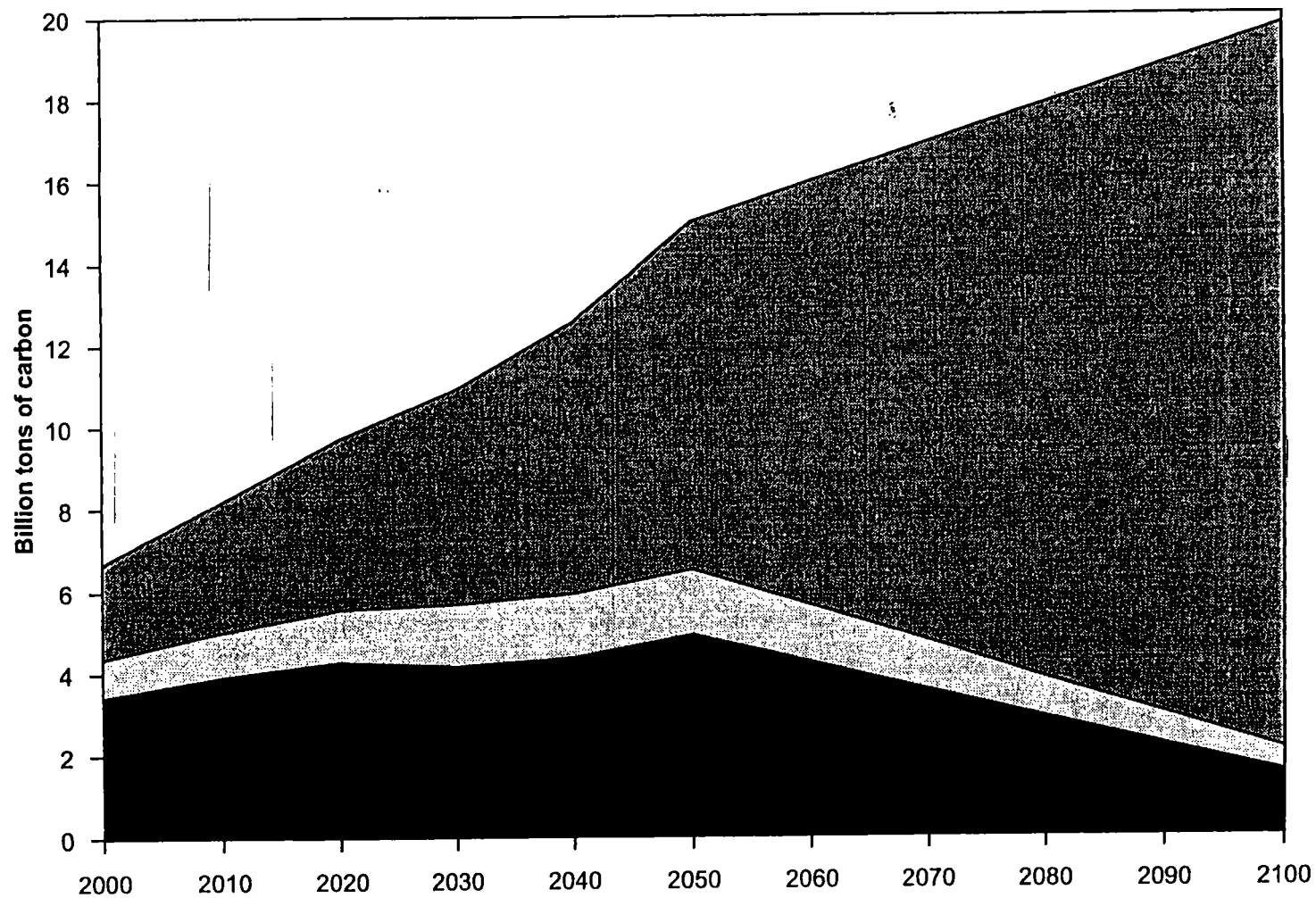


Figure 2.3 Total Primary Energy Use - Basecase

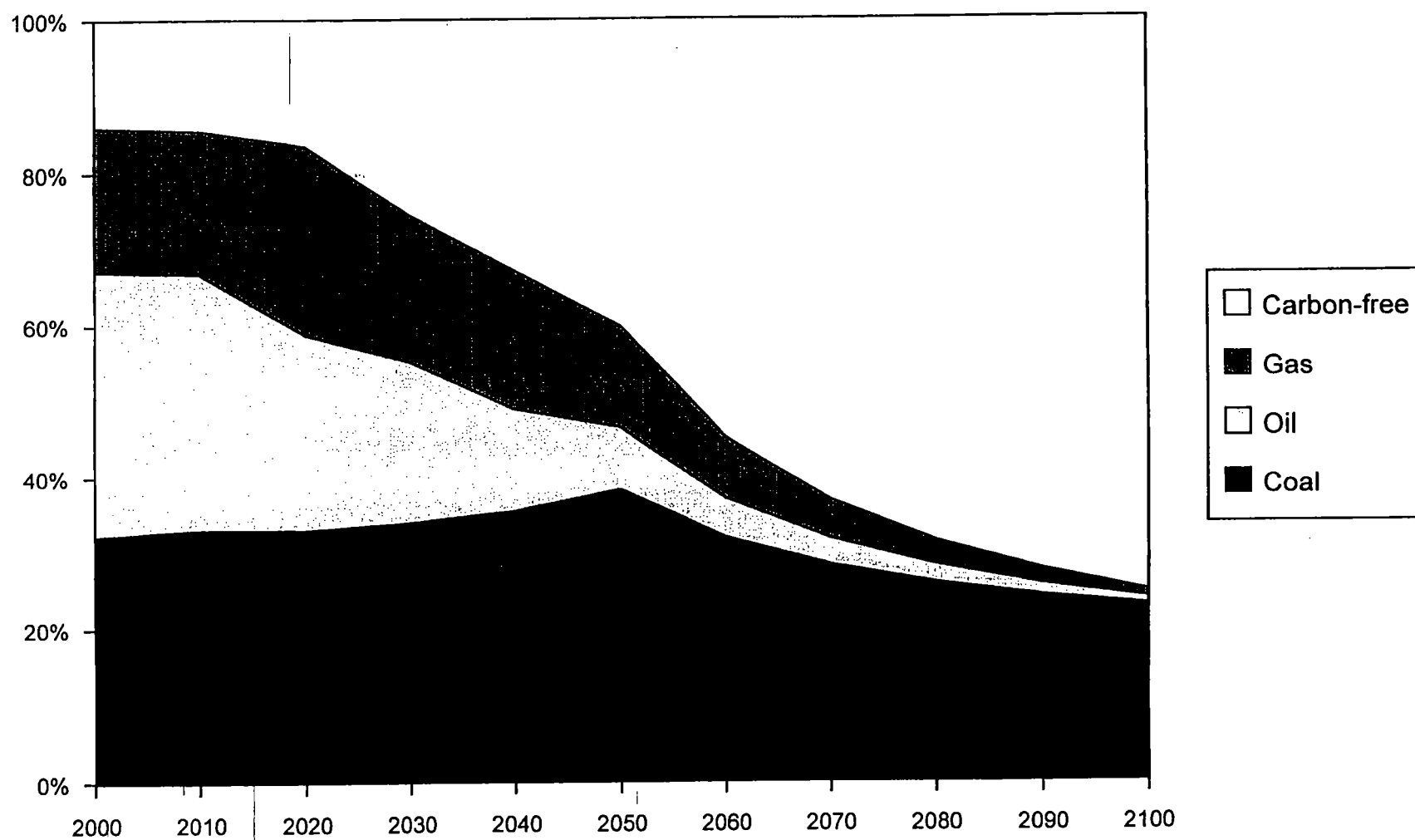
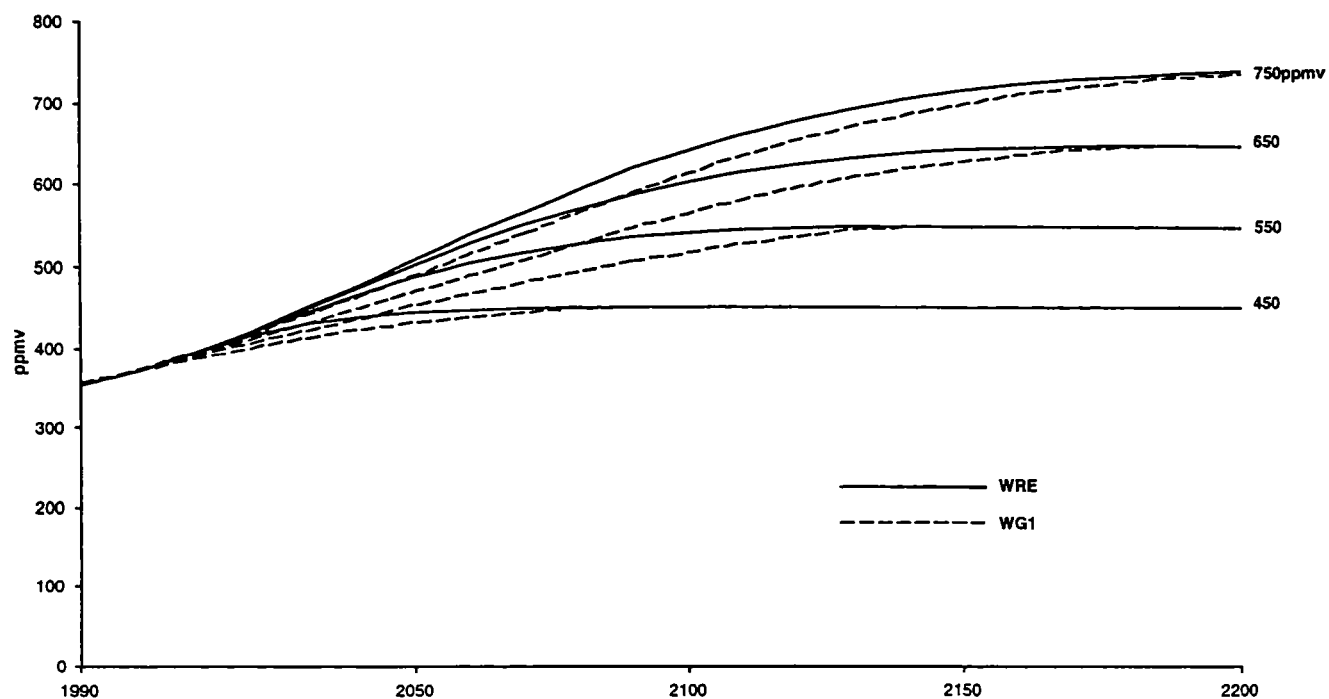
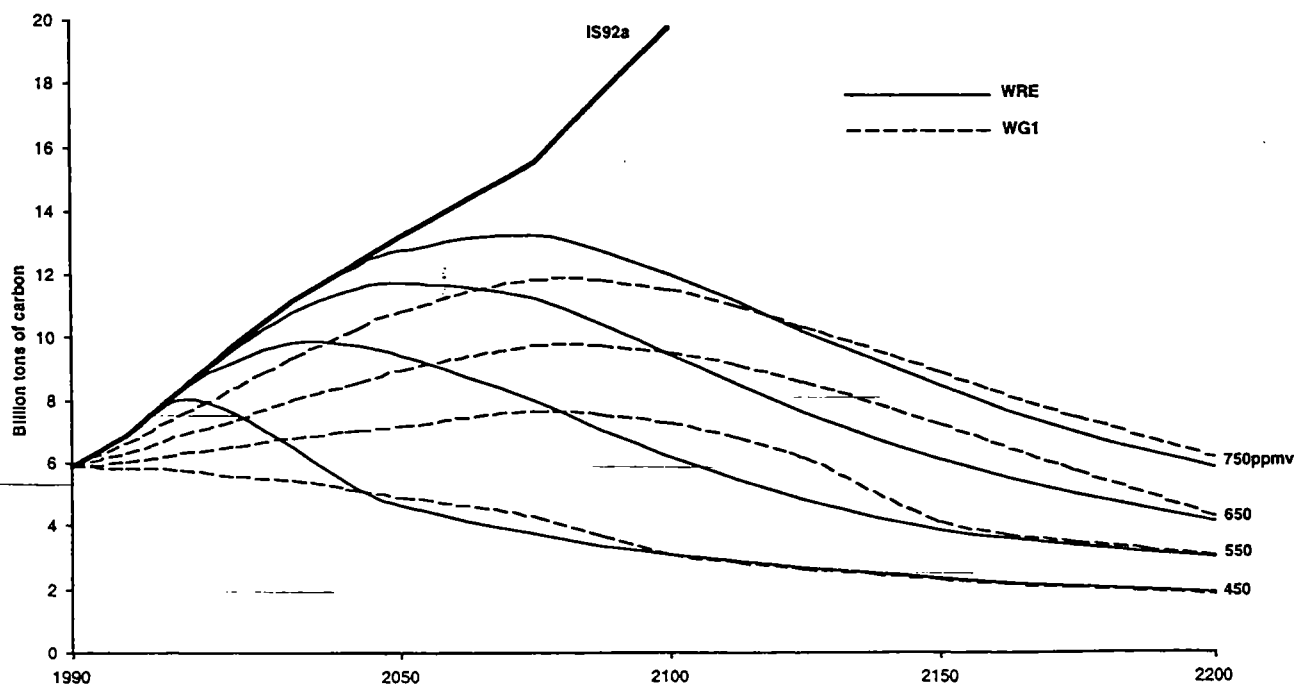


Figure 3.1 Alternative Routes to CO₂ Stabilization

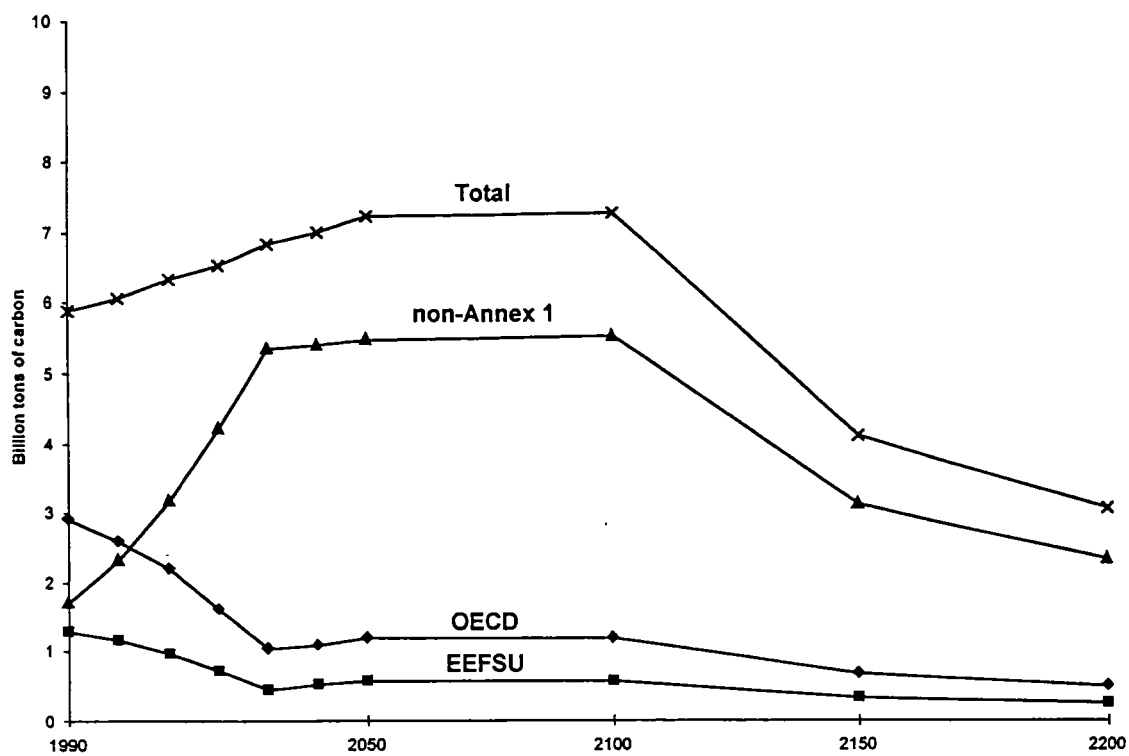


a) Alternative concentration profiles

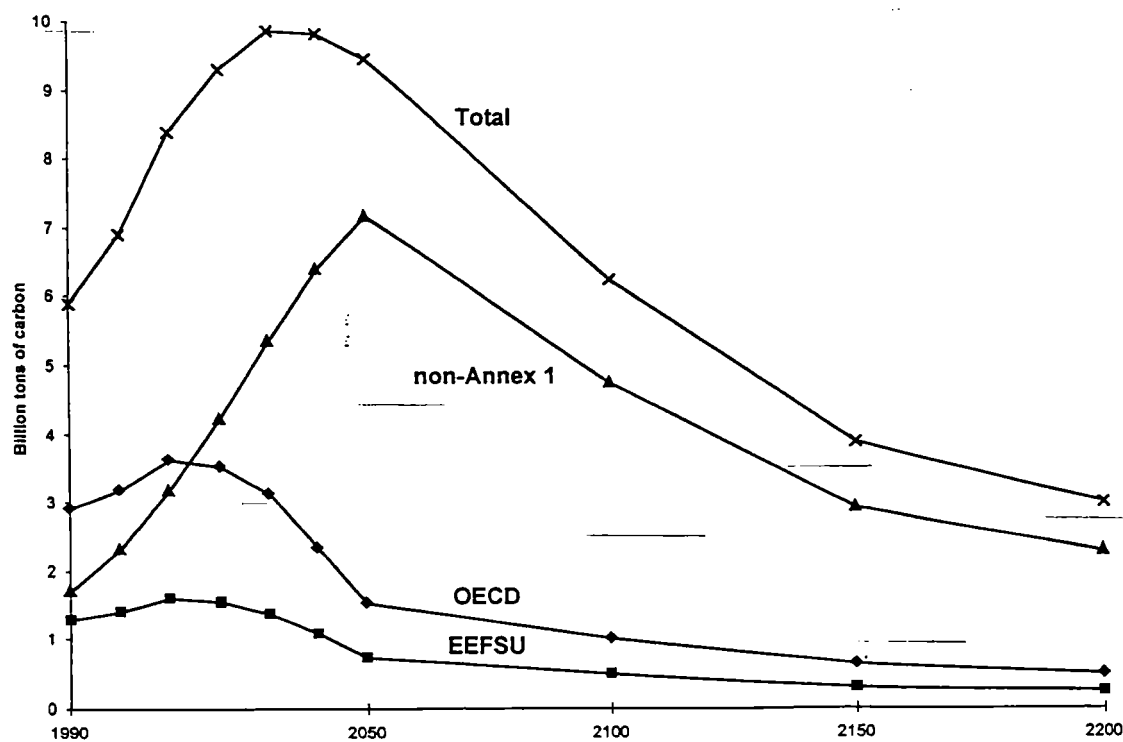


b) Alternative fossil fuel emission paths

Figure 4.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv



a) WG1



b) WRE

Figure 4.2 Regional Costs of Stabilizing Concentrations at 550ppmv
-- discounted to 1990 at 5%

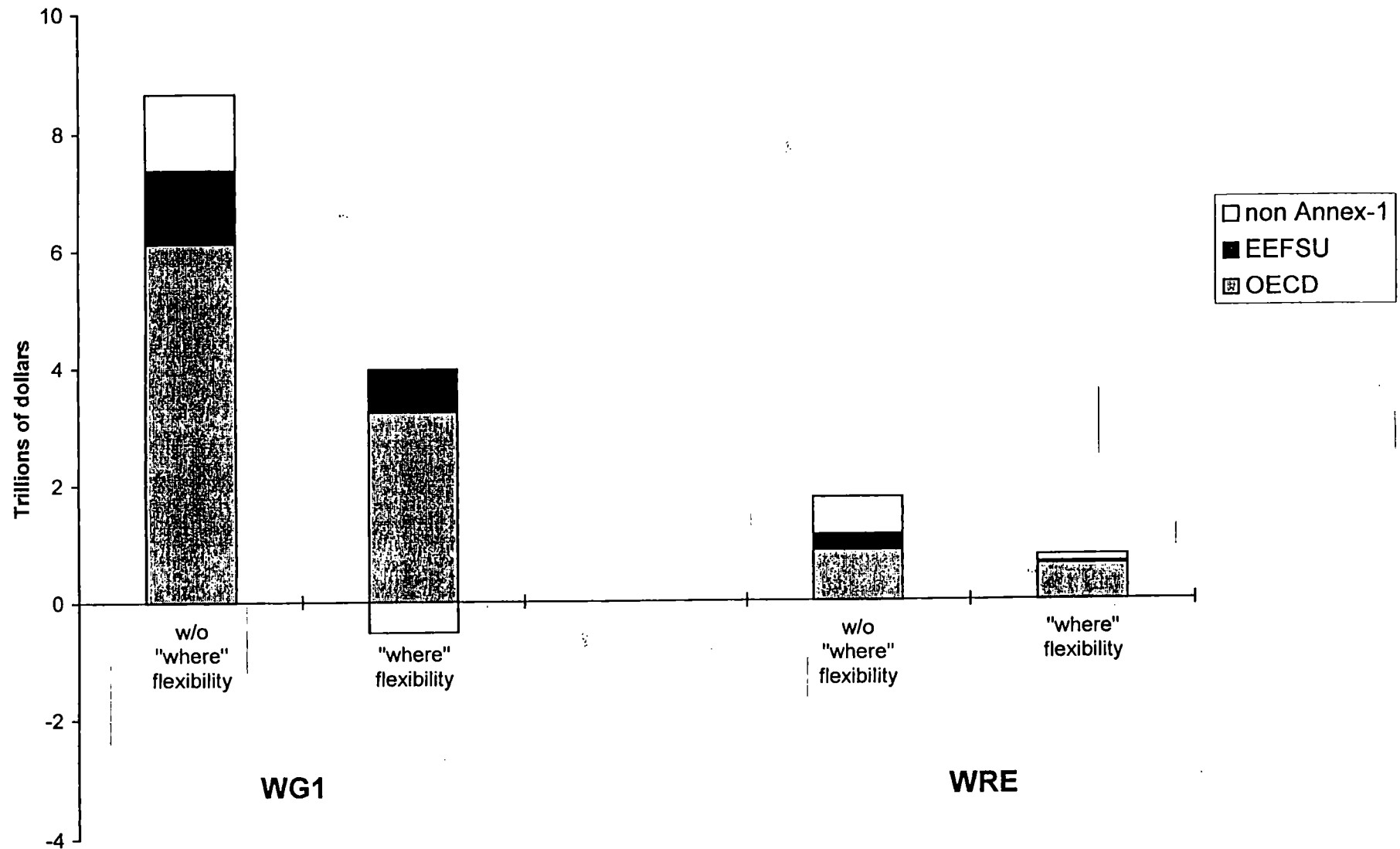


Figure 5.1 International Price of Crude Oil

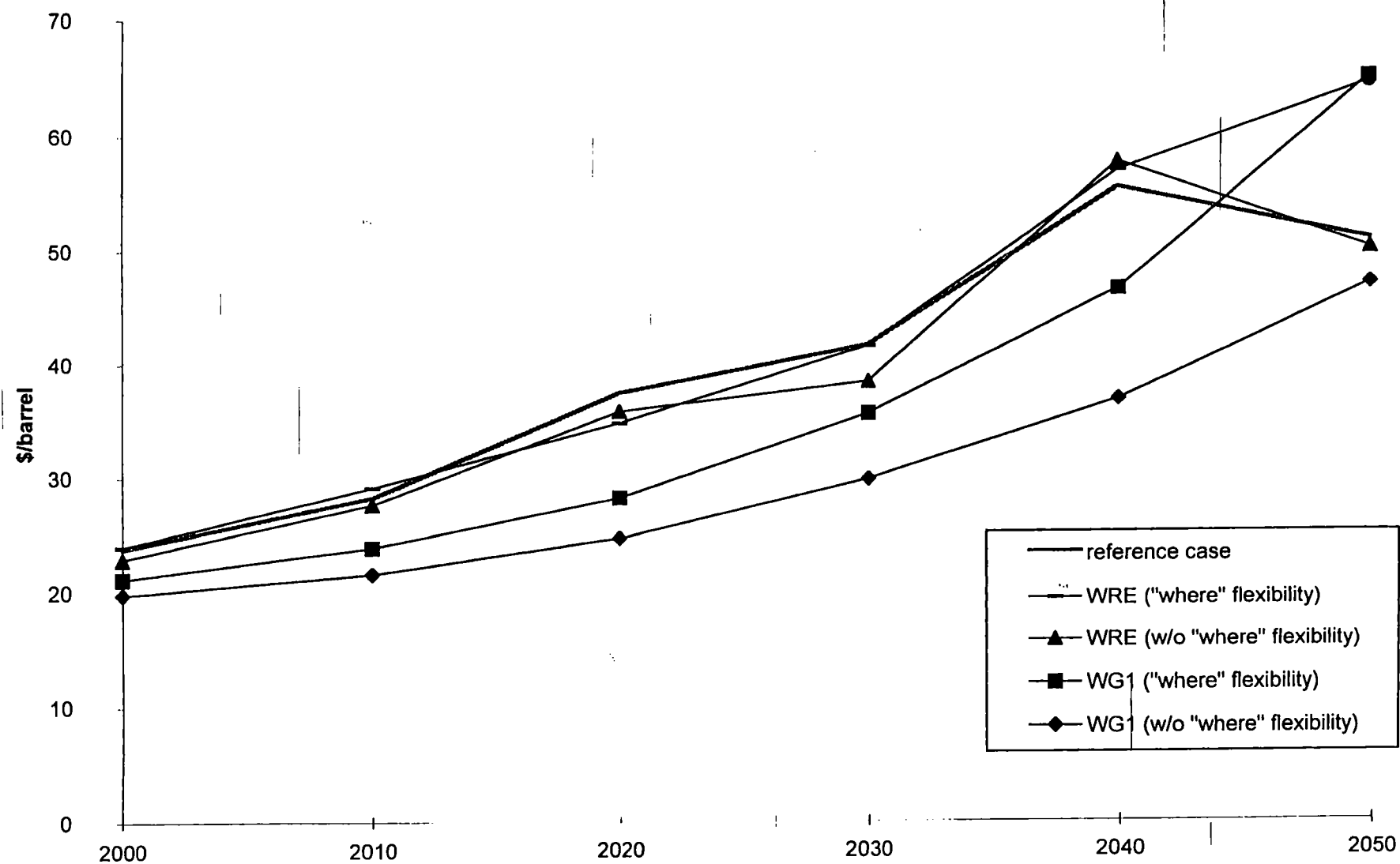


Figure 5.2 Annual % Consumption Losses

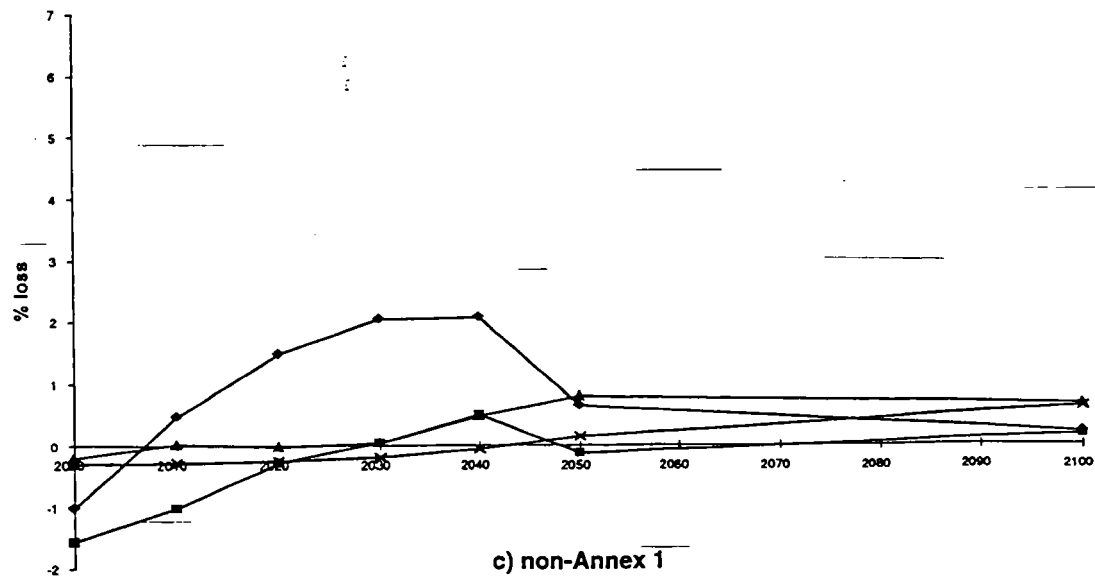
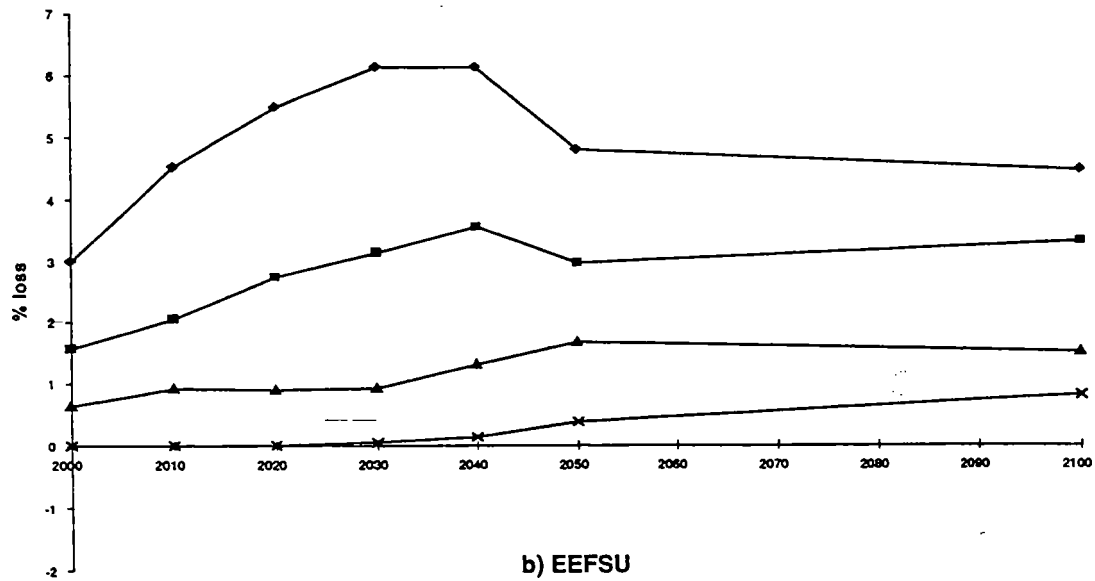
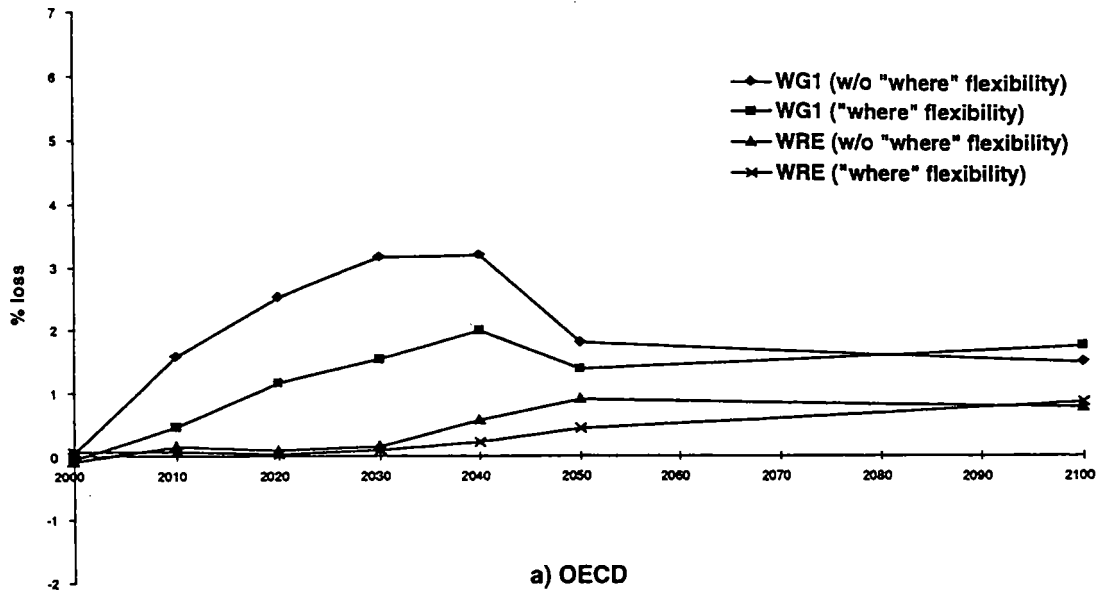


Figure 6.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

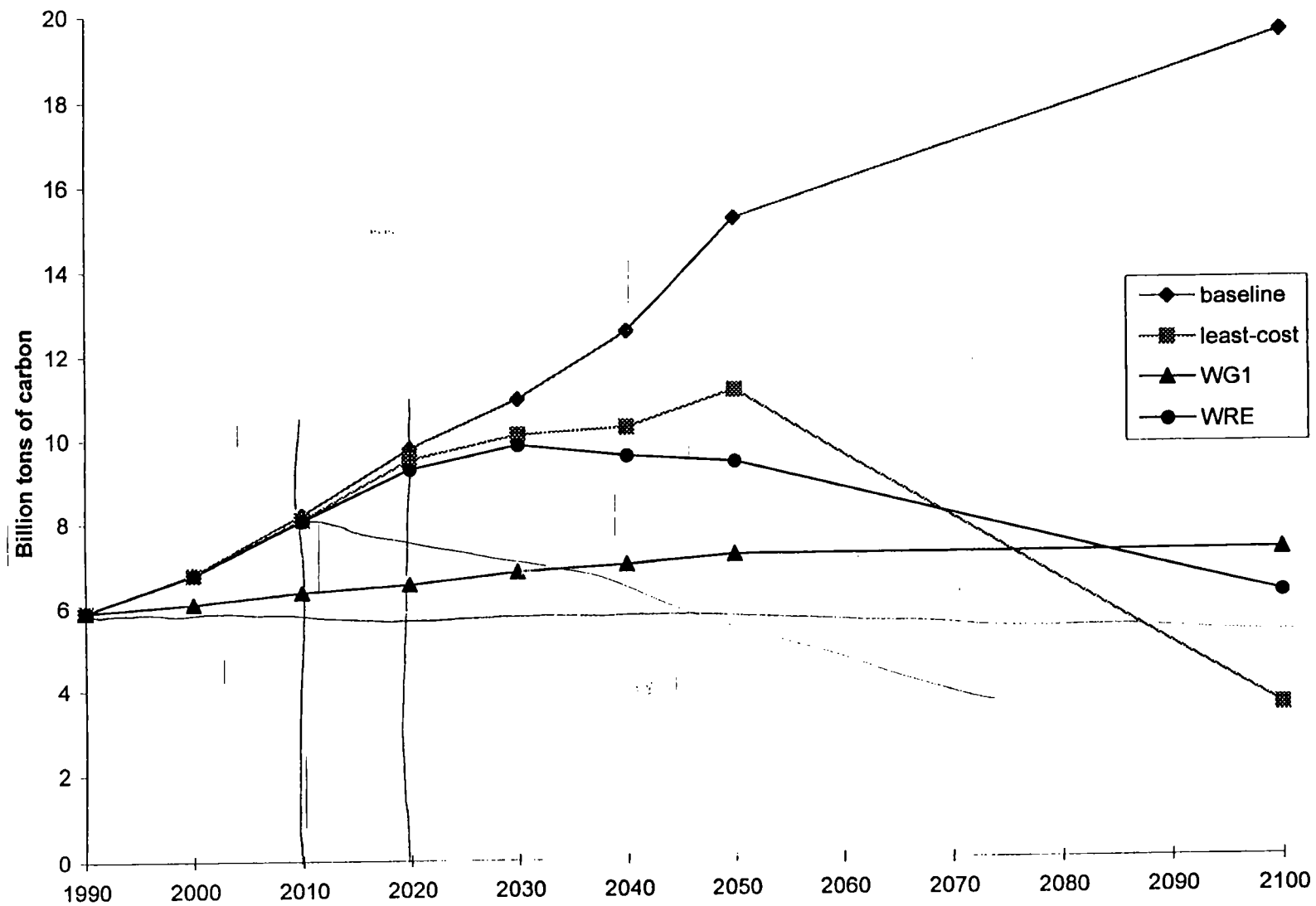


Figure 6.2 Global Costs of Stabilizing Concentrations at 550ppmv
-- discounted to 1990 at 5%

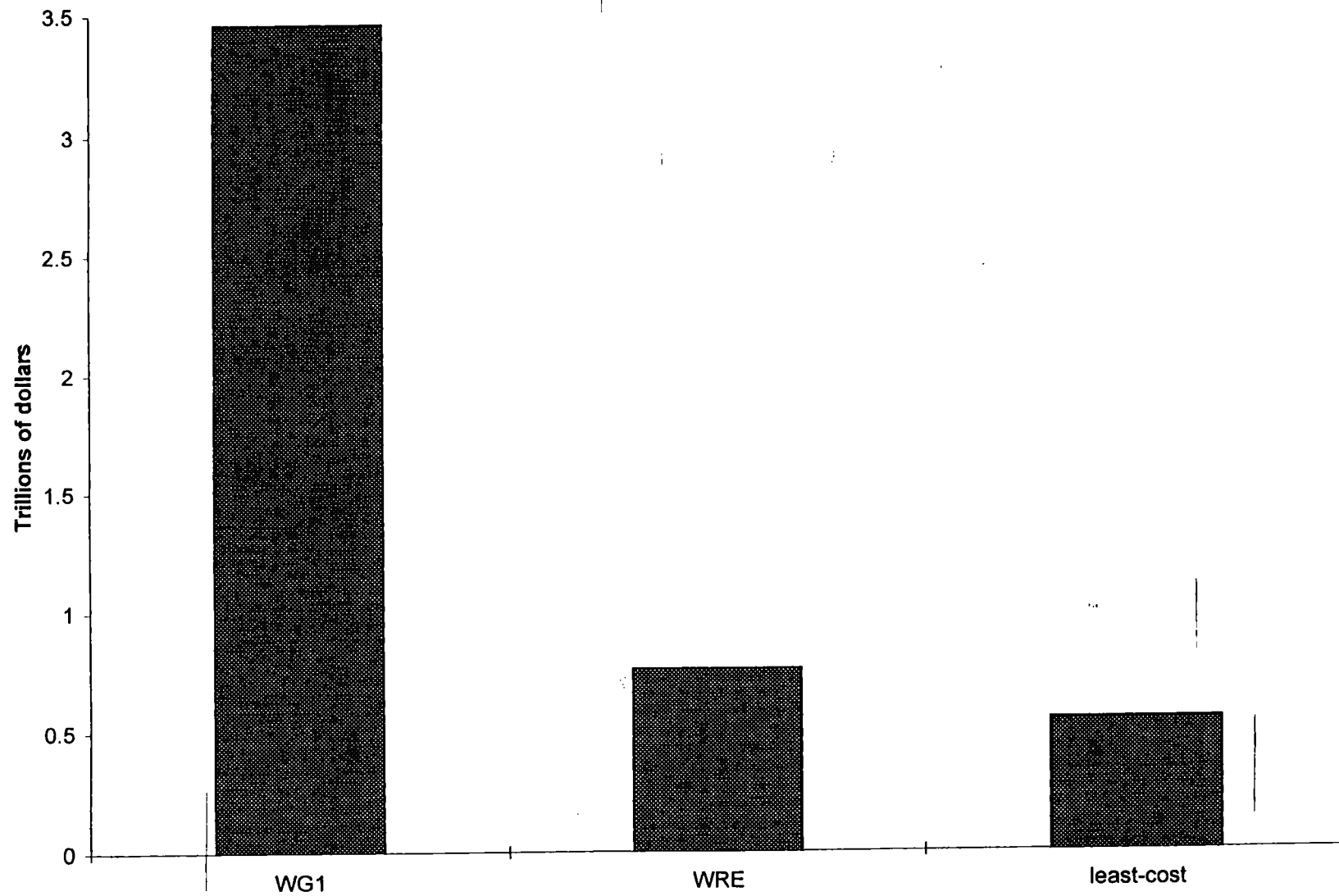


**Figure 6.3 Value of Carbon Emission Rights with Alternative Pathways
for Stabilizing Concentrations at 550ppmv**

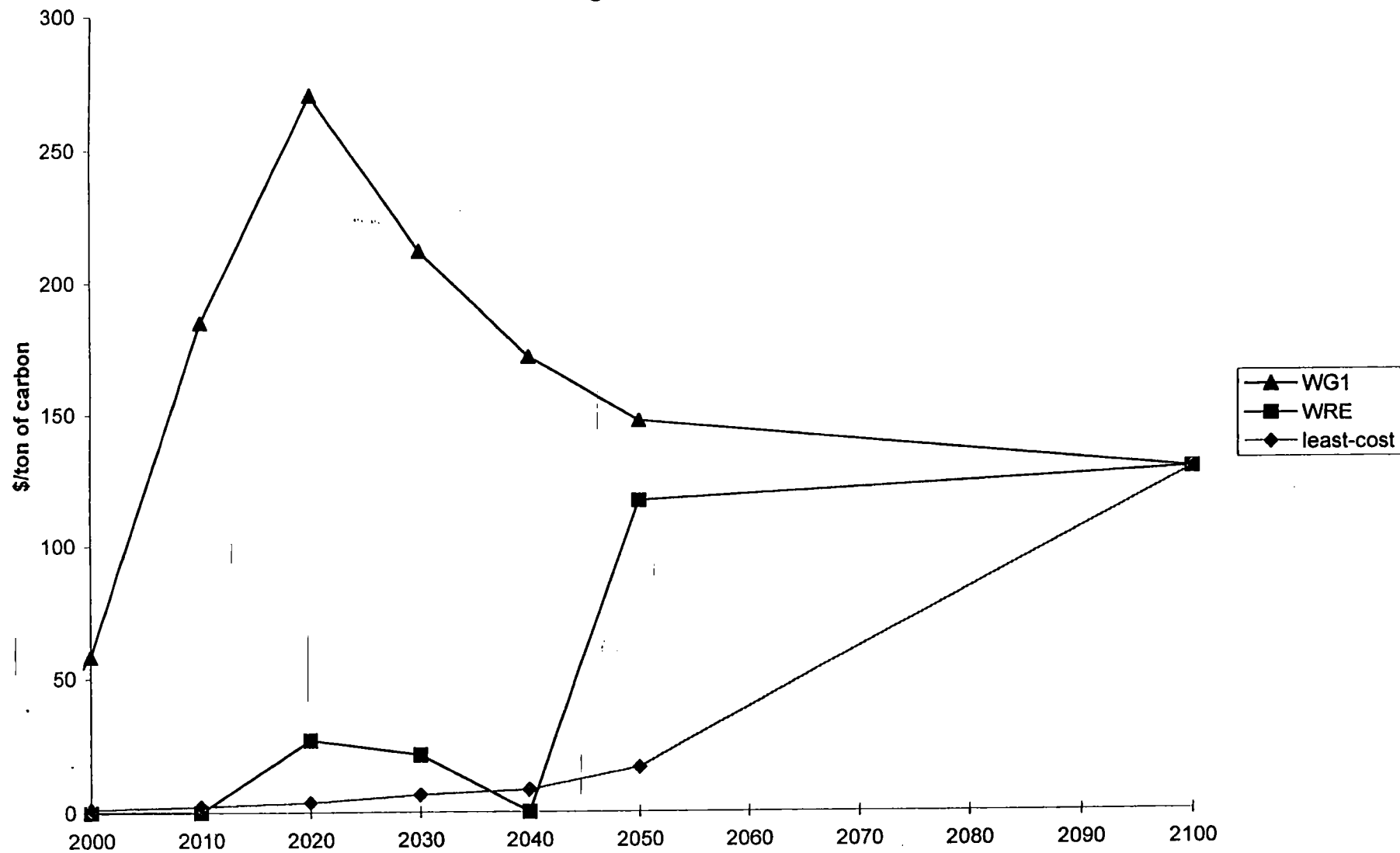
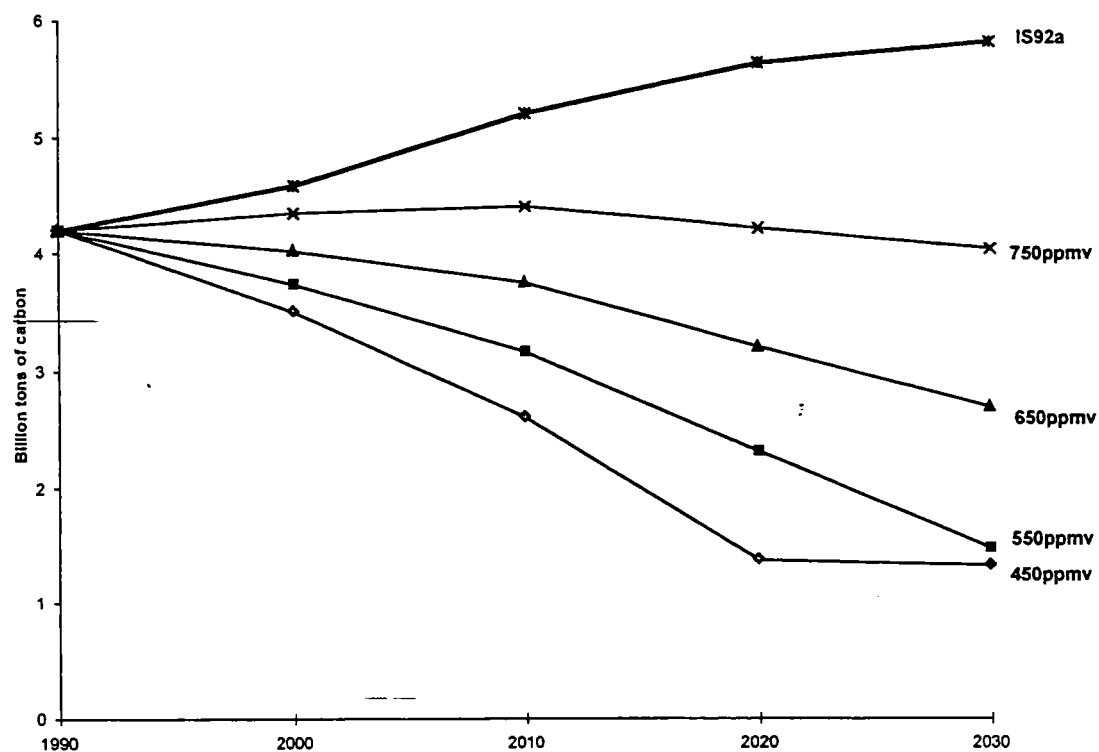
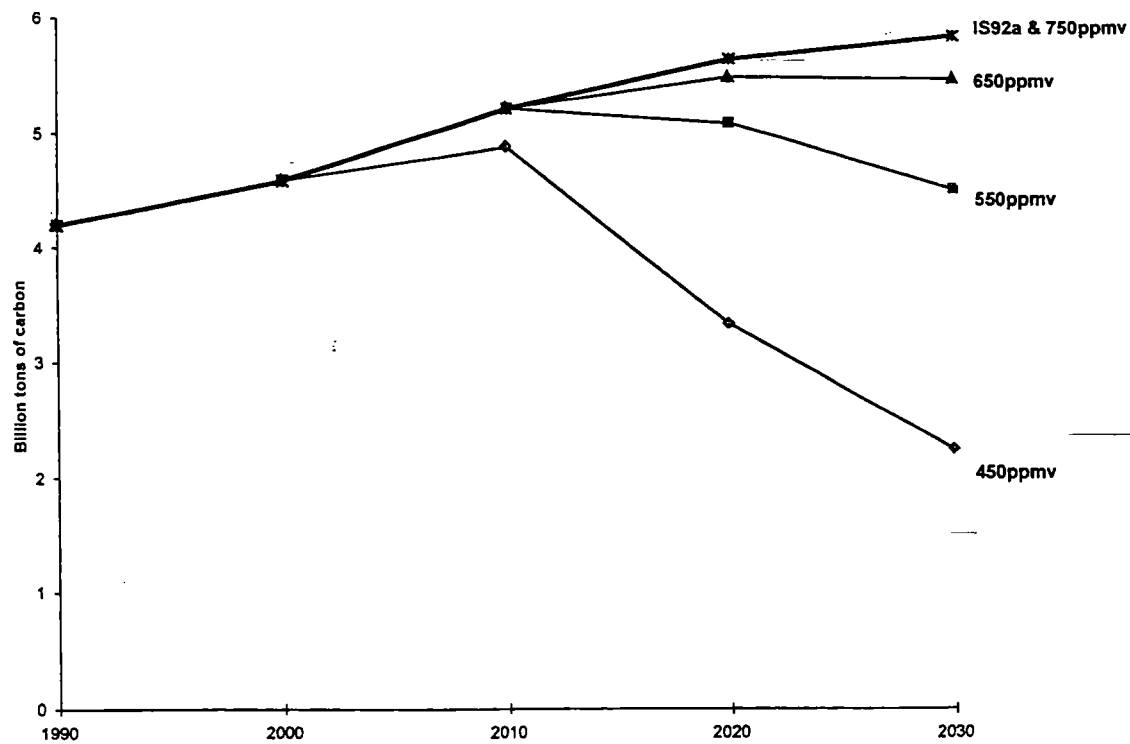


**Figure 7.2 Annex 1 Emission Constraints under
Alternative Concentration Targets**



a) WG1



b) WRE

NOTE TO JEFFREY FRANKEL

Attached is the paper on flexibility that I mentioned yesterday. In looking back over it, a few points jumped out. It's a draft. I don't know if it changed before it was finalized. It focuses on a 20 percent cut by 2010, not the targets you included in your literature summary. It also focuses on changes in GDP loss, not energy price impacts. Figure 4 b shows the expected savings from interregional trading (globally) of about 70 percent and from intertemporal trading of about 40%. Together, the savings appears to be about 85%. Without showing any data, the text states that if the goal was stabilization at 1990 levels (emissions), the cost savings would be between 30 and 60 percent.

Hope this is helpful.

Steve Seidel

"When and where flexibility"

DRAFT

70% ↓ where
40% ↓ when

The Berlin Mandate: The Design of Cost-Effective Mitigation Strategies

by Richard Richels¹, Jae Edmonds², Howard Gruenspecht³ and Tom Wigley⁴

with contributions from Henry Jacoby⁵, Alan Manne⁶, Stephen Peck⁷,
Tom Telsberg⁸, Marshal Wise⁹ and Zili Yang¹⁰

February 3, 1996

This paper reports initial results of the Subgroup on the Regional Distribution of the Costs and Benefits of Climate Change Policy Proposals, Energy Modeling Forum-14, Stanford University. Helpful comments were received from Sally Kane and John Weyant. The authors are much indebted to Amy Craft for research assistance. The views presented here are solely those of the authors.

Abstract

The Berlin Mandate calls for strengthening developed country commitments for limiting greenhouse gas emissions. This paper addresses a key issue in the current analysis and assessment phase -- the costs of proposals to limit CO₂ emissions. Employing four widely-used energy-economy models, we explore the direct and indirect effects of alternative proposals on the global economy. We also examine the implications for atmospheric CO₂ concentrations.

We begin by examining an AOSIS-like proposal in which OECD countries agree to reduce CO₂ emissions by 20% below 1990 levels by a specified date. We find that implementing such a proposal could be quite costly. Not surprisingly, OECD countries would be hardest hit. Their costs could be as high as several percent of GDP. The analysis also shows that because of trade effects, non-OECD countries would likely incur costs even when reductions are confined to the OECD. An economic slowdown in the OECD would affect the full range of developing country exports, and hence their economic growth. This would likely be the case for both oil-importing and oil-exporting developing countries.

We then explore alternatives that are apt to be quite similar in terms of environmental benefits, but allow for flexibility in where and when emission reductions are made. We find that costs could be substantially reduced through international cooperation and the optimal timing of emission reductions. Indeed, such flexibility can reduce costs by more than 80%, potentially saving the international community *trillions* of dollars in mitigation costs. We find that reliance on more flexible alternatives reduces costs more effectively than adopting weaker, but still inflexible, commitments.

1. Introduction

The Berlin Mandate calls upon the Parties to the United Nations Framework Convention on Climate Change to strengthen developed country commitments to reduce greenhouse gas emissions.¹¹ A number of proposals have been put forward. These range from slowing the current growth in emissions to sharp reductions below present levels. The choice is a difficult one. Acting too slowly risks irreversible environmental damages. Acting too aggressively risks imposing large, and perhaps unnecessary costs on the global economy. As noted by the Intergovernmental Panel on Climate Change (IPCC), the challenge is to develop a prudent hedging strategy in the face of climate-related uncertainties.¹²

The Framework Convention is the mechanism established by the international community for implementing precautionary measures. It recognizes that a sensible hedging strategy should be flexible, with ample opportunities for learning and mid-course corrections. Periodic reviews are required "in light of the best available scientific information on climate change and its impacts, as well as relevant technical, social and economic information." Based on these reviews, appropriate measures would be taken, including the adoption of new commitments.

Upon entering into force in 1994, the Convention established an initial (but non-binding) aim for developed countries to return emissions to their 1990 levels by 2000. At the first meeting of the Conference of the Parties (COP-1) in Berlin in April of 1995, it was determined that existing commitments under the Convention were inadequate. Further commitments for developed countries are to be negotiated, and prepared for approval at COP-3 in 1997.

While calling for new commitments, the Berlin Mandate does not specify what these commitments should be. Rather it seeks further analysis and assessment to guide and inform the decision making process. This paper addresses a key issue in the analysis and assessment phase -- the costs of proposals to limit CO₂ emissions. Rather than rely on a single model, the analysis is based on independent runs of four widely-used energy-economy models.¹³ In each instance, we explore both the direct and indirect effects on the global economy.

We also examine the impact of alternative proposals on atmospheric concentrations. The ultimate objective of the Framework Convention is "the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."¹⁴ Although the issue of what constitutes an appropriate limit has yet to be resolved, it is instructive to explore the implications that alternative emission pathways have for future concentrations.

We pay particular attention to the design of cost-effective mitigation strategies. The Framework Convention states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible costs." Adopting least-cost mitigation strategies will free up valuable resources for further addressing the threat of climate change or for meeting other societal needs. We explore two ways of promoting this objective. In the first, emission reductions take place *where* it is cheapest to do so. In the second, they take place *when* it is cheapest to do so.

A number of studies have suggested that the cost of emission reduction can be substantially reduced through international cooperation.¹⁵ From a global perspective, it would be economically wasteful to incur high marginal abatement costs in one country when low-cost alternatives are available elsewhere in the world. We discuss ways to ensure that emission reductions are made where it is cheapest to do so, and explore the potential gains.

The timing of emission reductions can also influence costs. What is important in meeting a concentration target is cumulative -- not year-by-year -- emissions.¹⁶ A particular concentration target can be met through a variety of emission time paths. Several studies have suggested that emission time paths that provide flexibility in making the transition away from fossil fuels will be less costly.¹⁷ We examine the implications for the design of cost-effective mitigation strategies under the Berlin Mandate.

Mitigation costs are, of course, only part of the story. The more difficult question is the appropriate level of emissions abatement. This requires consideration of both costs *and* benefits. The present analysis is confined to the cost-side of the ledger. That is, we focus on the costs of emissions reduction. Policy makers will also want to know what they are buying in terms of reducing the undesirable consequences of global climate change. Such an analysis is beyond the scope of the present effort.

2. The models

The analysis employs four energy-economy models: CETA¹⁸, EPPA¹⁹, MERGE²⁰, MiniCAM²¹. These models reflect the recent trend towards hybrid modeling tools which incorporate features from both bottom-up and top-down approaches to energy modeling. On the supply-side, each model employs a bottom-up representation of the energy system. Energy technologies are described in process model detail (e.g., availability dates, heat rates, carbon emission coefficients, etc.). The technology vector includes both existing sources and new options that are likely to become available. Cost and performance constraints are adjusted for regional differences. A more top-

down perspective is taken towards the balance of the economy. This is done using macroeconomic production functions that provide for substitution between capital, labor, and energy inputs.

The models provide a consistent way to examine alternative strategies for limiting CO₂ emissions and to examine the impacts of higher energy prices on economic output. They can be used, for example, to estimate the increase in fossil fuel prices required to induce consumers to reduce emissions. They also can be used to analyze the possibility of significant regional differences in marginal abatement costs that would lead to opportunities for cost savings through international cooperation.

The models employ a general equilibrium formulation of the global energy and economic system. This allows us to examine the impacts of actions taken in one region on the economies of another. This is particularly important in the case of the Berlin Mandate. Constraints imposed on developed countries may have unexpected consequences for developing countries. For example, the international price of oil will be affected by the imposition of carbon constraints on oil importing countries.

While general equilibrium models are useful in tracing the long-term implications of a carbon constraint, they may ignore important short-term effects. This is because they assume full employment of the economy and instantaneous adjustment to policy shocks. The lack of attention to adjustment costs, means that these models may *understate* the short-run cost of economic shocks, particularly if these are large and unexpected.

On the other hand, some have argued that the exogenous specification of technology change tends to *overstate* the cost of a carbon constraint. This is an important issue in the energy policy debate – one that is deserving of considerably more attention than it has received to date. It should be noted, however, that the direction of any bias is still unclear. An acceleration of energy related technical progress may be accompanied by a slowdown in labor and capital productivity improvements throughout the economy. To receive proper consideration, the issue of endogenous change must be examined on an economy-wide basis.²²

Although similar in many respects, the models differ in important ways. For example, EPPA is a recursive rather than an intertemporal optimization model. EPPA and MERGE employ a "putty-clay" rather than a "putty-putty" approach to the vintaging of capital stocks (i.e., they explicitly recognize that one type of capital cannot be "transformed" into another, once it is put into place). And all models differ in regional disaggregation: CETA (2 regions), EPPA (12 regions), MERGE (5 regions) and MiniCAM (9 regions).²³

The models also differ with respect to key inputs, e.g., population, per capita productivity trends, the fossil-fuel resource base, the cost and availability of long-term supply options, etc. Rather than try to impose a common set of driving assumptions, the choice of inputs was left to the discretion of the modeling teams. It was felt that, with a diverse set of energy futures, we would be better able to assess the robustness of our results.

3. Future emissions

We begin with an examination of how fossil fuel emissions are projected to grow in the absence of policy intervention. The costs of a carbon constraint are quite sensitive to the emissions baseline. The baseline describes how emissions will grow under existing policies. The higher the emissions baseline, the more carbon must be removed from the energy system to meet a particular target, and the higher become the costs.

Figure 1 compares baseline projections for our four models.²⁴ Note that in each instance emissions are projected to grow in the absence of policy intervention. This is the case for the OECD and for the world as a whole. This is consistent with the overwhelming majority of analyses recently reviewed by the IPCC.²⁵ Of the dozens of studies surveyed, all but a few showed a rising emissions baseline.

In reviewing these emission projections, several points are worth noting. First, although the annual growth rates are substantial -- between 1.5 percent and 2 percent -- they represent a marked slowing in the historical trend. Indeed, global emissions grew at an annual rate of approximately 3.5 percent between 1950 and 1990. In part, the slowdown is due to a projected decline in global economic growth. Since 1950, gross world product grew at an average annual rate of 2.9 percent. The projected growth rate for the next half century or so is closer to 2.5 percent. Also at work is the gradual decoupling between energy and GDP growth and a decoupling between CO₂ emissions and energy use.

The differences in emission baselines should come as no surprise given the uncertainty over the period studied and thus the freedom the modelers had in the choice of input assumptions. Although it would be impractical to sort out all of the reasons for the differences, several factors have been identified as being particularly important when modeling future emissions.²⁶ High up on the list is economic growth. Those models with higher GDP growth rates tend to project higher emissions. Conversely, the more optimistic one is about the prospects for reducing energy intensity or the availability of low-cost carbon-free substitutes, the lower the CO₂ growth rate.

Although the models differ on the cost and availability of supply and demand side alternatives, it should be noted that each includes some "no regrets" emission reduction options. These are alternatives that would be worth adopting apart from climate considerations. A growing emissions baseline does not imply the absence of economically competitive alternatives to fossil fuels. It only means that such options are in insufficient supply to arrest the growth in carbon emissions.

The focus of the Berlin mandate is on developed country emissions. Negotiators will be interested in how a particular proposal changes the emissions baseline. We start by examining a case in which OECD countries return emissions to 1990 levels by the year 2000, reduce them by an additional 20% by 2010, and hold them at that level thereafter. This is similar in many respects to the proposal put forward by the Alliance of Small Island States (AOSIS).²⁷ For the present analysis, we place no constraints on non-OECD emissions.

Figure 2 shows the implications for global emissions. An AOSIS-like proposal may slow the growth in global emissions, but it is unlikely to stabilize them at anywhere near present levels. This is because non-OECD countries currently account for over half of the global total and their share is expected to grow. The implications for climate policy are clear. Stabilization of global emissions will eventually require the participation of developing countries.

4. The costs of alternative commitments

We next turn to the issue of costs. In recent years, a number of studies have highlighted the potential role of international cooperation and flexible timing in reducing the costs of a carbon constraint.²⁸ To explore the implications for the Berlin Mandate, we first estimate the costs of adopting the AOSIS-like proposal described above. We then examine three variants. Each results in the same cumulative emissions, but there are significant differences in the geographical location and timing of the emission reductions.

Before proceeding, one caveat is in order. We use trade in emission rights to examine the potential gains from international cooperation. By allowing such trade, we ensure that, at a given point in time, emission reductions are made where it is cheapest to do so. It should be noted that this is but one of a number of mechanisms that could be used to facilitate international cooperation. For example, various forms of bilateral joint implementation could accomplish the same objective. Hence, trade in emission rights is intended only as a proxy for any of a number of cooperative mechanisms.

With the above caveat in mind, we now describe our four cases:

- Case 1 (no interregional or intertemporal efficiency) -- Each OECD region is required to meet its annual emissions constraint independently. There is no trade in emission rights between the OECD and other regions.²⁹
- Case 1a (interregional efficiency) -- The constraint is still on year-by-year emissions, but trade in emission rights is now permitted between the OECD and other regions. Non-OECD countries are allowed to emit in each period up to the level of their emissions in Case 1. If they reduce their emissions below this level, they may benefit from the sale of the emission rights generated.
- Case 1b (intertemporal efficiency) -- Rather than a set of year-by-year emission limits, the constraint on emissions from each OECD region is expressed as an upper limit on its cumulative emissions. This allows for higher emissions in years where the cost of emissions abatement is highest. "Payback" must occur by 2050. There is no trade in emission rights between the OECD and non-OECD regions.
- Case 1c (interregional and intertemporal efficiency) -- The constraint is now on cumulative emissions at the global level. Both interregional and intertemporal trading is permitted. Emission rights are based on Case 1. As a result, reductions take place both where and when it is cheapest to do so.

Figure 3 shows costs for Case 1 discounted to 1990 at 5% per year. The constraint on carbon-emitting activities leads to a reallocation of resources, away from the pattern that is preferred in the absence of this limit and into potentially costly conservation activities and fuel substitution. Relative prices change as well. These forced adjustments lead to a reduction in economic performance, as measured by GDP or some other indicator depending on the model. The tighter the constraint the greater the effect.

Note that, because of trade effects, many non-OECD countries will incur costs even when reductions are confined to the OECD. Restrictions on carbon emissions lead to lower OECD demand for oil, which results in lower revenue for the oil-exporting countries. In addition, an economic slowdown in the OECD countries affects the full range of developing country exports, and thus their growth. For many oil-importing developing countries these broader trade effects outweigh the gain from lower world oil prices. Three of the four models shown account for at least some of these effects (MiniCAM is the exception) and show a spillover of OECD losses onto non-OECD countries.

Not surprisingly, the models differ as to the magnitude of the economic impacts. This is to be expected given the large differences in emission baselines. EPPA, with the highest baseline, shows the highest costs. MiniCAM, with the lowest baseline, shows the lowest costs.

A second factor contributing to the large spread among models is the speed with which the capital stock is allowed to adjust to higher energy prices. As noted earlier, two of the models, EPPA and MERGE employ a so-called putty clay formulation. They attempt to track the economic lifetime of existing plant and equipment. As a result, these models show less responsiveness of energy demand to price changes in the short run than over the long run. Alternatively, models which assume greater malleability of capital (CETA and MiniCAM) produce lower cost estimates.

Potential gains from interregional efficiency. The models are in more agreement on the relative costs of the various alternatives (Figure 4). Note that the potential benefits from economic efficiency are substantial. In Case 1, each OECD region is required to act independently to reduce its emissions. There is no opportunity to take advantage of low-cost emission reduction options elsewhere in the world. From the perspective of global economic efficiency, this makes little sense. Clearly, it is inefficient to incur high marginal domestic abatement costs when low-cost alternatives exist in other countries. In Case 1a, we allow OECD countries to take advantage of the lower cost alternatives. We do this by permitting trade in carbon emission rights. Note that cooperation of this type can cut the costs of a carbon constraint by well over one-half.

Figure 5 shows the impact on non-OECD countries. International cooperation not only reduces costs within the OECD, it may also result in substantial wealth transfers. Indeed, for three of our models, the revenue received from the sale of emission rights more than offsets the trade-related losses to non-OECD countries. Alternatively, one could devise a burden sharing scheme which imposes zero net costs on non-OECD countries.³⁰ Such a scheme would compensate non-OECD countries for losses accruing through international trade, but results in no additional wealth transfers. In this instance, costs to the OECD would be equivalent to global costs.

Potential gains from intertemporal efficiency. We next turn to the issue of timing (Case 1b). When given the choice, each model shifts some emission reductions into the future. That is, it chooses to emit more in the early years with payback coming later on (see Figure 6a). This behavior can best be understood in terms of an optimal allocation problem. A constraint on cumulative emissions defines a carbon budget. That is, it specifies a total amount of carbon to be emitted over a fixed period of time. For Case 1b, each

OECD region's carbon budget is defined as the sum of its permissible emissions between 2000 and 2050 (as specified in Case 1). The issue is how best to allocate the carbon budget over this period.

There are several factors that argue for using more of the available budget in the early years.³¹ Deferring emission reductions provides valuable time to reoptimize the capital stock. Energy producing and energy using investments are typically long-lived (e.g., power plants, houses, transport). They were put into place with a particular set of expectations about the future. Abrupt changes are apt to be expensive. This is particularly the case when it comes to premature retirement of existing plant and equipment. Time is needed for the capital stock to adapt.

The optimal timing of emission reductions is also influenced by the prospects for new supply and conservation technologies. There has been substantial progress in lowering the costs of carbon-free substitutes (e.g., solar, biomass, energy efficiency) in the past. With a sustained commitment to R&D, there should be further cost reductions in the coming decades. It would make sense to draw more heavily on the carbon budget in the early years when the marginal costs of emissions abatement are highest. With cheaper alternatives in the future, there will be less need for reliance on carbon-intensive fossil fuels.

Finally, with the economy yielding a positive return on capital, future reductions can be made with a smaller commitment of today's resources. For example, suppose that the net real return on capital is 5% per year and it costs \$100 to remove a ton of carbon – regardless of the year in which the reduction is made. If we were to remove a ton today, it would cost \$100. Alternatively, we could invest \$31 today to have the resources to remove a ton in 2020.

Before leaving the timing issue, several additional caveats are in order. First, it should be noted that the two emission paths of Figure 6 result in different levels of atmospheric concentrations (prior to 2050). They may therefore differ in terms of environmental impacts. Given that the concentration paths lie so close together, however, the differential impacts on temperature and sea level are likely to be negligible.³²

Second, the above considerations (capital stock turn over, R&D and discounting) argue for shifting some emission reductions into the future. They cannot, however, be used as an excuse for deferring these reductions indefinitely. The carbon budget is finite. There is an upper limit on the amount to be emitted between now and 2050 which continued deferral would soon exceed. The issue is one of optimal timing.

Finally, note that the amount of deferral depends on the size of the carbon budget. In this instance, there is insufficient flexibility to defer emission reductions altogether in the early years. The optimal emissions path lies between Case 1 and business as usual.

Returning to Figure 4, we see that the most efficient strategy is one which combines international cooperation with flexible timing (Case 1c).³³ In this instance, costs are reduced by more than 80%. Figure 7 provides some insight into why the savings are so large. It shows OECD GDP losses averaged across the four models. In Case 1, GDP losses grow to 2.4% over the next quarter century -- roughly \$400 billion in today's economy. In Case 1b, GDP losses grow more slowly. Although annual losses exceed those of Case 1 toward the end of the time horizon, they are considerably lower early on. As a result, cumulative losses are smaller. If OECD countries are able to take advantage of low-cost emission reduction options elsewhere in the world, losses can be held to under 1% of GDP.

The costs of less stringent carbon constraints. One way to reduce costs would be to design more cost-effective strategies. A second way would be to make the constraint less stringent. We now consider two additional variants on Case 1. In Case 2, we delay the date by which OECD countries must achieve the 20% reduction by 10 years. In Case 3, we put off the 20% reduction altogether. That is, OECD countries continue to hold emissions at 1990 levels.

From Figure 8, note that a substantial fraction of the costs of a 20% reduction would be incurred simply by extending the existing target. That is, much of the costs result from reducing emissions from the business-as-usual path to 1990 levels. Between 40% and 70% of the costs are associated with the decision to stabilize emissions at 1990 levels.

Figure 9 compares OECD GDP losses for the three cases. In Case 1, annual losses rise to 2.4% of GDP by 2020. Postponing the 20% cut by 10 years results in lower GDP losses during the initial two decades of the next century. But losses are similar thereafter. For Case 3, GDP losses are lower for the entire period. On average, lowering the target cuts GDP losses by nearly one-half.

5. Some final comments

Estimating mitigation costs is a daunting task. It is difficult enough to envisage the evolution of the energy-economic system over the next decade. Projections involving a half century or more must be treated with considerable caution. Nevertheless, we believe that exercises like the present one contain useful information. The value, however, lies not in the specific numbers, but in the insights for policy making. With this in mind, we attempt to summarize what we have learned.

- Implementing an AOSIS-type proposal may require substantial CO₂ reductions for OECD countries. With a growing emissions baseline, more and more carbon must be removed from the energy system to maintain an absolute target. Such reductions could be quite costly -- perhaps, as much as several percent of GDP to OECD countries.
- Because of trade effects, the non-OECD countries likely will incur costs even when emissions reductions are confined to the OECD. Restrictions on carbon emissions lead to lower demand for oil, which results in lower revenue for oil-exporting countries. In addition, an economic slowdown in the OECD countries affects the full range of developing country exports, and thus their growth. For many oil-importing developing countries, these broader trade effects outweigh the gain from lower world oil prices.
- One way to reduce mitigation costs would be to design cost-effective constraints. Indeed, the present analysis suggests that the potential gains from international cooperation (interregional efficiency) and flexible timing (intertemporal efficiency) are huge. Taken together, they can reduce costs by more than 80 percent. The key is to allow emission reductions to take place both *where* and *when* it is cheapest to do so.
- A second way to reduce mitigation costs would be to adopt less stringent constraints. For example, rather than a 20 percent cutback, the OECD could agree to hold emissions at 1990 levels. The analysis suggests that the reduction in overall mitigation costs would be between 30 and 60 percent. The savings, however, must be weighed against the impacts of the incremental emissions through larger changes in climate.
- The following steps could substantially reduce the costs of implementing a carbon constraint under the Berlin Mandate: 1) allow developed countries to purchase low-cost abatement options in developing countries, 2) allow time for the economic turn over of existing plant and equipment, 3) invest in the development of economically attractive substitutes for carbon-intensive fuels, and 4) ensure that cost-effective options are adopted to the greatest extent possible.
- Our results are consistent with other studies which suggest that carbon emissions will continue to grow in the absence of policy intervention. Proposals which focus exclusively on developed countries may slow the growth in global emissions, but they will not stabilize them at anywhere near present levels. Nor will they stabilize atmospheric concentrations, the ultimate goal of the Framework Convention. To do so, would eventually require developing country participation.

The present paper identifies enormous savings from international cooperation and flexible timing. Realizing this potential, however, may be another matter. For example, how do we divide up the savings from international cooperation? Or, how do we ensure that parties maintain a credible path toward fulfilling commitments? Considerable ingenuity will be required, but given the stakes, even partial success is likely to be well worth the effort.

Fortunately, some of the necessary concepts are already being tested. For example, efforts to incorporate international cooperation can build upon the experience gained from national and international joint implementation initiatives. With regard to flexible timing, a limit might be placed on a country's cumulative emissions. Subject to this constraint, the country could lay out its own projected emissions time path and prepare a formal plan that builds on existing experience with National Action Plans under the Framework Convention. Periodic reviews could then track adherence to the commitment. Technology development efforts, with suitable performance milestones, also could be an integral part of both the path definition and review processes.

Negotiators must consider a myriad of competing ideas and interests inherent in shaping a global policy. One of their greatest challenges will be to meet the injunction of Article 3 of the Framework Convention: "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible costs." Our success in confronting the challenge of climate change may depend directly on their success in doing so.

The larger question, of course, is what constitutes an appropriate set of emission constraints. This requires consideration of both benefits and costs. The present analysis has been confined to the cost side of the ledger. That is, we examine the costs of reducing CO₂ emissions. Policy makers will also want to know what they are buying, in terms of reducing the undesirable consequences of global warming. Such an analysis is beyond the scope of the present effort.

Notes

- ¹Electric Power Research Institute
- ²Pacific Northwest Laboratory
- ³US Department of Energy
- ⁴University Corporation for Atmospheric Research
- ⁵Massachusetts Institute of Technology
- ⁶Stanford University
- ⁷Electric Power Research Institute
- ⁸Teisberg and Associates
- ⁹Pacific Northwest Laboratory
- ¹⁰Massachusetts Institute of Technology
- ¹¹For the text of the Berlin Mandate, see United Nations Climate Change Bulletin, Issue 7, 2nd Quarter 1995, published by the interim secretariat for the UN Climate Change, Convention, Geneva. For the text of the Framework Convention, see Intergovernmental Negotiating Committee for A Framework Convention on Climate Change, Fifth Session, Second Part, New York, 30 April-9 May 1992
- ¹²See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapter 1, forthcoming, Cambridge University Press.
- ¹³The four models comprise the Subgroup on the Regional Distribution of Costs and Benefits of Climate Change Policy Proposals. The Subgroup is open to models participating in Stanford University's Energy Modeling Forum (EMF) Study on "Integrated Assessment of Climate Change."
- ¹⁴See Intergovernmental Negotiating Committee for A Framework Convention on Climate Change, Fifth Session, Second Part, New York, 30 April-9 May 1992.
- ¹⁵See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapter 9, forthcoming, Cambridge University Press.
- ¹⁶See Intergovernmental Panel on Climate Change (IPCC). *Climate Change 1994*, Cambridge University Press, 1994. Also see, Wigley, T., Richels, R. and Edmonds, J. "Economic and Environmental Choices in the Stabilization of Atmospheric CO₂ Concentrations," *Nature*, Vol. 379, 18 January, 1996.
- ¹⁷See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapters 9 & 10, forthcoming, Cambridge University Press.
- ¹⁸See Peck, S. and Teisberg, T. "International CO₂ Emissions Targets and Timetables: Analysis Using CETA-M", Working Paper, 1995.
- ¹⁹See Z. Yang, et. al, "The MIT Emissions Projection and Policy Assessment (EPPA) Model", Draft report, MIT Joint Program on the Science and Policy of Global Change, February 1996.
- ²⁰See Manne, A. and Richels, R. "The Berlin Mandate: the Costs of Meeting Post-2000 Targets and Timetables", Stanford University, Stanford, CA, forthcoming in *Energy Policy*, 1995.
- ²¹See Edmonds et al
- ²²See Hogan, W. and Jorgenson, D. "Productivity Trends and the Costs of Reducing CO₂ Emissions" *Energy Journal* 12 No. 1, 1991.

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- ²³For a detailed model comparison, see EMF-14.
- ²⁴These projections are intended as examples of how emissions might evolve under existing policies. They should not be interpreted as each analysis team's "best guess" of future emissions.
- ²⁵See Intergovernmental Panel on Climate Change (IPCC). *Climate Change 1994*, Cambridge University Press, 1994.
- ²⁶See Manne, A. and Richels, R. "The Costs of Stabilizing Greenhouse Gas Emissions: A Probabilistic Analysis based on Expert Judgments," *The Energy Journal* 15(1), 1994.
- ²⁷The AOSIS proposal calls for Annex 1 countries to reduce emissions by 20% by 2005.
- ²⁸See notes 15 and 16.
- ²⁹There is some trade in emission rights within the OECD, however. This is the consequence of aggregating single countries into larger regions.
- ³⁰With an international market in carbon emission rights, global abatement costs are independent of the burden sharing scheme. This allows us to separate the difficult issues of efficiency and equity. For the theoretical considerations underlying this proposition, see Manne, A. "Greenhouse Gas Abatement - toward Pareto Optimality in Integrated Assessments", in *Education in a Research University*, edited by Kenneth J. Arrow, Richard W. Cottle, B. Curtis Eaves and Ingram Olkin, Stanford University Press, Stanford CA, 1996.
- ³¹For a more detailed discussion of the timing issue, see Wigley et al, note 16.
- ³²For the analysis, we use the carbon cycle model of Wigley. See Wigley, T.M. "Balancing the Carbon Budget: the Implications for Projections of Future Carbon Dioxide Concentration Changes," *Tellus*, 45B, 1993.
- ³³EPPA is a recursive rather than an intertemporal optimization model. Several alternative emission paths were explored for Cases 1b and 1c. The results reported here are for the lowest-cost of the paths tested, and the results are not strictly comparable with those from the other models.

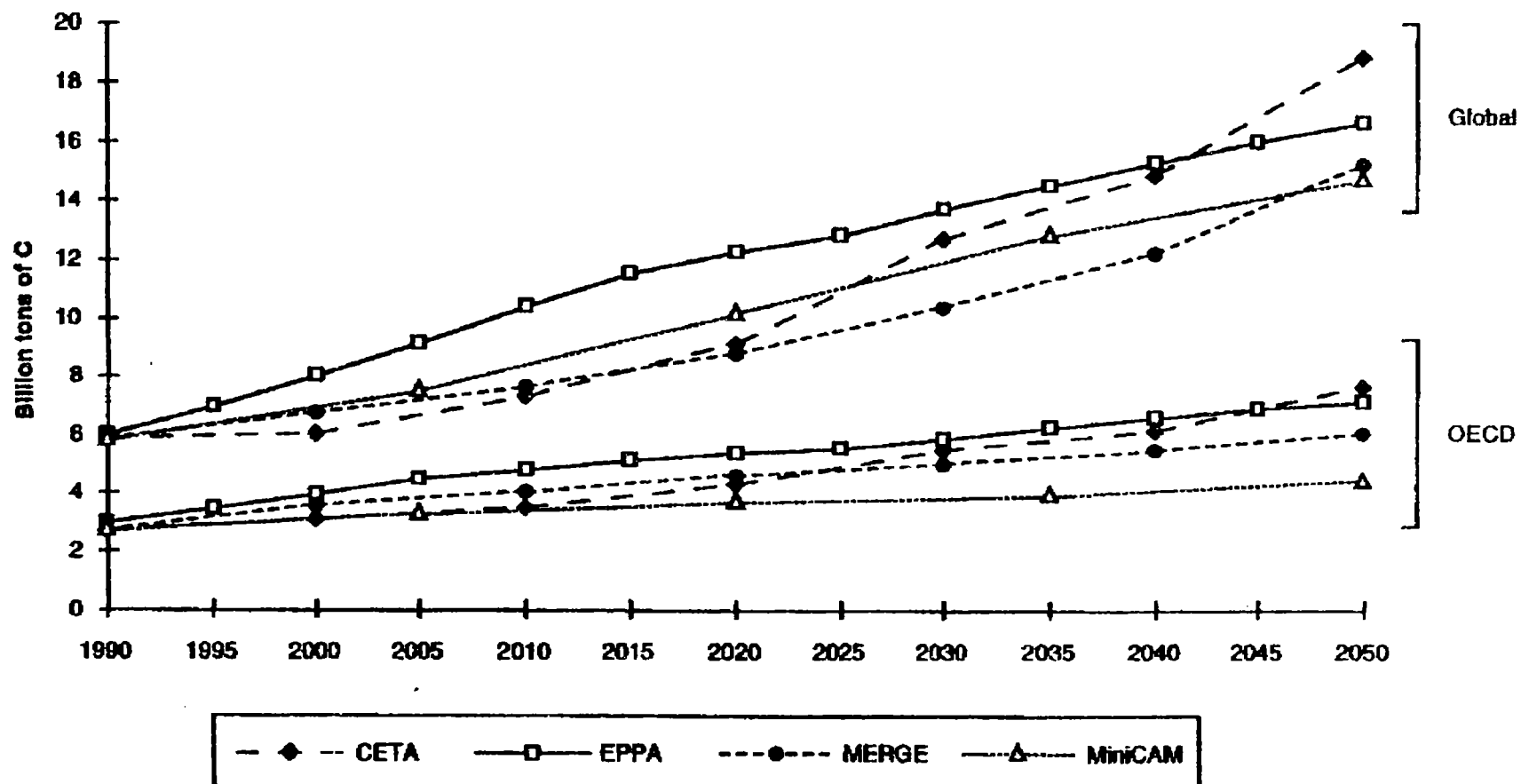
Figure 1. Carbon Emissions under Business As Usual

**Figure 2. Global Emissions under Business as Usual and with a 20% Cut in OECD Emissions
(based on average of model results)**

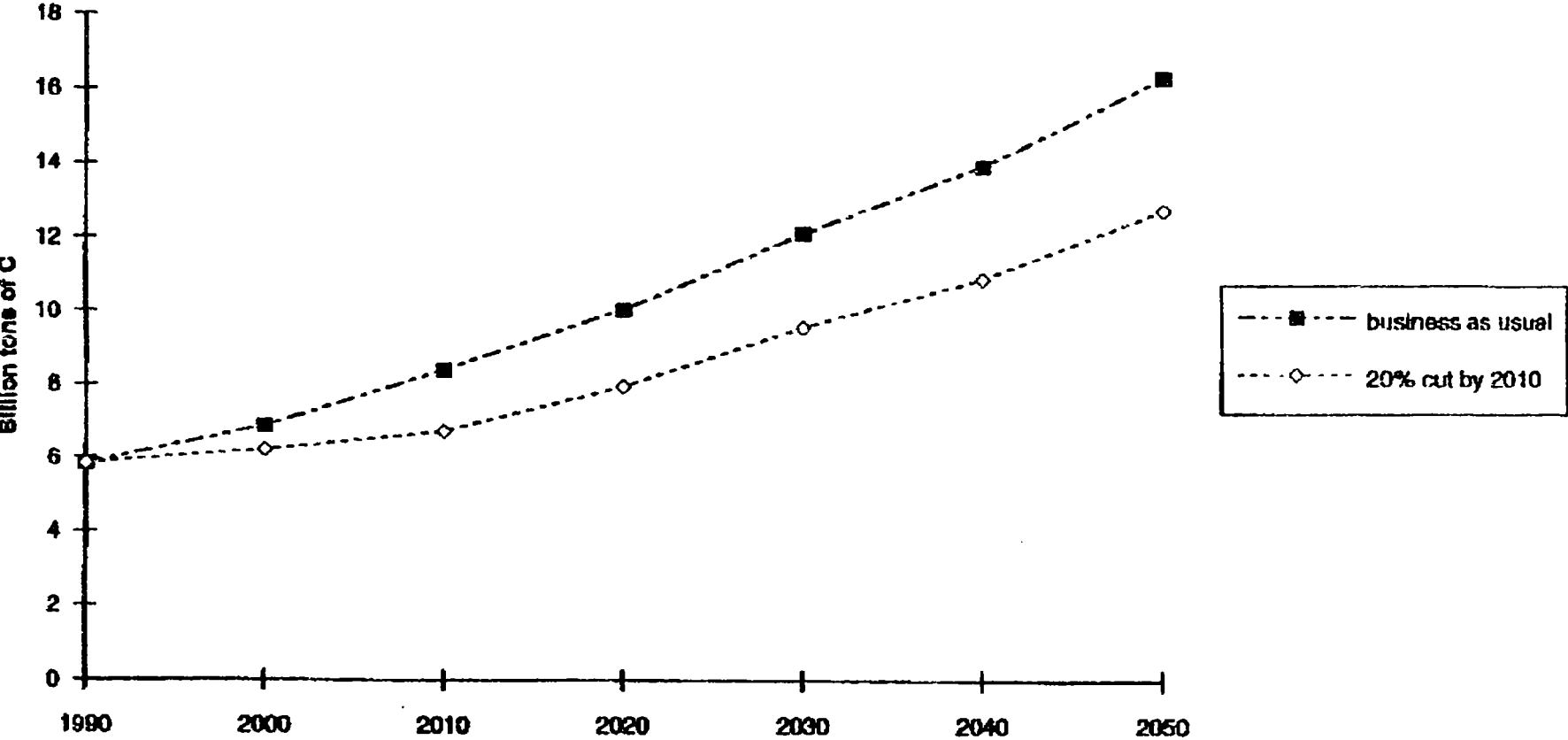


Figure 3. Costs of 20% Cut in OECD Emissions by 2010 – Case 1
(costs through 2050 discounted to 1990 at 5%)

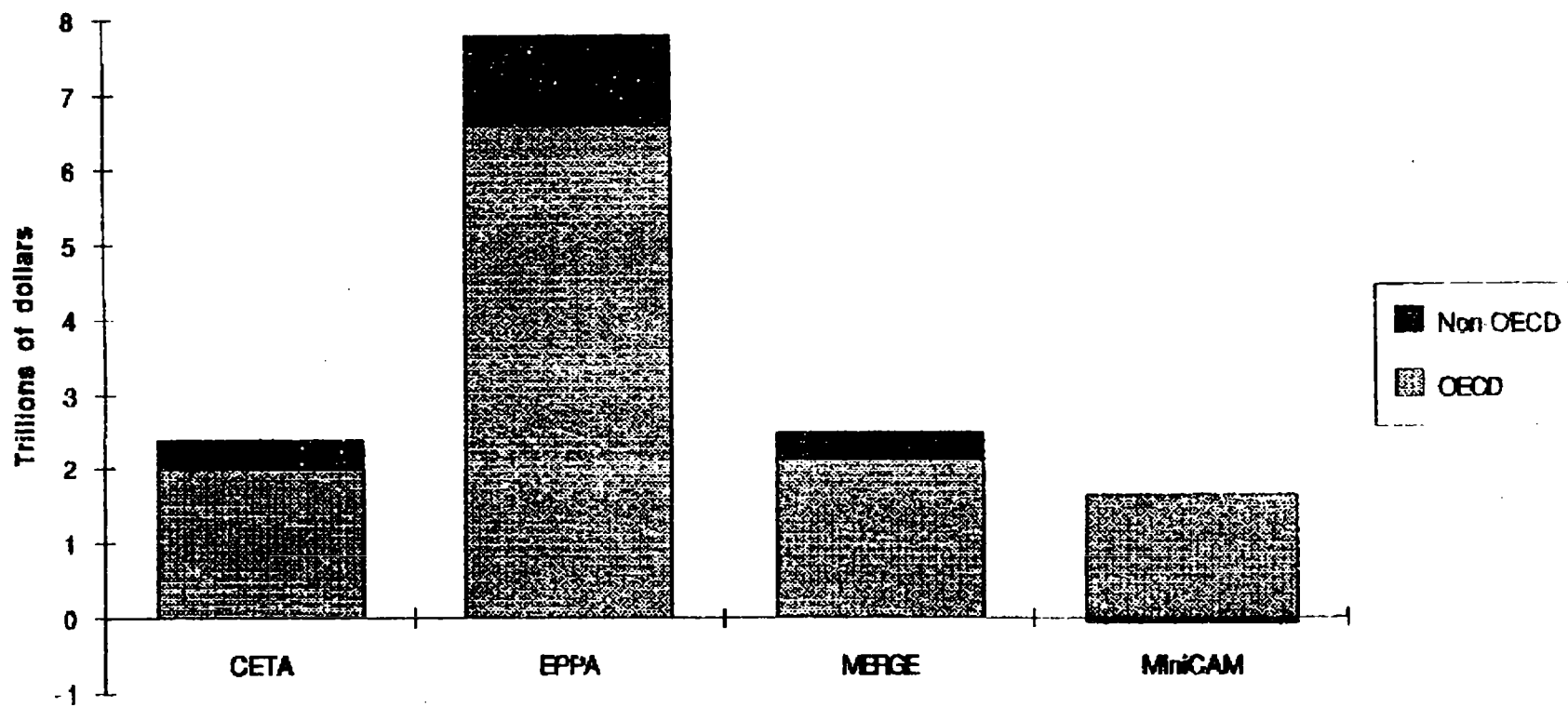
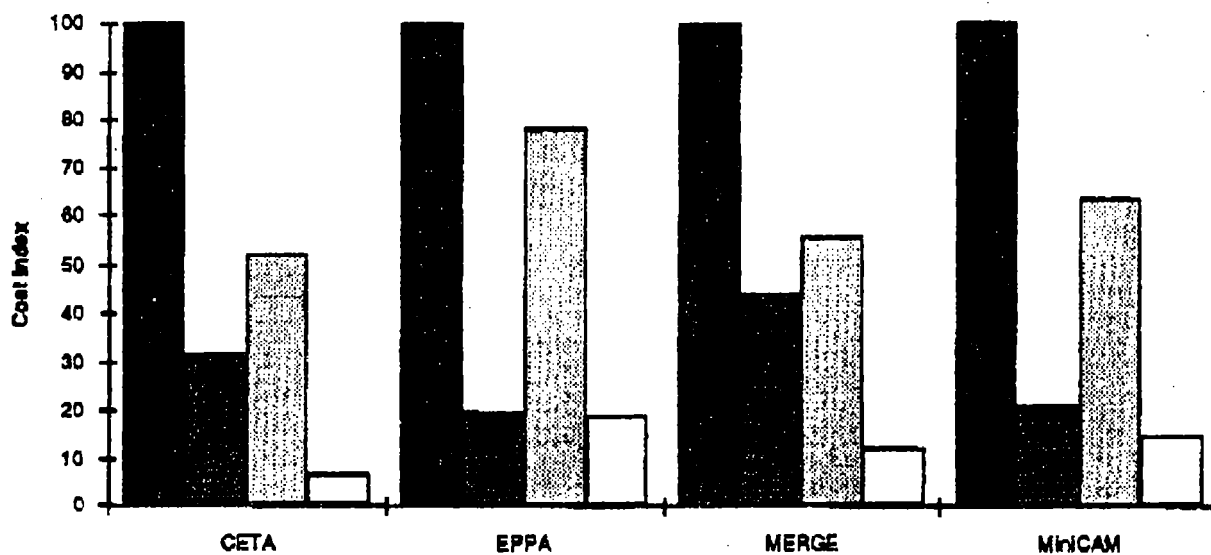
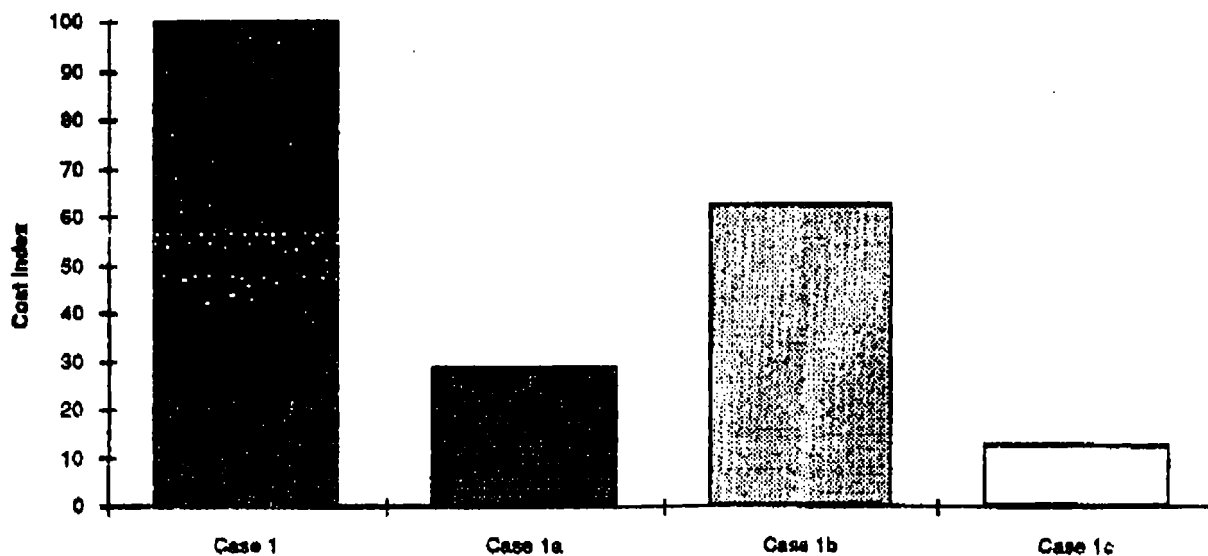
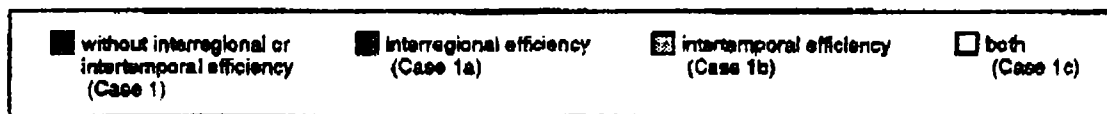


Figure 4. Global Costs under Four Alternative Cases



a) Case 1 = 100



b) Average of model results

Figure 5. Regional Costs under Four Alternative Cases
(costs through 2050 discounted to 1990 at 5%)

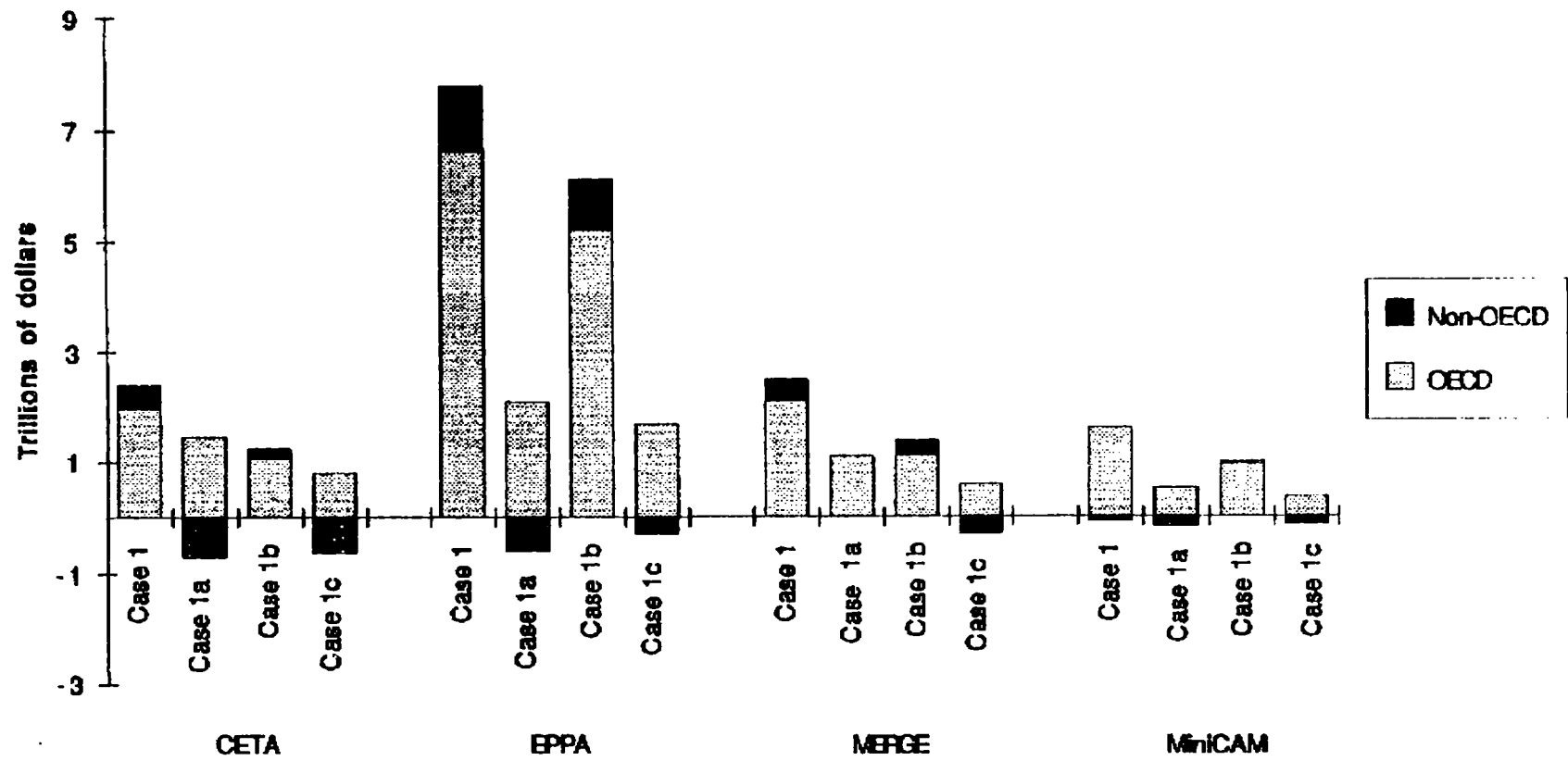
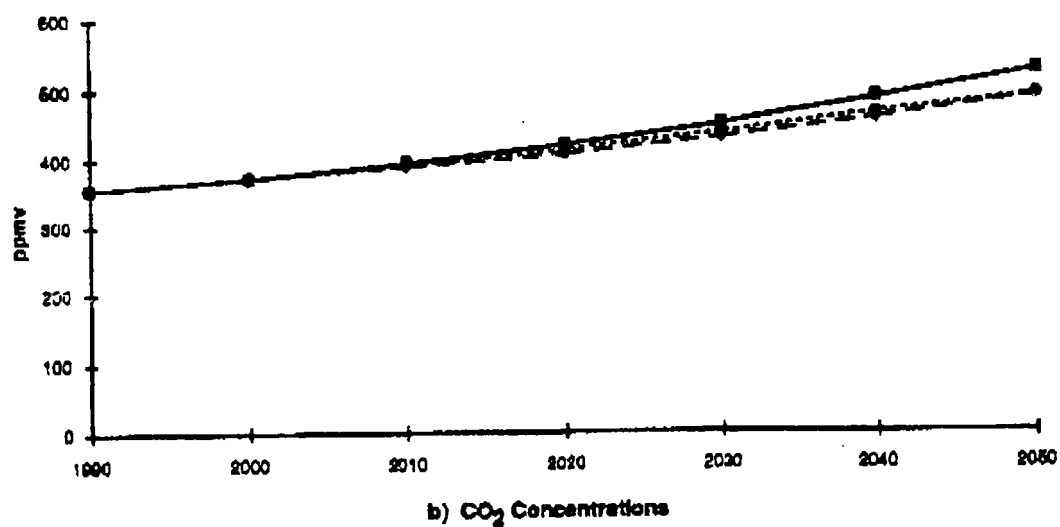
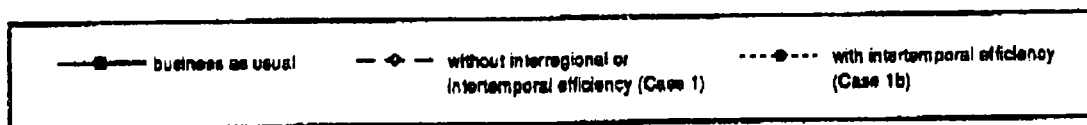
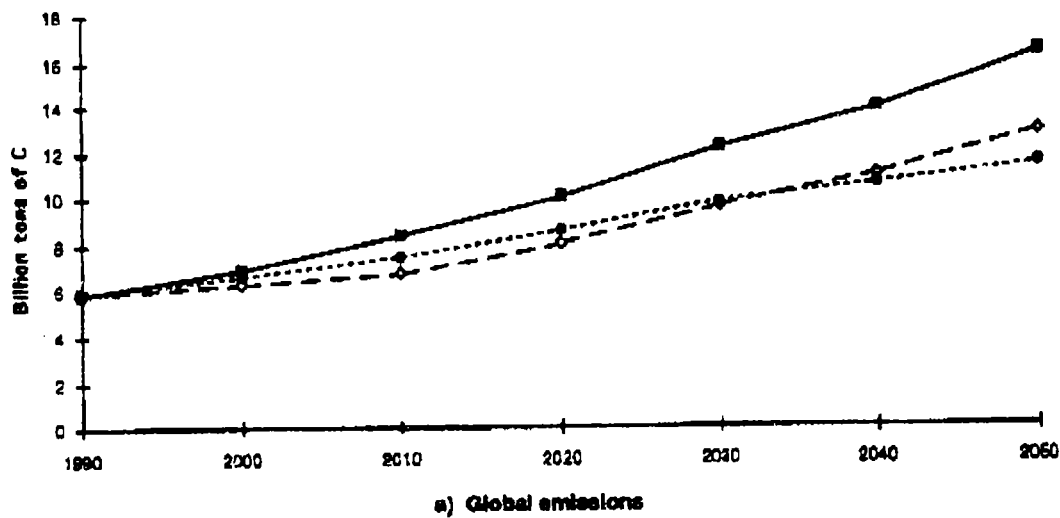


Figure 6. Global Emissions and CO₂ Concentrations with and without Intertemporal Efficiency (based on average of model results)



3 much lower
Figure 7. OECD GDP Losses under Alternative Assumptions about Economic Efficiency
(based on average of model results)

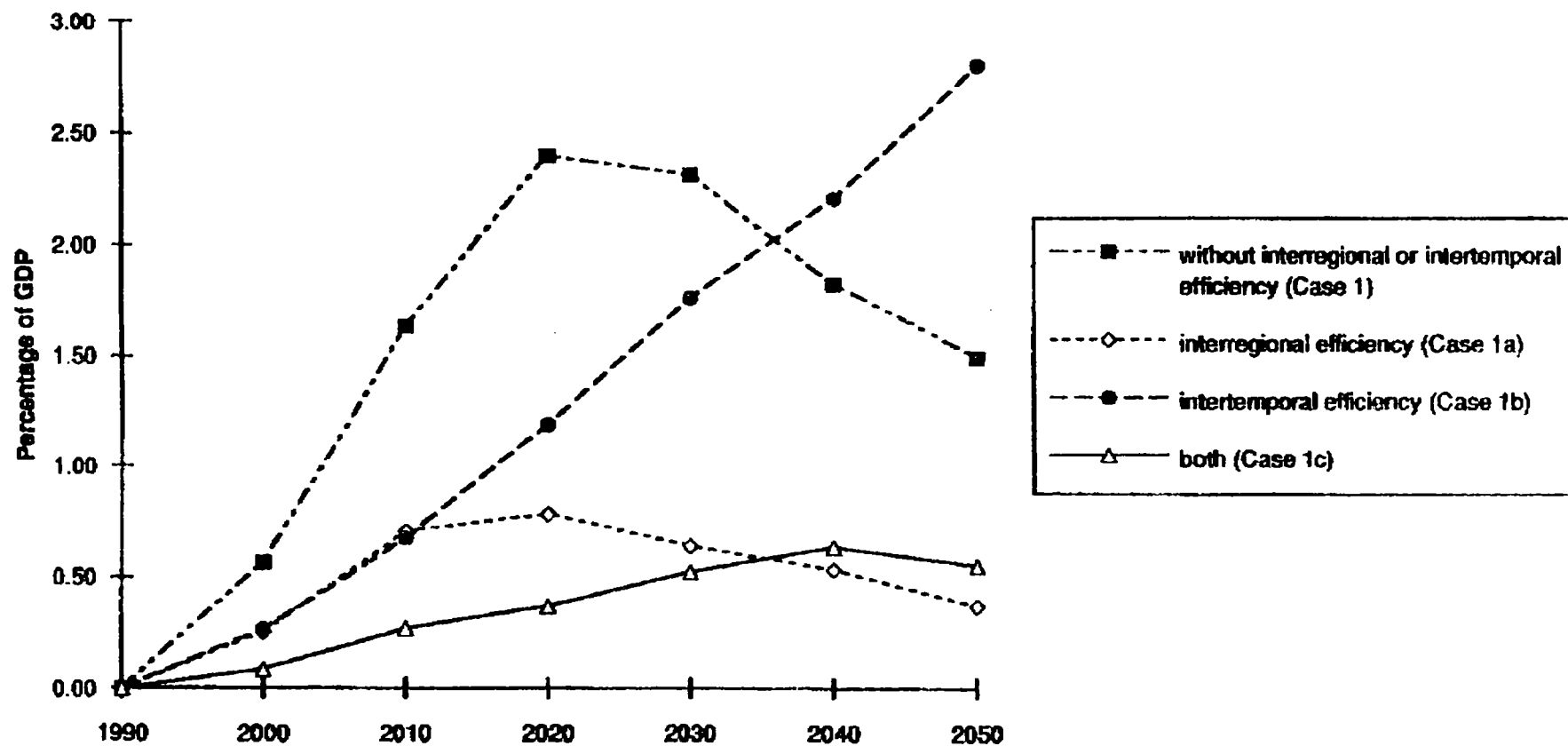
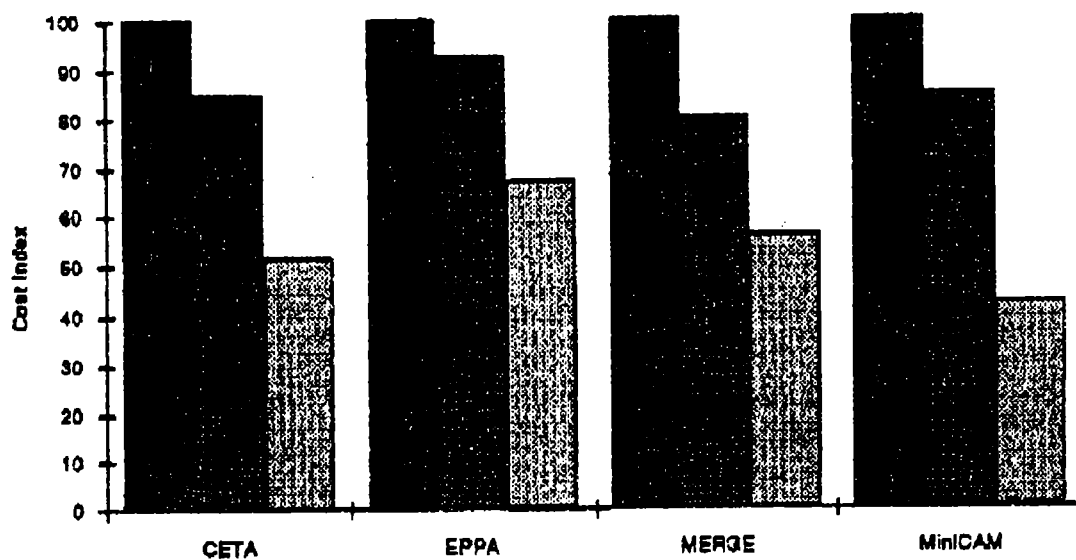
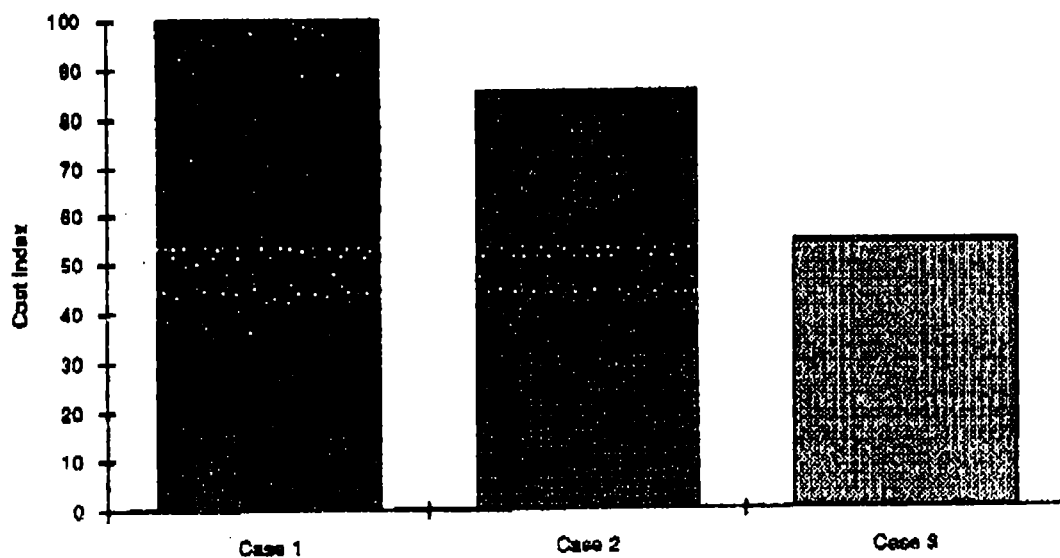
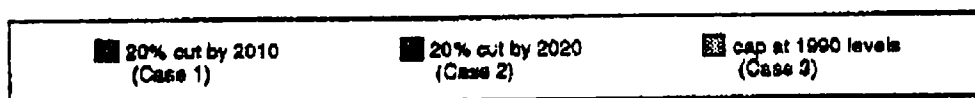


Figure 8. Costs of Alternative Sets of Targets and Timetables

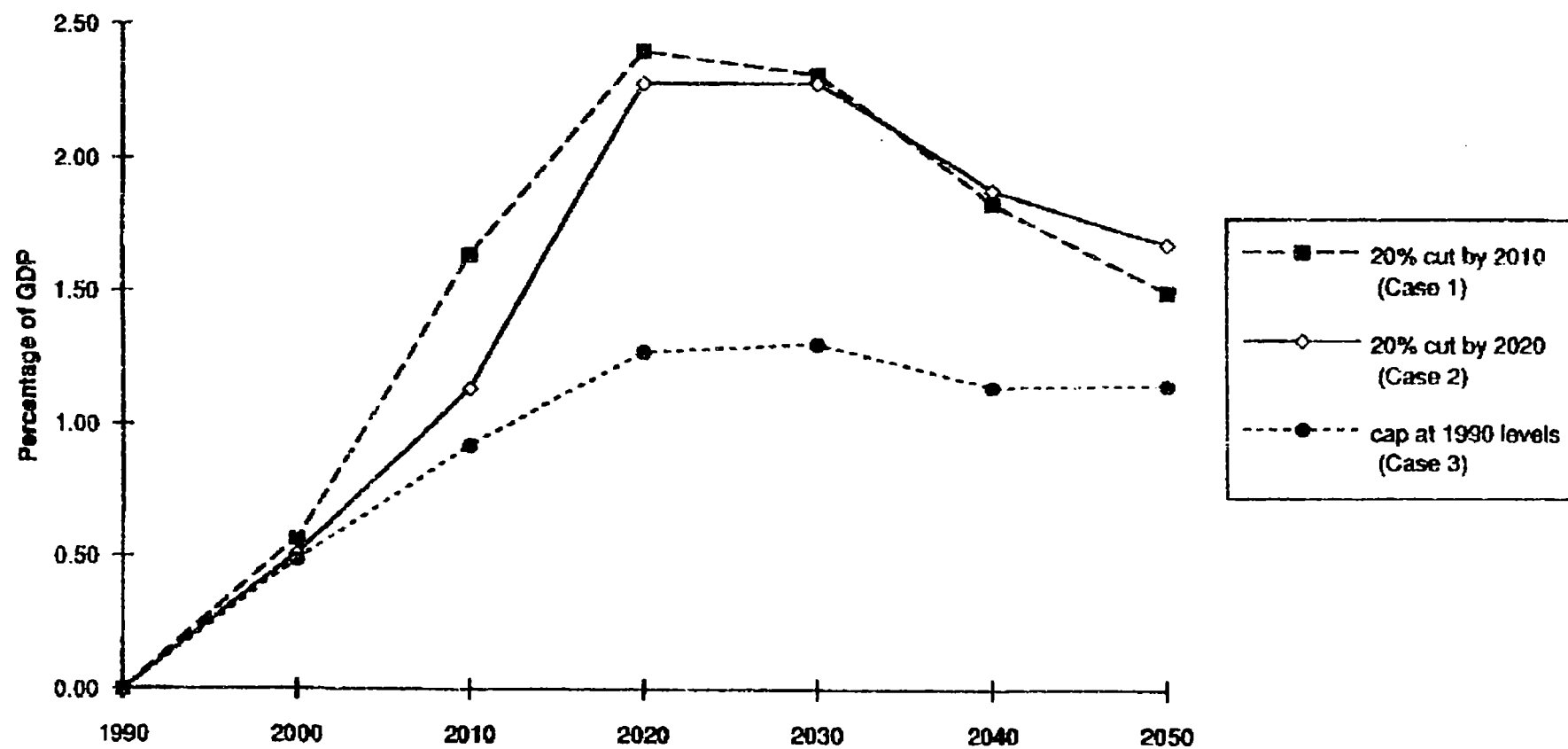


a) Case 1 = 100



b) Average of model results

Figure 9. OECD GDP Losses under Alternative Targets and Timetables
(based on average of model results)





The Greenhouse Debate: Economic Efficiency, Burden Sharing and Hedging Strategies

Alan Manne* and Richard Richels**

We address the issue of economic efficiency as it relates to climate change. We begin with a classical cost-benefit perspective. That is, we focus on emission trajectories which maximize net benefits. We then examine the consequences of adopting alternative decision making paradigms—for example, those based on limiting atmospheric concentrations so as to achieve an "ample margin of safety." We also consider the regional distribution of costs and benefits under alternative burden sharing schemes. Although the climate issue is often viewed from a global perspective, international negotiators will be acutely interested in how damages and mitigation costs might be distributed among individual regions. Finally, we address the issue of decision making under uncertainty. The challenge confronting today's policy makers is to identify a sensible hedging strategy—one that balances the risks of waiting against those of premature action.

INTRODUCTION

There are many perspectives on the greenhouse debate. At one end of the spectrum, there are those who urge that climate change is so poorly understood that mitigation costs should be the sole determinant of today's decisions. Until we have a better understanding of the impacts of global warming, any response should be limited to "no regrets" policies. These are defined as measures that reduce emissions and at the same time have directly beneficial economic effects. There is considerable disagreement about how far one might get by relying upon such a strategy for limiting greenhouse gases. The projections vary widely.

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At the opposite end of the spectrum, there are those who feel that mitigation costs are of only secondary importance. They liken the climate debate to that on the Ozone Hole. The stakes are so high that emissions must be controlled at all costs. To act otherwise would be to court ecological disasters. From this perspective, the only justifiable policies are those that provide an ample margin of safety. There are no limits on how much we should be willing to pay for buying greenhouse insurance.

In between these extremes, there is a third school of thought—those who believe that both costs *and* damages are important. The authors belong to this school. We believe that greenhouse policy makers need to balance the costs of abatement against what such proposals might achieve in terms of reducing environmental damages. We are a society of limited resources. We cannot guard against all conceivable environmental threats. Cost-benefit analysis is a logical way to ensure that society's resources are allocated wisely. Neither costs nor benefits are easy to quantify, but we can do our best to evaluate them.

During the past decade, there have been a number of proposals put forward for dealing with climate change. Initially, these took the form of targets and timetables. Emission targets were proposed for specific dates. For example, the Toronto target (the most widely cited of the early proposals) called for reducing global CO₂ emissions by 20% below 1988 levels, and for achieving this goal by 2005. Although this target has often been characterized as arbitrary, in fact, it was the logical consequence of a "no regrets" approach to climate policy-making. The drafters arrived at it by extrapolating recent trends in energy efficiency and in fuel switching. They were persuaded that a 20% reduction could be accomplished at little or no cost.

By contrast, the UN Framework Convention on Climate Change (1992), belongs to the "eliminate the evil" school of thought. According to Article Two of the Convention, the ultimate goal is "the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The presumption is that there is an objective and scientific way to determine a maximum safe level of concentrations. Mitigation costs are of secondary importance. Article Three states only that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."

With the focus shifting from short-term emission goals to long-term atmospheric concentrations, international negotiators now have the flexibility to select emission time paths that minimize the costs of meeting a particular concentrations target. Although this change represents an improvement from the perspective of economic efficiency, it can still be argued that this does not go far enough. An appropriate concentrations level can only be determined through a careful balancing of costs and benefits.

This paper addresses the issue of economic efficiency as it relates to climate change. We begin with a classical cost-benefit perspective. That is, we focus on emission trajectories which maximize net benefits. Alternatively, these can be described as minimizing "total costs"—the discounted sum of mitigation costs and damages. We then examine the consequences of adopting alternative decision making paradigms—for example, those based on limiting atmospheric concentrations so as to achieve an "ample margin of safety." What are the likely impacts on mitigation costs, and on damages?

Next, we address the issue of burden sharing. Although the climate issue is often viewed from a global perspective, international negotiators will be keenly interested in the implications for their individual country or region. We examine how the distribution of costs might vary under alternative burden-sharing schemes. Typically, we are able to demonstrate that the economically efficient level of global emission reductions is virtually independent of how the costs might be shared among the participants.

Finally, we address the issue of decision making under uncertainty. Climate policy making is not a once-for-all event, but an ongoing process. There will be many opportunities for learning and for mid-course corrections. The challenge confronting today's policy makers is to identify a sensible hedging strategy—one that balances the risks of waiting against those of premature action.

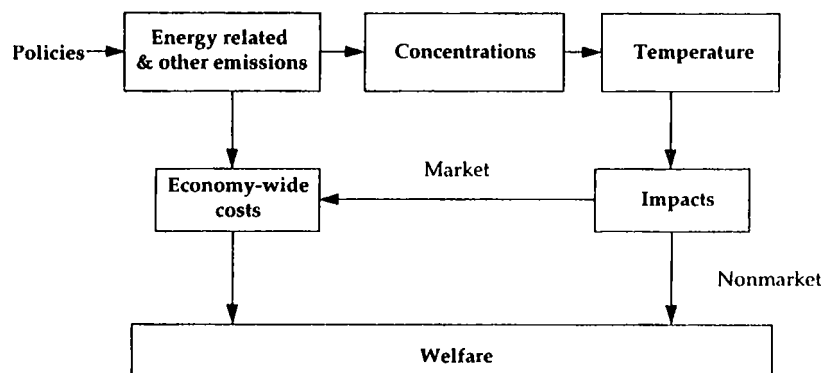
AN OVERVIEW OF MERGE 2

This analysis represents an extension of MERGE (a model for evaluating the regional and global effects of greenhouse gas reduction policies). See Manne, Mendelsohn and Richels (1995). Like its predecessor, MERGE 2 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, climate change and damage assessment. (See Figure 1.) There are five geopolitical regions: the US, other OECD nations (Western Europe, Japan, Canada, Australia and New Zealand), the former Soviet Union (FSU), China, and the rest of world (ROW). This section contains a brief overview of the model. Technical details and a list of key assumptions are available in a set of appendices (available upon request).

A bottom-up approach is used to model the energy supply sector. For each scenario, a least-cost choice is made among specific physical activities for the generation of electricity and for the production of nonelectric energy. The fossil fuels (oil, gas and coal) are each viewed as exhaustible resources. There are limits upon individual types of low-cost renewable energy such as

hydroelectricity. There are introduction constraints on new technologies—both those that are carbon-based (e.g., synthetic fuels) and those that are carbon-free (e.g., advanced generating technologies based on photovoltaics, wind, fission or fusion).

Figure 1. MERGE 2



A top-down approach is taken for the balance of the economy. This is modeled using nested constant elasticity of substitution production functions. Population trends are taken as exogenous. Per capita incomes are determined primarily by the rate of labor force productivity growth—and by the assumption of a narrowing gap between per capita incomes in the OECD countries and those in the rest of the world. Aggregate output depends upon the inputs of capital, labor, electric and nonelectric 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.

Three greenhouse gases are considered explicitly: carbon dioxide, methane and nitrous oxides. Atmospheric CO₂ concentrations are tracked by a five-box reduced form carbon cycle model. CH₄ and N₂O concentrations are each projected by a one-box exponential decay model. Concentrations are translated into their impacts on radiative forcing, then into the changes in global potential and actual surface temperature. We assume that the temperature change in temperate countries is identical to the global mean, and that the change in tropical countries is half this value.

Unlike its predecessor, MERGE 2 can be used to identify global emissions trajectories that are economically efficient. We use the term "Pareto

optimal" to describe those scenarios in which the costs of abatement are balanced against the damages of global climate change. Each region is viewed as a trustee for current and future generations. It maximizes the discounted utility (the logarithm of consumption) subject to an intertemporal budget constraint.¹ Each region's wealth includes not only capital, labor and exhaustible resources, but also its negotiated share in global carbon emission rights.

Over time, human activities are likely to lead to increased concentrations of greenhouse gases, and this could in turn lead to an increase in the global mean temperature. 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.

For Pareto-optimal outcomes, 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 damages represent a direct claim on gross economic output—along with energy costs, aggregate consumption and investment. Nonmarket damages enter into each region's intertemporal utility function, and are viewed as an adjustment to the conventional value of macroeconomic consumption.²

With the discounted logarithmic intertemporal utility function, an economically efficient program is one in which the rate of return on capital (i.e., the marginal productivity) equals the sum of the utility discount rate (sometimes known as the social rate of time preference) and the economic growth rate. For example, a 3% rate of time preference and a 2% rate of economic growth would be consistent with a 5% marginal product of capital.

Our approach to discounting is descriptive rather than prescriptive. We have chosen values for the utility discount rate and allowed for sufficient international capital mobility so that there is no region in which the future annual marginal productivity of capital differs greatly from 5% (expressed in real terms). We believe that 5% represents a lower bound on today's opportunity costs of capital in both developing and developed countries. There may be changes over time in the relative price of environmental and other goods, but it is economically inefficient to apply one discount rate for converting future environmental goods into their present values, and to apply a different discount rate for all other goods.

1. Technically, this is done by a computing algorithm termed "sequential joint maximization." For details on how this operates through the iterative determination of Negishi weights, see Rutherford (1995).

2. In cases that are not Pareto-optimal, adjustments for market and nonmarket damages are neglected in each region's objective function. They are, however, included in our accounting for global costs and benefits.

By contrast, suppose that one adopts the prescriptive viewpoint proposed by Cline (1992) and others. They suggest that intergenerational equity requires a much lower rate than 5% for the evaluation of the future costs and benefits of greenhouse gas abatement. This leads to logical difficulties with an intertemporal model such as MERGE 2. Here there are endogenous decisions with respect to the accumulation of both physical capital and also greenhouse gas concentrations. If one adopts the prescriptive perspective, one must then explain what policy measures will enable us to achieve a drastic immediate step-up in the rate of savings and investment. This is essential if we are to achieve a significant drop in the long-term rate of return on capital. For a numerical example and for a further discussion of these issues, see Manne (1995).

MERGE 2 is in the tradition of the work of Nordhaus (1991, 1994) and Peck and Teisberg (1992). It can be used to identify solutions which minimize total costs—the discounted sum of mitigation costs and damages. Our goal has been to include within a single framework: (1) a bottom-up representation of the global energy supply system, (2) regional disaggregation of mitigation costs and damages, and (3) explicit treatment of uncertainty. We begin by showing how the model can be used to examine deterministic scenarios—those in which all uncertainties are resolved prior to decision making. We then show how it can be used to identify hedging strategies that allow for low probability, high consequence futures.

VALUING IMPACTS

MERGE 2 employs highly aggregated representations of key physical and economic phenomena. In some areas (e.g., the carbon cycle), such representations are readily available for use in integrated assessments. In other areas, the state of the art is much less developed. This is particularly so in the case of impacts.

At the present time, there is little consensus on: (1) how changes in key climate variables will impact the things we care about, and (2) how—or even whether—to translate environmental impacts into their dollar equivalents. This paper does not attempt to resolve these issues. Rather our goal is to conduct thought-experiments with representative parameter values, and to explore the implications of alternative viewpoints.

We begin by dividing the impacts into two categories—market and nonmarket. For market damages, we rely on the earlier work of Nordhaus (1991). Noting that only 3% of US national output comes from climate-sensitive sectors and another 10% from sectors only modestly affected by temperature change, he estimated that damages to the US economy from the doubling of CO₂ concentrations (a 2 x CO₂ scenario) would be of the order of 0.25% of GDP. Accordingly, for the US, other OECD nations and the former USSR, we assume

that a 2.5-degree C increase in temperature (above 1990 levels) would result in market damages of 0.25 % of GDP.³

To date, 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-degree C increase in temperature would result in market damages of 0.50 % of GDP in China and the ROW. For all regions, market damages are projected as proportional to the amount of temperature change.

Even less is known about nonmarket damages. What will be the impacts of climate change on environmental quality, biodiversity, and human health? These areas do not lend themselves to monetary valuation. Yet we have little alternative but to try. In MERGE 2, we take a willingness-to-pay approach. The issue is framed in terms of how much consumers in each region would be willing to pay to avoid nonmarket damages. These damages enter into each region's intertemporal utility function and are viewed as an adjustment to the conventional measurement of macroeconomic consumption. The adjustment varies with the level of per capita income, and we suppose that it follows a logistic pattern. The higher the level of income, the greater will be the magnitude of these adjustments.

Our estimates of nonmarket damages are based on the following speculations about the form of the willingness-to-pay functions. According to Figure 2, we have assumed that when per capita incomes approach \$40,000 (about twice the 1990 level in the OECD nations), consumers would be willing to pay 2 % of their incomes to avoid a 2.5-degree C increase in temperature. (As a point of reference, the U.S. 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 global mean temperature. For example, consumers would be willing to pay 8 % of their incomes to avoid a 5-degree C increase.⁴

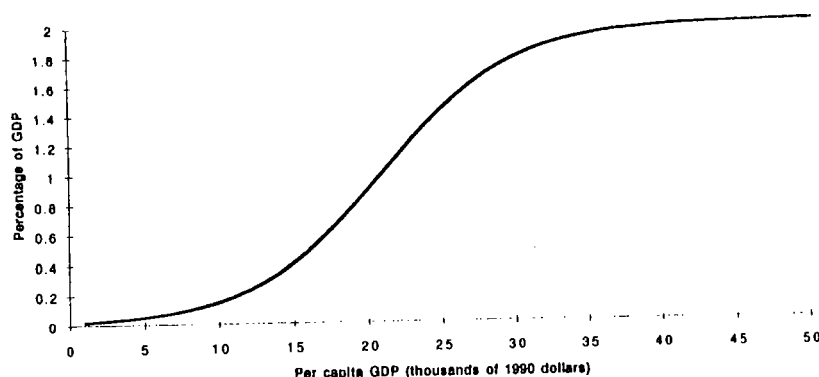
Perhaps most importantly, we assume that each region places a value on nonmarket damages that is independent of where such damages might occur. Consumers in each region are affected by wetland losses regardless of whether they occur within or outside their own boundaries. The same is true for the impacts of climate on human health and wildlife. The S-shaped logistic function implies, however, that low income regions will place a lower value on such losses. The lower the per capita GDP level, the lower will be the fraction of

3. In MERGE 2, the temperature sensitivity parameter implies that a doubling of CO₂ concentrations leads to a 2.5 degree C increase in the equilibrium temperature.

4. Our functional form (a "hockey-stick" function) has willingness to pay increasing at a faster than quadratic rate when annual per capita incomes are below \$40,000.

income that consumers would be willing to forego in order to avoid the nonmarket damages associated with a specific increase in the mean global temperature.

Figure 2. Willingness to Pay to Avoid a 2.5-degree C Change in Temperatures--Nonmarket (Ecological) Damages



We have adopted functional forms and parameter values that are consistent with the conventional wisdom. 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. These assumptions are intended only as a point of departure. Because of the major uncertainties inherent in the greenhouse debate, we can only provide insights through sensitivity analysis. In this way we can hope to identify those areas in which the resolution of uncertainty is critical to the choice of policy alternatives.

ECONOMIC EFFICIENCY

The model is designed to examine a broad range of policies. It can evaluate alternative proposals for controlling emissions or controlling atmospheric concentrations—even though these do not necessarily lead to global "least cost" solutions. With MERGE 2, we can also identify emission paths that minimize the sum of mitigation costs and damages. This provides a useful reference point for examining other proposals. We begin by considering the following four cases:

- 1) Business-as-usual—a scenario in which the nations of the world continue to emit as if the benefits of reducing greenhouse gas emissions were negligible. Alternatively, this could be interpreted as a failure to reach an international agreement on emission or concentration targets. For this scenario, emission reduction policies are adopted only if they are economically justifiable in their own right. That is, the responses are limited to "no regrets" measures such as the elimination of energy subsidies.
- 2) Cooperative (Pareto optimal) case—a scenario in which the international community agrees upon a policy of balancing costs and benefits. Mitigation takes place wherever it is cheapest to do so. Assuming that equitable compensation measures can be negotiated, this allows us to separate the issue of the globally optimal mitigation level from that of sharing the burden among individual participants.
- 3) Stabilize atmospheric CO₂ concentrations at 550 ppmv—The UN Framework Convention on Climate Change has adopted as its ultimate goal the stabilization of greenhouse gas concentrations in the atmosphere. There continues to be intense debate on what might constitute a dangerous amount of anthropogenic interference with the climate system. For illustrative purposes, we examine the consequences of a policy to stabilize carbon concentrations at 550 ppmv (parts per million by volume)—that is, twice the preindustrial level.
- 4) Stabilize global CO₂ emissions at 1990 levels—There have been numerous proposals for global emission targets. The Framework Convention calls for developed countries to take the lead and aim to stabilize emissions at 1990 levels by the year 2000. Emissions stabilization is seen as a first step in achieving the Convention's ultimate goal of stabilizing atmospheric concentrations. We explore a case where there is a global commitment to restrict emissions to 1990 levels.

Except for the business-as-usual scenario, all other cases require some type of assumption about the regional distribution of emission reductions. Uniform international carbon taxes might be an economically efficient way to implement emission controls. There is, however, a serious disadvantage if we were to rely solely upon taxes. This type of agreement would not provide automatic side payments to induce reluctant regions to participate. For this reason, we focus on mechanisms such as carbon quotas coupled with tradeable emission rights.

There is no unique formula for the allocation of emission rights among regions. We begin with one widely discussed proposal: a transition to equal per capita emission rights. For illustrative purposes, it is assumed that carbon rights are initially distributed among regions in proportion to their 1990 level of emissions. Over time, the shares change gradually, and by 2030 are distributed in proportion to 1990 population levels. Note that the 1990 population base would provide a modest incentive for nations to control their rate of population growth. Later on, we explore the implications of alternative burden sharing schemes.

Figures 3, 4 and 5 compare carbon emissions, atmospheric concentrations and temperature change for the four scenarios. Under business as usual, emissions continue to rise into the 22nd century. The growth reflects the net effect of shifting to carbon-free sources of electricity, but increasing dependence on coal in the nonelectric sector. With the eventual exhaustion of oil and gas resources, coal-based synthetic fuels are apt to become the marginal source of nonelectric energy supply. This could exacerbate the greenhouse problem. Synthetics emit twice as much CO_2 per unit of useful energy as conventional oil.

In the longer term, CO_2 emissions will begin to decline—even under business as usual. There are finite resources of coal. As the economically recoverable reserves are exhausted, coal will be replaced by carbon-free alternatives. This could also be interpreted as the availability in the 22nd century of unlimited amounts of low-cost, carbon-free substitutes for coal-based synthetic fuels. Thus, even in the absence of greenhouse considerations, the world's dependence on fossil fuels is likely to decline in the 22nd century.

Because of its chemical stability and because of the inability of the oceans and terrestrial systems to absorb CO_2 rapidly, the concentrations of this greenhouse gas continue to rise long after emissions begin to decline (Figure 4). The rate of growth, however, slows significantly. As we would expect, there is a corresponding slowdown in the rate of temperature increase (Figure 5).

A useful benchmark is provided by the emissions trajectory corresponding to the cooperative case. This can be described either as maximizing net benefits or as minimizing the discounted sum of mitigation costs and damages. Note that the economically efficient emissions trajectory is quite close to that of business as usual during the early decades of the next century. Initially, there is only a small reduction in emissions. Over time, however, it becomes cost-effective to increase the level of mitigation.

The shape of the cooperative emissions profile reflects our assumptions about damages and costs. On the damage side, nonmarket impacts are the principal determining factor. This is where there is the greatest potential for exceptionally large impacts.

Figure 3. Global Carbon Emissions

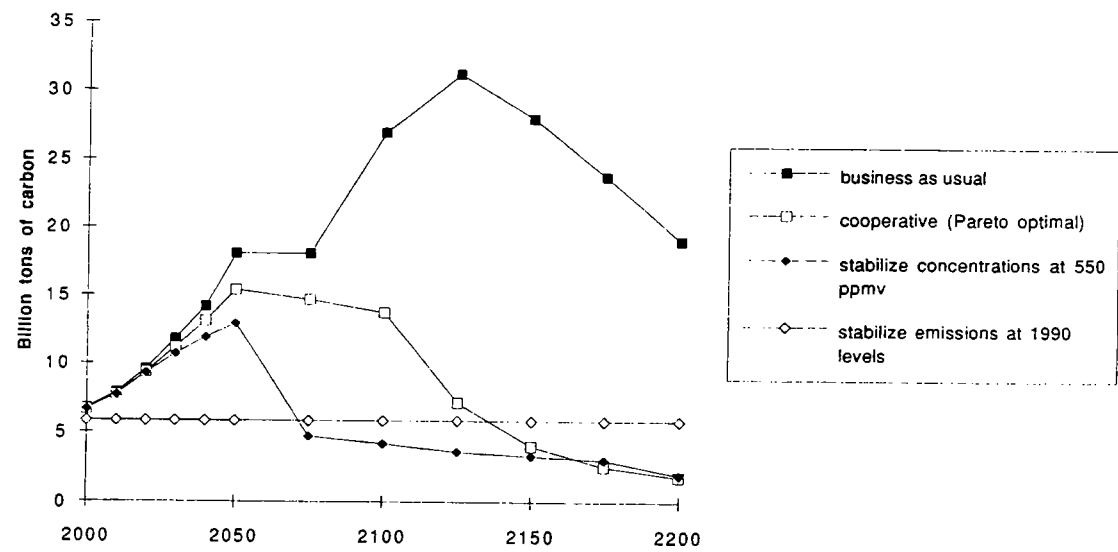


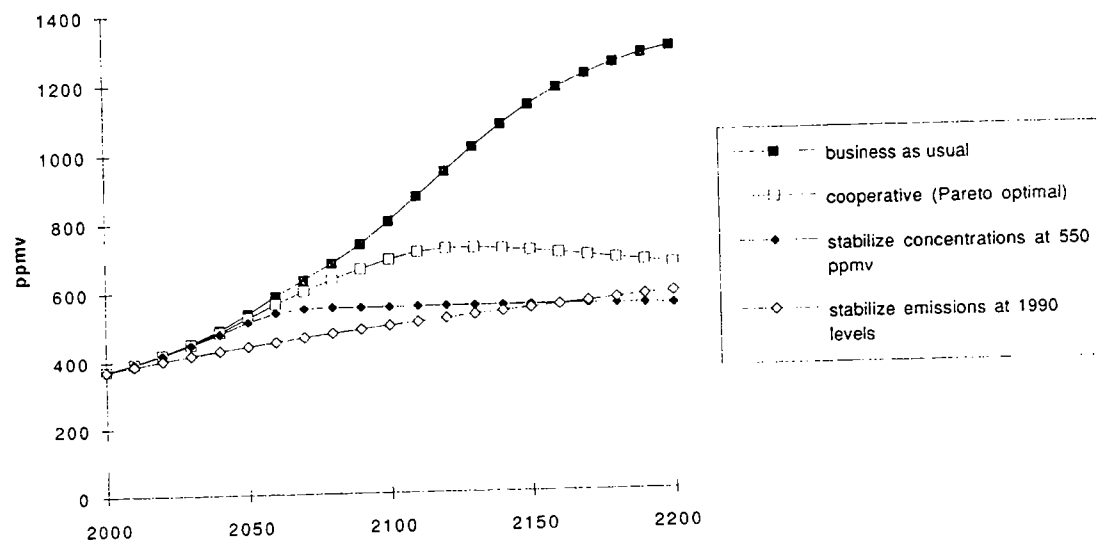
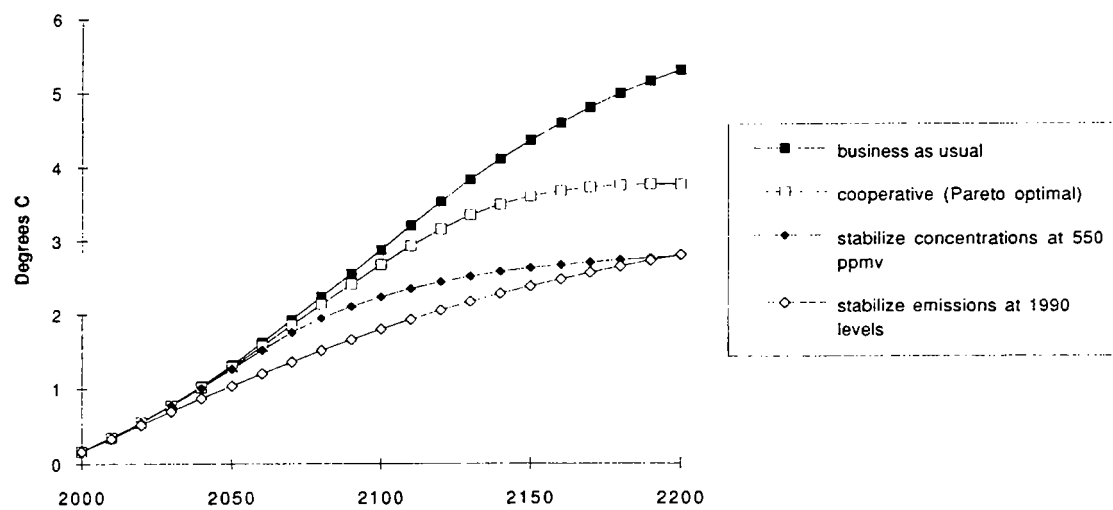
Figure 4. Atmospheric CO₂ Concentrations

Figure 5. Mean Global Temperature Increase



We assume that nonmarket damages depend both upon per capita income and upon mean global temperature change. Figure 6 shows our projections of growth in per capita income. Through 2100, these rates represent the average of the higher and lower growth cases adopted by the IPCC's Working Group III (1990). From 2100 onward, it is supposed that per capita incomes will begin to converge, but that the gap between the industrialized and the developing countries will continue to be substantial.

Figure 7 shows nonmarket damages corresponding to our business as usual scenario. Nonmarket damages start off low, and they rise slowly. The global mean temperature does not rise above 1990 levels by more than 2.5 degrees C until the second half of the next century. This is the point where wealthy countries might be willing to pay 2% of their GDP to avoid the nonmarket impacts of global warming. Less affluent countries do not reach the 2% point until a much later date.

Both market and nonmarket damages occur in the distant future, but mitigation costs occur early. Except for "free lunch" possibilities, there are three reasons why early mitigation could be expensive. First, the existing capital stock has been put into place given a set of expectations about the future. Abrupt changes will be costly. Time is needed for the capital stock to adapt. Secondly, the availability and cost of technologies for fuel switching will improve over time. As a result, the costs of reducing a ton of carbon will decline. Finally, even if the costs of removing a ton of carbon were the same in all periods, a positive discount rate will favor the deferral of reductions.

If one adopts a benefit-cost perspective, there are strong arguments for a strategy involving modest cutbacks in the early years, followed by sharper reductions later on. And indeed, this is what happens in our cooperative scenario. More aggressive emissions reduction might lead to lower ultimate damages, but the savings would be more than offset by the increase in near-term mitigation costs. Conversely, less aggressive emissions reduction would lower the mitigation costs, but the savings would be more than offset by the increase in damages.

We next turn to the case in which atmospheric CO₂ concentrations are capped at 550 ppmv. With a concentrations target, the issue becomes one of cumulative rather than year-by-year emissions. A particular target may be achieved through a variety of emission time paths, but some will be more costly than others (see Richels and Edmonds, 1995). Figure 3 (above) shows the least-cost global emissions path for achieving a 550 ppmv concentrations target. The path allows for emissions growth in the early years, but there are sharp declines at a later date. Even with a concentrations target as low as 550 ppmv, there does not appear to be a need for a substantial departure from the business-as-usual path during the early years.

Figure 6. Per Capita GDP

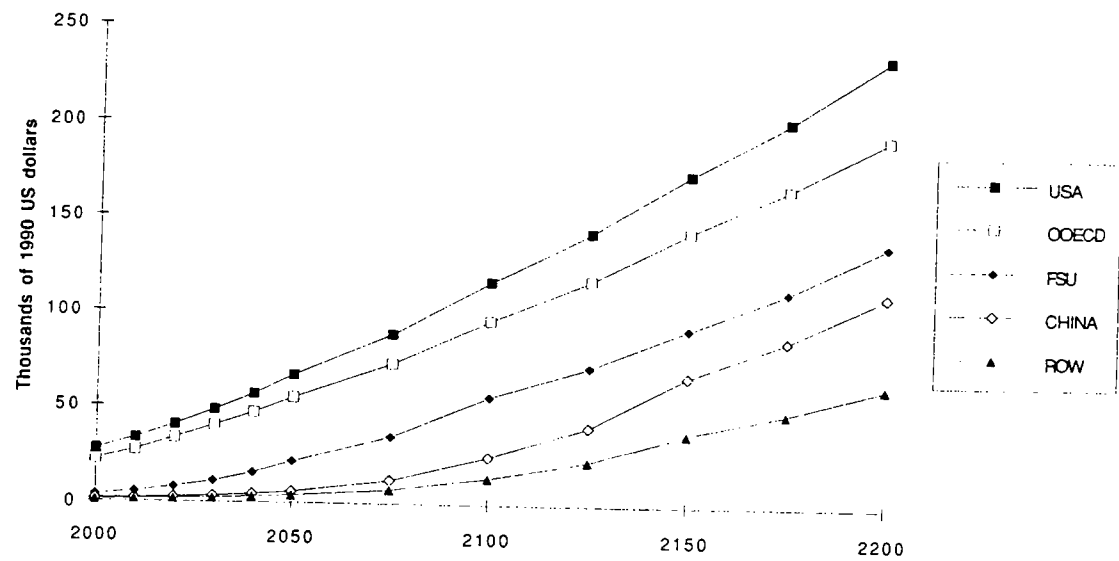
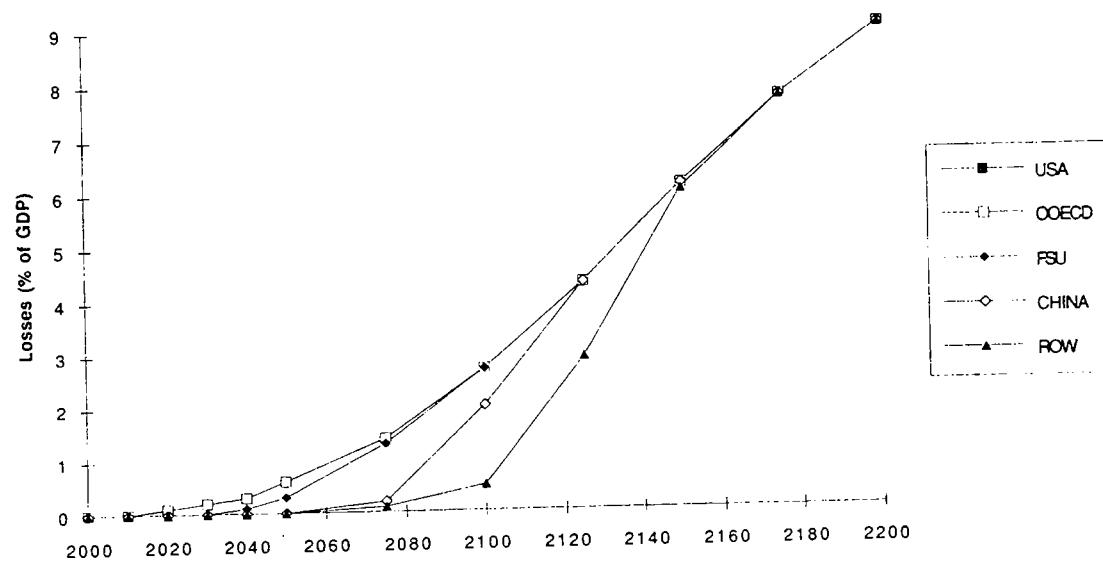


Figure 7. Nonmarket Damages Under Business as Usual



It is instructive to compare the emissions path for this concentrations target with the Pareto optimal solution. Although the two paths are quite similar in the early years, they diverge later on. From the perspective of economic efficiency, our analysis suggests that 550 ppmv may be too tight a cap.

Stabilizing global emissions at 1990 levels requires a significant departure from the business-as-usual emissions path, particularly in the early years. From the long-term perspective of cumulative emissions, however, it is not that different from the policy of stabilizing concentrations at 550 ppmv. Two centuries from now, these two cases would lead to virtually identical results in terms of the concentrations level and the increase in mean global temperature.

Figure 8 summarizes our cost-benefit analysis in terms of present values. Here all costs are discounted to 1990 at 5 % per year. The costs are large in absolute terms (left vertical axis), but energy and environmental costs are small in relation to any nation's GDP. This is why costs amount to only a small fraction of discounted gross world product (right vertical axis). By definition, cooperation entails the least cost. A further reduction in global emissions will lead to lower damages, but the savings will be more than offset by the increase in mitigation costs.

The bar chart in Figure 8 shows the extent to which the three non-Pareto alternatives are suboptimal. With business as usual, we do too little mitigation. With the purely physical criteria (stabilize emissions or concentrations), we do too much. The outlier policy is the stabilization of emissions at 1990 levels. This leads to slightly lower damages over the long term, but the savings are more than offset by the huge increase in near-term mitigation costs. Interestingly, the other three policies are relatively close in terms of total costs.

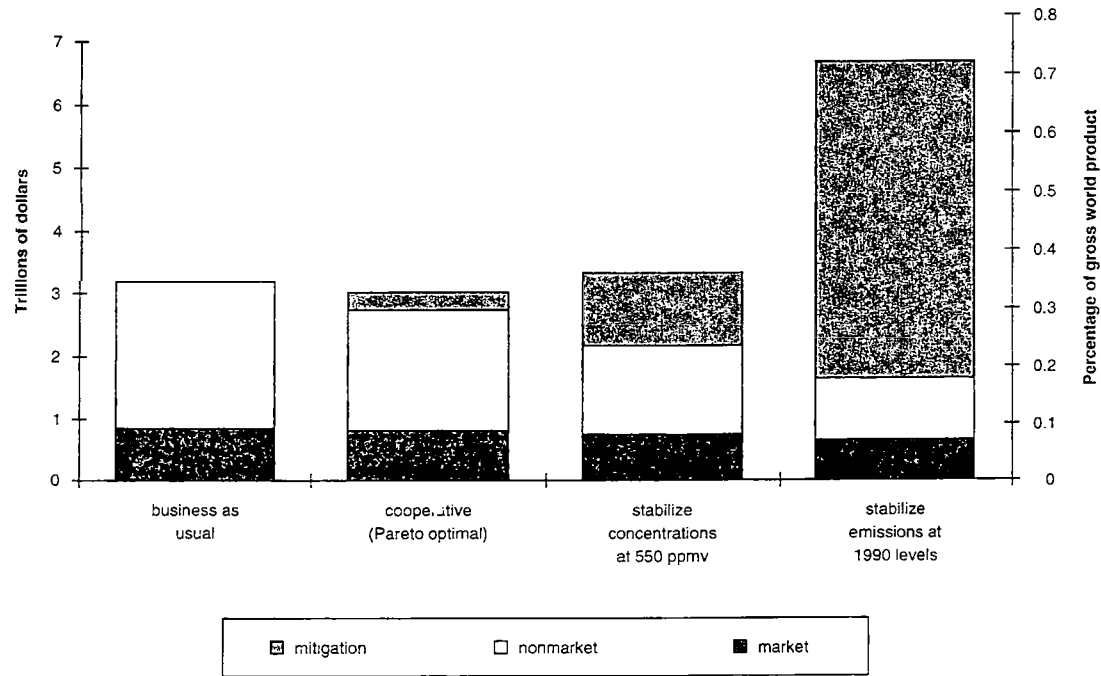
THE IMPACT OF A LOWER DISCOUNT RATE

The discount rate is a critical issue in global climate change benefit-cost analysis. In a present value calculation, when damages occur one century in the future, they receive 20 times more weight with a 2 % discount rate than with a 5 % discount rate. Damages occurring in two centuries are weighted 400 times more heavily.

As noted earlier, our basic approach to discounting is descriptive rather than prescriptive. There is no empirical evidence that the cost of capital has declined substantially during the past 50 years in the industrialized countries, and we believe that 5 % represents a lower bound on the current international opportunity cost of capital.

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Figure 8. Global Costs (mitigation+damages)--discounted to 1990 at 5%



Another logical possibility would be to maintain a constant rate of utility discount and to allow the rate of return on capital to decline gradually along with the economic growth rate. We have performed numerical experiments with this formulation, and have observed that near-term decisions remain virtually the same as with a constant 5% rate of return.

To employ a constant rate of return that is much lower than 5% (e.g., 2% throughout the planning horizon) would imply an unrealistically rapid immediate step-up in the rate of aggregate investment. Despite our misgivings about low discount rates, we nonetheless show the difference between scenarios in which costs and benefits are evaluated at rates of 2% rather than 5% per year.

Figure 9 compares the four scenarios in present value terms—at a 2% rate. The business-as-usual scenario is now the outlier. The distant future damages from climate change have much more influence in the present value calculation. Figure 10 shows how the choice of discount rate affects the Pareto optimal emissions trajectory. With the lower rate, we are willing to pay more to reduce near-term emissions. Interestingly, even with a 2% discount rate, there is still some growth in near-term emissions.

A CLOSER LOOK AT STABILIZING ATMOSPHERIC CO₂ CONCENTRATIONS

The goal of the Climate Convention is to stabilize atmospheric concentrations—at a yet to be determined level. Although the idea may be questionable from the perspective of economic efficiency, the Climate Convention has now been ratified. It is important to understand how mitigation costs and damages might change with the choice of the long-term target.

Figure 11 shows the emission paths corresponding to alternative concentration targets. For each one, the path was chosen so as to minimize mitigation costs. This is consistent with Article Three of the Climate Convention which states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."

In each instance, note that the optimal path allows for some growth in the early years, but this is followed by sharp reductions later on. From the perspective of mitigation costs, it is desirable to shift reductions into the later years. Figure 11 also suggests that the near-term emissions strategy is not sensitive to the ultimate target—within a very wide range. Indeed, for targets of 500 ppmv and above, the emission paths are quite similar through 2020.

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Figure 9. Global Costs (mitigation+damages)--discounted to 1990 at 2%

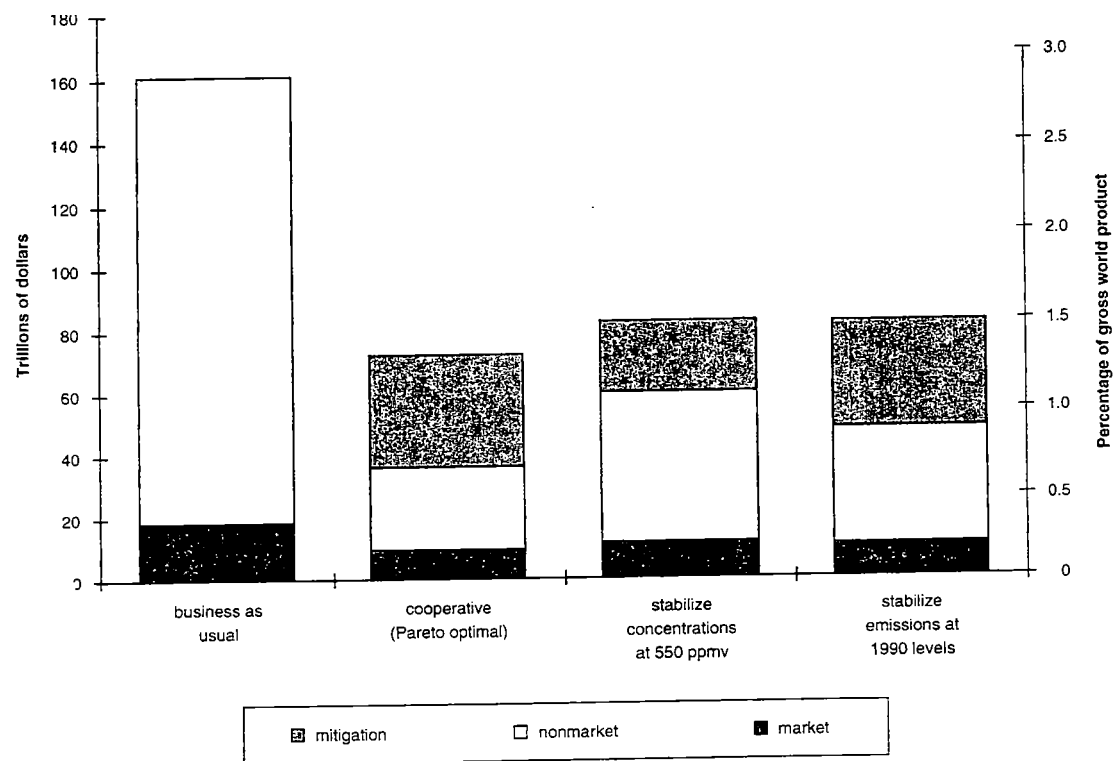


Figure 10. Sensitivity of Global Emissions to Discount Rate--Cooperative (Pareto Optimal) Case

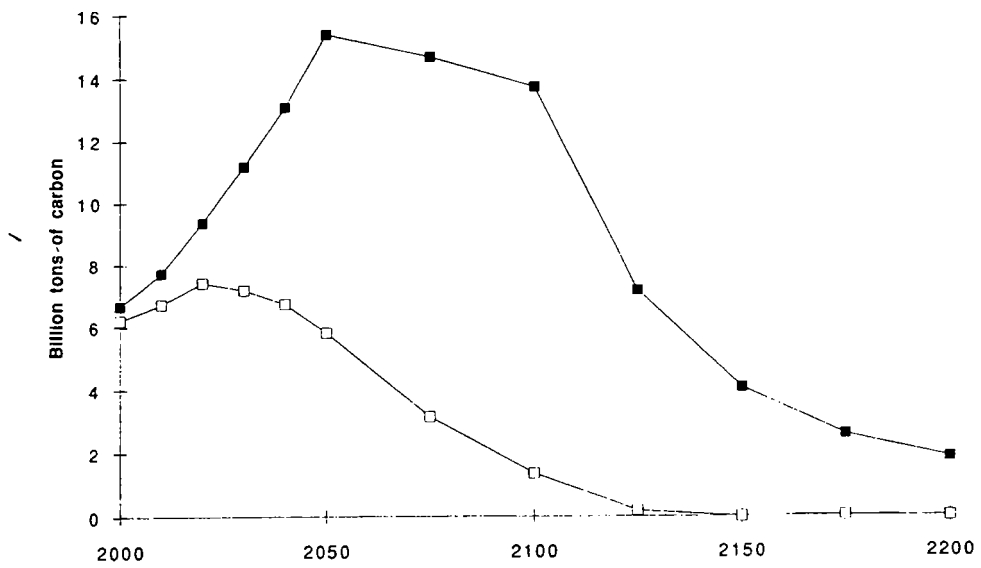


Figure 11. Least-Cost Emission Paths for Achieving Alternative Atmospheric Concentration Targets

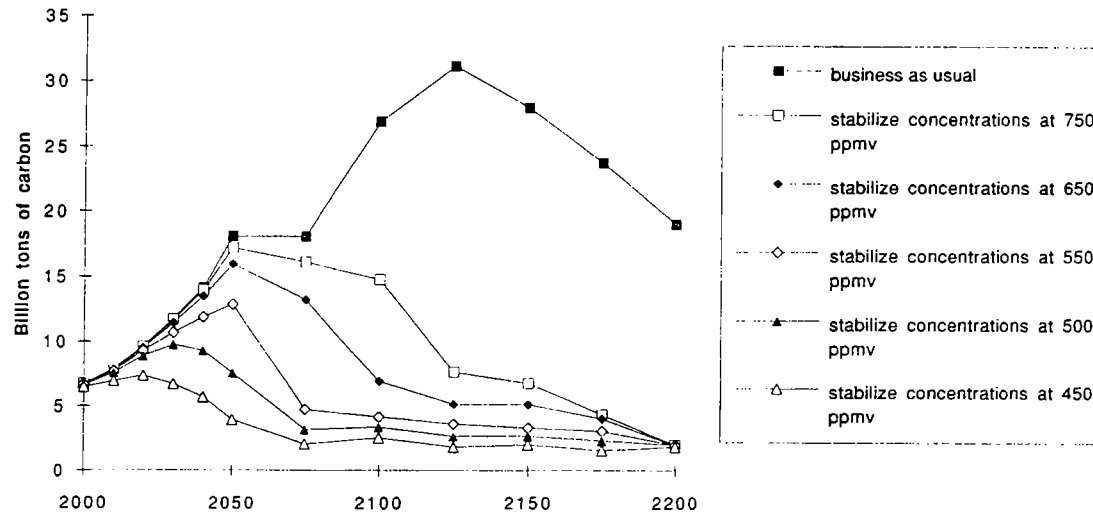


Figure 12 shows how costs and damages might be affected by the concentrations target. As might be anticipated, the mitigation costs increase when the ultimate concentrations target is lowered. The nonlinearity in the total discounted cost curve needs some explanation. To meet a target below 500 ppmv would require an immediate departure from the business-as-usual emissions path. Difficult short-term adjustments would be required. This is where the marginal cost of emissions abatement tends to rise most rapidly. Conversely, damages increase as we relax the ultimate concentration target. At a 5% discount rate, the present value of total costs increases only gradually with concentrations.

The *total* cost curve—the discounted sum of mitigation costs and damages, is asymmetrical. The flat portion lies between 550 and 800 ppmv. Within this range, any reduction of damages achieved by a tightening of the target will be offset by a comparable increase in mitigation costs.

ALTERNATIVE BURDEN SHARING SCHEMES

Thus far, we have examined only global results. Although this perspective is useful, international negotiators will be acutely interested in how damages and mitigation costs might be distributed among individual regions. Our model is designed specifically to address these issues. This is why the globe was divided into five geopolitical regions.

In MERGE 2, we are able to separate the difficult issues of economic efficiency and equity. For the theoretical considerations underlying this proposition, see Manne (1996) and Olsen (1994). The key idea is to allow for international trade in carbon emission rights. This ensures that cutbacks will take place in those regions where it is least expensive to do so. The rules for the allocation of emission rights imply that there will be wealth transfers, but empirically we have found that the general equilibrium effects of these transfers are too small to influence the overall level of emissions. In this sense, our results are consistent with the Coase Theorem—the proposition that wealth transfer effects are too small to influence the Pareto-optimal level of provision of a public good (the mean global temperature).

Although the allocation of emission rights has virtually no effect upon the Pareto-optimal emissions trajectory, it does determine who pays the costs of abatement. To see this, we examine the distribution of costs and damages under our standard burden sharing scheme and compare it with one more nearly oriented toward the status quo.

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Figure 12. Total Costs under Alternative Concentration Targets--discounted to 1990 at 5%

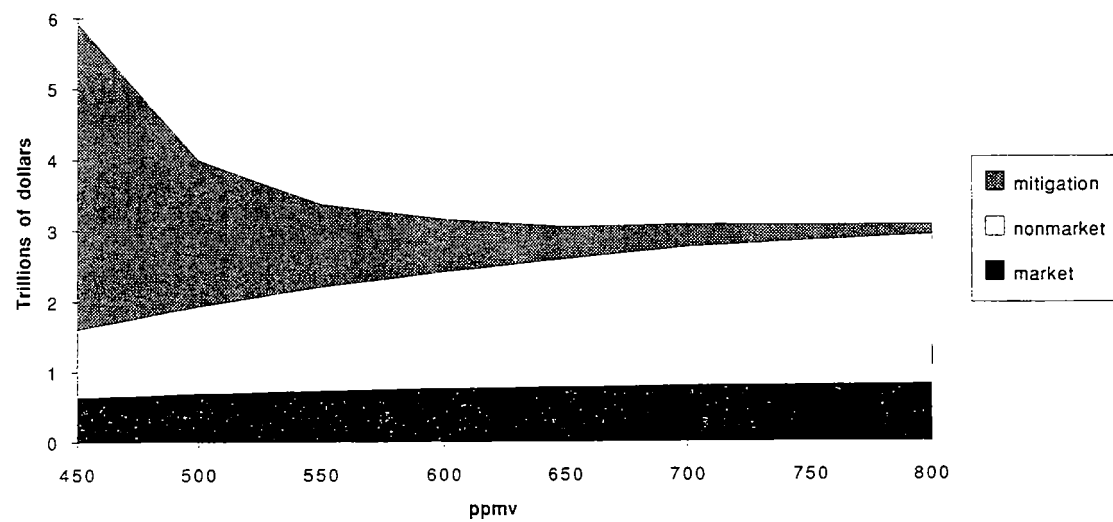
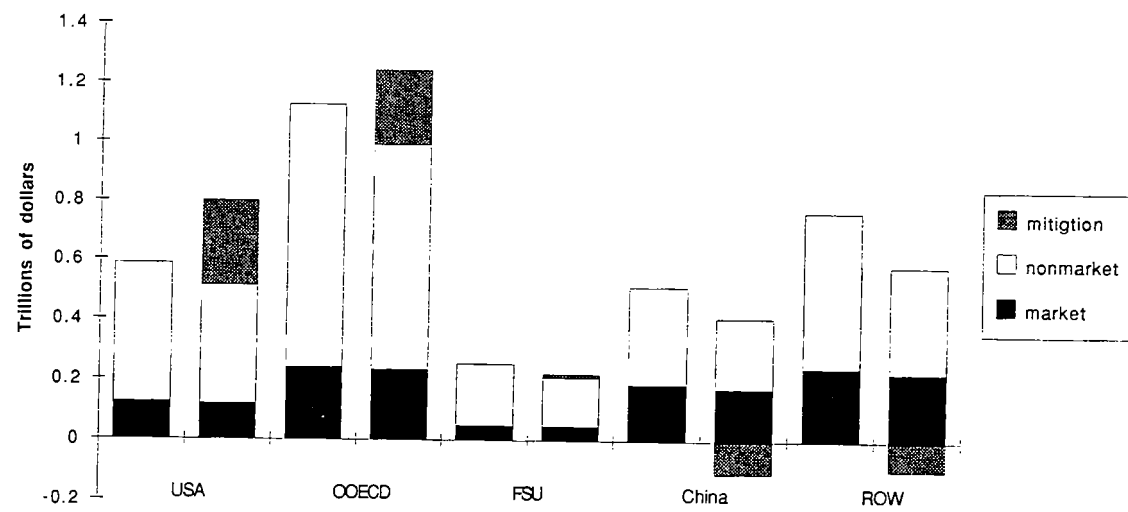


Figure 13. Total Costs by Region--business as usual vs. cooperative
(transition to equal per capita emission rights by 2030)



Unless indicated otherwise, our standard calculations are based on the rule that carbon rights are initially distributed among regions in proportion to their 1990 level of emissions, but that there are gradual changes in these shares over time. By 2030, carbon rights are distributed in proportion to 1990 population levels. Figure 13 compares the region-by-region distribution of mitigation costs and of damages for the business as usual and cooperative solutions.

In terms of damage costs, note that all regions are better off with cooperation than with business as usual. The emission reductions lead to less warming—both at the global and regional level. Each region sees a reduction in its market and nonmarket damages. If this were the whole story, there would be little disagreement at the international negotiations table. But unfortunately, this is not the whole story. There is the matter of who pays the bill.

Under our standard allocation scheme, the burden would fall on the three industrialized regions: USA, OECD and FSU. In 1990, they were responsible for approximately 66% of global CO₂ emissions. By 2030, their population-based shares would fall to only 22%. China and ROW, on the other hand, do quite well. They would receive a novel form of "double dividend" through the reduction in their damages and also through the sale of carbon emission rights.

Next, we examine a burden sharing scheme more nearly weighted to the status quo. This is done by slowing the rate of transition to equal per capita carbon emission rights. Suppose that instead of completing this transition by 2030, the target date is pushed out all the way to 2200. Figure 14 shows the two trajectories. In this case, industrialized countries would still be allowed to emit 60% of the global total in 2030.

Figure 15 shows the distribution of costs and damages under the slower transition scenario. First, note that market and nonmarket damages are the same as in the rapid transition scenario. The Pareto optimal emissions trajectory—and therefore the impacts—are unaffected by the distribution of emission rights.

There is a change, however, in the distribution of gains and losses. With the much slower transition to equal per capita emission rights, OECD countries would now receive positive net benefits, but the ROW would no longer gain from participation in this type of global agreement. As a group, these developing countries would be worse off because of smaller wealth transfers. China would still come out ahead, but not by nearly as much as under the rapid transition scheme.

Figure 14. Transition to Equal Per Capita Emission Rights

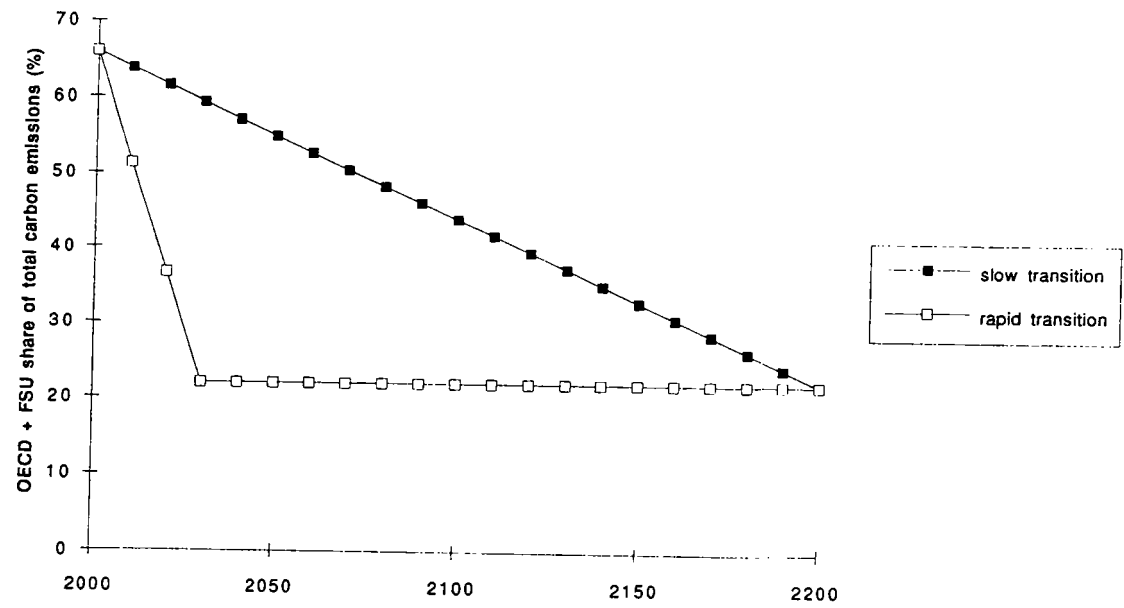
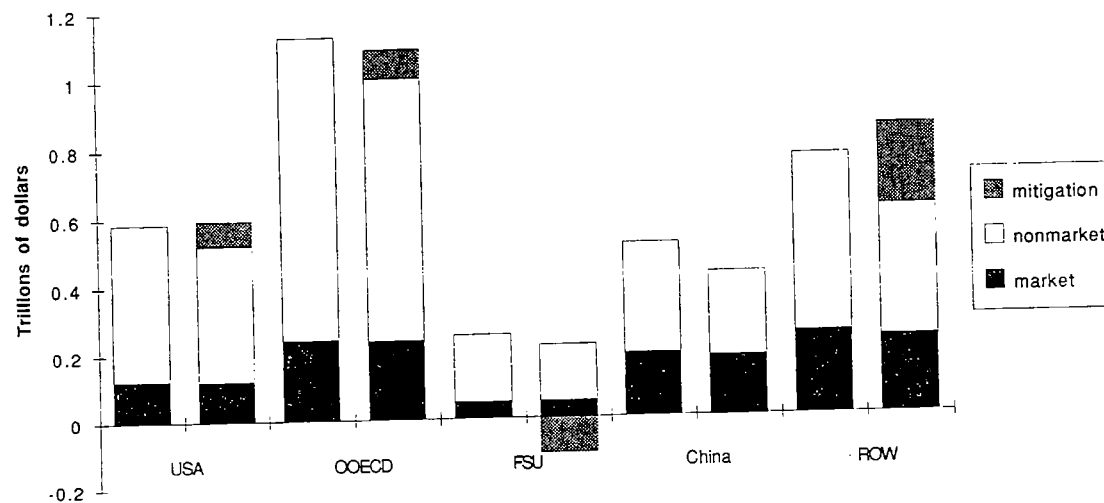


**Figure 15. Total Costs by Region--business as usual vs. cooperative
(transition to equal per capita emission rights by 2200)**



HEDGING STRATEGIES

Today's policy makers are not required to make once-for-all decisions binding their successors over the next century. There will be ample opportunities for mid-course adjustments. Climate negotiations are best viewed as an ongoing process of "act-then learn." Today's decisions makers must aim at evolving an acceptable hedging strategy—one that balances the risks of premature actions against those of waiting too long. The approach put forward in this section is designed to help identify such a strategy.

The first step is to determine the sensitivity of *today's* decisions to major uncertainties in the greenhouse debate. How important is it to know what energy demands will be in 30 years? To identify the technologies that will be in place to meet those demands? Or to be able to predict damages for the second half of the next century. An exhaustive analysis of these questions is beyond the scope of this paper, but considerable insight can be gleaned from several examples. For our sensitivity analysis, we will examine the following alternative cases:

- 1) Base case. The Pareto-optimal solution described in the fourth section. This incorporates our best guesses at the parameters to be examined in the sensitivity analysis. This case should not be taken too literally, but it provides a useful point of reference.
- 2) High GDP growth. The rate of GDP growth is a key determinant of energy demands. The overall growth rate depends on both population and per capita productivity. From Figure 6, recall the per capita income assumptions employed in the base case. These are derived from earlier estimates made by the IPCC. For our sensitivity analysis, we assume that per capita growth rates are 1 % per year higher from 2020 onward.
- 3) Optimistic backstop cost. There is a great deal of controversy over the cost of a nonelectric backstop such as hydrogen or biomass fuels. These technologies could provide a long-term carbon-free alternative to conventional oil and coal-based synthetic fuels. For the base case, we assumed that the nonelectric backstop becomes available in 2020 at a cost of approximately \$80 per barrel of oil equivalent. For purposes of a sensitivity analysis, we assume that the nonelectric backstop will be slightly cheaper than \$50 per barrel, the cost of synthetic fuels.
- 4) High temperature sensitivity. Our standard assumption is that a doubling of atmospheric CO₂ concentrations will lead to an equilibrium

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increase of 2.5 degrees C in the mean global temperature. This is the "best estimate" of the IPCC (1990). In this section, we explore a scenario in which the temperature sensitivity coefficient is twice as high as this estimate.

- 5) High willingness to pay to avoid nonmarket damages. We have speculated that consumers in high income countries would be willing to pay 2% of their incomes to avoid the nonmarket damages associated with a 2.5-degree C increase in temperature. Of all the parameters in our model, this is perhaps the most uncertain. For purposes of sensitivity analysis, we explore a much less favorable scenario, one in which consumers are willing to pay 2% of their incomes to avoid just a 1-degree C increase in temperature.
- 6) High damages. For this case, we combine two unfavorable assumptions. It is supposed that there will be a high temperature sensitivity *and* high nonmarket damages. Based on our reading of the literature, we believe that this is a representative example of a low probability, high consequence scenario.

Figure 16 compares emission paths for these six alternatives. Except for the high damage scenarios, note that in the early years, the Pareto-optimal choice of emissions is quite insensitive to the choice of parameter values. That is, the choice of hedging strategy would change very little if we were told that any one of these parameters were to take on the value adopted for the sensitivity analysis.

It is only when we evaluate the extremely unfavorable scenario—both high temperature sensitivity and high willingness to pay—that we see a substantial impact on the optimal near-term decision. If we are sure that such a scenario will materialize, it would make sense to incur the high mitigation costs associated with stabilizing emissions at present levels.

This type of sensitivity analysis permits us to identify which uncertainties may have a critical impact upon near-term decisions. The next step is to reflect these uncertainties in the choice of a hedging strategy. The following example is suggested for illustrating how we might think about this problem. Suppose that there are just two possibilities: a high probability, low consequence outcome and a low probability, high consequence outcome. Under these circumstances, a logical procedure would be to identify an emissions strategy that maximizes the *expected discounted* utility of consumption in each region over time.

Figure 16. Sensitivity of Near-Term Decisions to Long-Term Uncertainties

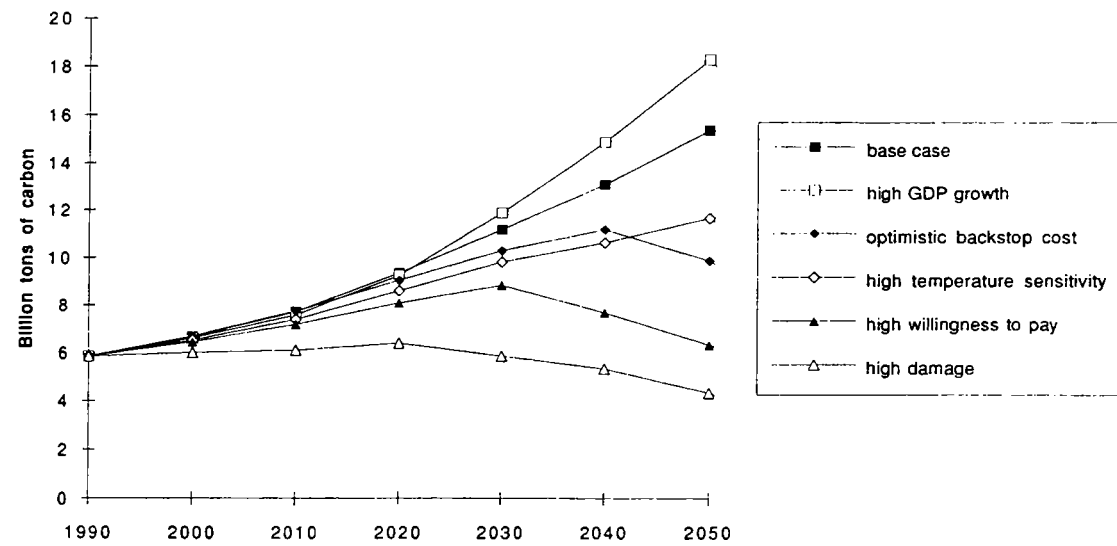


Figure 17. Carbon Emissions--5% Probability of High Damage Scenario

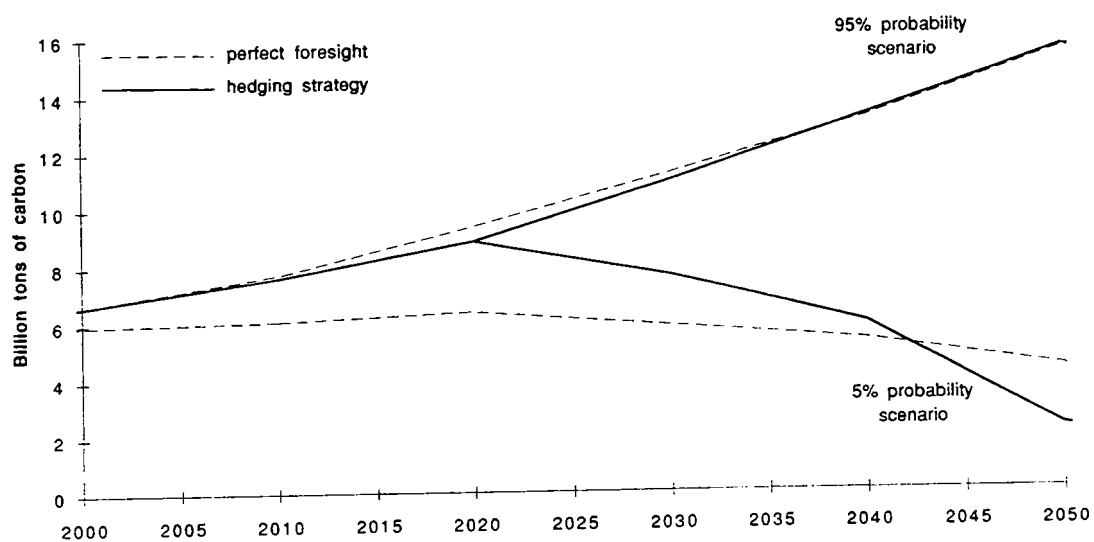


Figure 18. Value of Carbon Emission Rights--5% Probability of High Damage Scenario

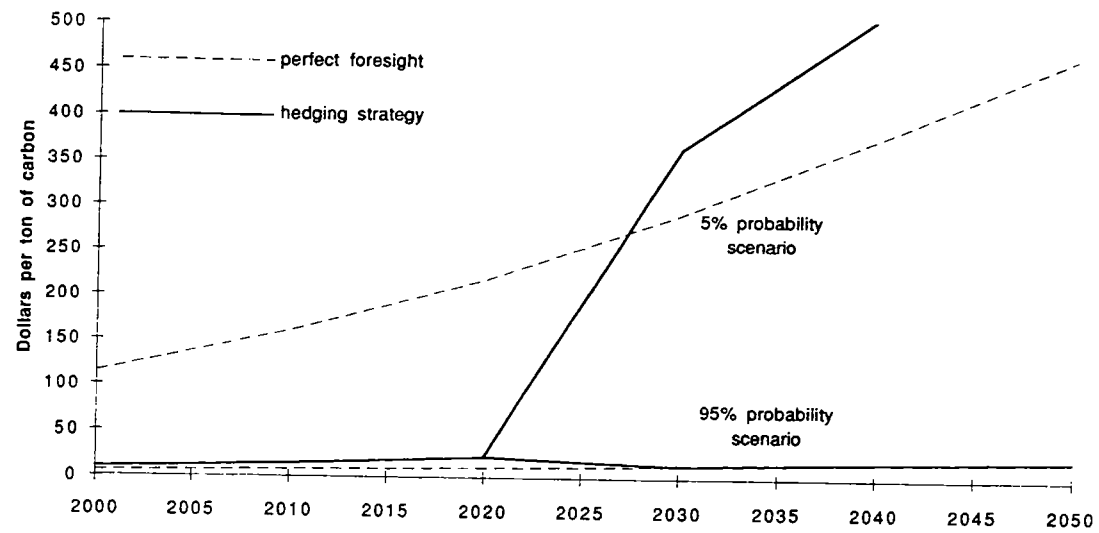


Figure 17 describes the results of such an experiment. For this stylized example, we assume just two possible futures: the base case and the high damage scenario. The dashed lines show what happens when we are endowed with perfect foresight, and can make today's decisions in full knowledge of which of these outcomes will occur. The upper dashed line shows the emissions path corresponding to the base case. The lower dashed line shows the path when we are told today that temperature sensitivity and nonmarket damages are both high.

For this illustration, assume that there is only a 5% chance that we will find ourselves in the high damage world. Further, suppose that uncertainty about the true state of the world will not be resolved until just after 2020. Not surprisingly, the hedging strategy consists of adopting an emissions path that lies somewhere between the two cases shown along the dashed lines. With a 5% probability of the high damage scenario, we depart just slightly from the upper dashed line. We must be prepared, however, to lower emissions rapidly after 2020 if we find ourselves in a high damage world.

For each emissions path, Figure 18 shows the value of emission rights. When we are endowed with perfect foresight, we can adapt smoothly. For the base case, the tax starts at \$6 per ton of carbon and rises slowly. For the high damage case, the tax starts at \$114 per ton of carbon and rises more rapidly. With the hedging strategy, we do not know the true state of nature until after 2020. Prior to that date, it would be efficient to value carbon rights at a level that lies between the two cases shown along the dashed lines. With a 5% probability of high damages, the optimal value in 2000 is \$10. The tax rises gradually to 2020, and then—with a 5% probability—rises abruptly.

CONCLUSIONS

The climate debate is enormously complex. Scientists disagree on the magnitude of the problem; policy makers disagree on appropriate response measures; and international negotiators disagree on who should pay. None of these issues lend themselves to easy solutions. Consensus will come slowly and only through a sustained commitment to research and to the international negotiations process.

We believe that models such as MERGE 2 can contribute to the consensus building process. The model provides a flexible and transparent framework for exploring alternative viewpoints on a wide range of contentious issues. As such, it can be used to determine where differences in perspective are likely to lead to differences in the choice of policy options. Such insights can help focus the policy debate and inform the research planning process.

The present analysis, although illustrative in nature, highlights some important considerations for policy making. First, with regard to mitigation

costs, there are strong reasons for preferring emission strategies involving modest reductions in the near term followed by sharper reductions later on. The reasons are three-fold: (1) time is needed to adapt the capital stock; (2) low-cost substitutes are apt to be in more plentiful supply in the future; and (3) even if the cost of removing a ton of carbon were the same in all periods, a positive discount rate would still favor deferred reductions.

The picture is much cloudier on the benefits side of the analysis. Two issues are critical: the magnitude of damages and their timing. The conventional wisdom is that damages will be low in the early years and rise as a function of temperature change. Much of the published literature places damages at between 1 to 2% of gross world product for a doubling of atmospheric CO₂ concentrations. Under such a scenario, impacts remain modest until the second half of the next century. If one adopts a benefit-cost perspective, there is ample time for an economical transition to less carbon-intensive fuels and for developing low-cost substitutes.

On the other hand, if one believes that high damages are likely *within* the next 50 years, an immediate departure from the business-as-usual emissions path may make sense. Under this scenario, the impending threat to the environment would justify costly near-term measures. The timing of the threat is crucial. The prospect of high damages in itself does not justify substantial emission reductions today. If the damages are far enough in the future, there would still be time for an economical turnover of existing plants and equipment and for developing the technologies needed for low-cost emissions abatement.

We have examined the consequences of adopting decision criteria other than economic efficiency. This is particularly important in light of the current debate. The goal of the Climate Convention is to limit atmospheric concentrations to a level that will prevent dangerous interference with the climate system. The Convention's objective is not the balancing of benefits and costs, but establishing an ample margin of safety. Although such a strategy is likely to entail higher total costs than one based on benefit-cost analysis, we find that the sacrifice of economic efficiency need not be large. This is likely to be the case if cost minimization is the criterion for achieving the particular concentrations target. For a wide range of concentration targets, the least-cost emissions path turns out to be quite similar to the economically efficient emission path—at least during the next several decades. This suggests that the optimal near-term decision is fairly robust.

Next, we considered the regional distribution of costs and benefits under alternative burden sharing schemes. Although a region may experience reduced damages with a reduction in CO₂ emissions, it will not necessarily be better off. This depends on who pays the bill. Not surprisingly, developing countries benefit most from a rapid transition to equal per capita emission rights. Under such a scenario, they receive a "double dividend"—a reduction in market

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and nonmarket damages and a wealth transfer through the sale of carbon emission rights. Conversely, developed countries benefit most when the allocation of emission rights preserves the status quo. By helping to identify the winners and losers under alternative burden sharing schemes, models like MERGE 2 can provide useful information to international negotiators.

Finally, we examined the issue of optimal hedging strategies. Fortunately, policy makers do not have to commit today to a global emissions path for the next 100 years. There will be ample opportunities for learning and mid-course corrections. The challenge facing today's policy makers is to arrive at a prudent hedging strategy—one that balances the risks of waiting with those of premature action. MERGE 2 deals explicitly with these issues. In doing so, it addresses a key consideration in climate policy making: concerns about low probability, but high consequence events. Our analysis suggests that the impact of such concerns on the optimal hedging strategy is small if critical uncertainties can be resolved in a timely manner. The longer it takes to resolve uncertainty, the greater the need for precautionary action. This underscores the importance of scientific research among the portfolio of options for dealing with global climate change.

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**WORKSHOP ON DESIGN OF
INTERNATIONAL EMISSIONS TRADING SYSTEMS**

National Bureau of Economic Research

William Nordhaus and Robert Stavins, Organizers

Snowmass, Colorado, August 13-14, 1997

On Stabilizing CO2 Concentrations - Cost-Effective Emission Reduction Strategies

Alan Manne, Stanford University

Richard Richels, Electric Power Research Institute

April 1997

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Abstract

With the adoption of the Berlin Mandate, developed countries are being asked to set emission limits for the early decades of the next century. The size of the reductions is currently the subject of international negotiations. This paper is intended to contribute to the analysis and assessment phase leading up to the adoption of new targets and timetables. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO₂ concentrations to alternative levels. We then explore the implications for near-term mitigation decisions and for long-term participation by the developing countries.

1. Introduction

In recent years, global climate change has become one of the most contentious environmental issues facing the international community. The UN Framework Convention calls for the "stabilization of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."¹ Yet the issue of what constitutes "dangerous anthropogenic interference" is likely to remain the subject of intense scientific and political debate for some time. For the present, international negotiations must remain an ongoing process -- with ample opportunities for learning and for midcourse corrections.

We are currently in the midst of one such review cycle. When initially put forward at the "Earth Summit" in 1992, the Framework Convention called upon developed countries to aim to return emissions to 1990 levels by the year 2000. At the first meeting of the Conference of the Parties in 1995, these commitments were deemed inadequate. As a result, the so-called "Berlin Mandate" was adopted. This called upon developed countries to set "quantified limitation and reduction objectives" for the post-2000 time frame.²

Although the Berlin Mandate is explicit in its call for additional reductions, it does not specify how large the reductions should be. Rather it specifies an "analysis and assessment" phase to help inform the decision making process. The deadline for new commitments is December 1997. A wide variety of proposals have been put forward in anticipation of this deadline. These proposals range from sharp cuts in near-term emissions to a more gradual transition away from carbon-intensive fuels. The international research community is actively engaged in trying to understand the environmental and economic implications of these policy proposals.

This paper is intended to contribute to the process of analysis and assessment. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO₂ concentrations to alternative levels. We then explore the implications for near-term mitigation decisions and for long-term participation by the developing countries.

There are several reasons why a broader perspective is desirable. The Intergovernmental Panel on Climate Change (IPCC) has demonstrated that if CO₂ concentrations were to be stabilized at any of the levels it examined, this would require an eventual and sustained reduction in emissions to

substantially below current levels.³ Developed countries cannot do the job by themselves. Nor can the transition be accomplished overnight. Cost-effective strategies will require both a global and a long-term perspective.

Any analysis of stabilization must confront the divisive issue of burden sharing. With trade in carbon emission rights, emission reductions can be made where it is cheapest to do so, regardless of their geographical location. The allocation of permits will have little impact on the least-cost global strategy.⁴ It will, however, have profound affects on who pays. Consistent with the Framework Convention, we adopt a burden sharing scheme that initially places the onus on developed countries. We then discuss the implications for international negotiations.

Economic analysis can play an important role in the climate debate. It can help policy makers identify least-cost mitigation strategies from a global perspective. In doing so, this helps to minimize the size of the overall burden. It can shed light on the implications of alternative burden sharing schemes at the regional level. Economic analysis, however, cannot tell us how a given burden *should* be allocated. Fairness and equity issues must necessarily be left to the international negotiation process.

Finally, we emphasize that our analysis is confined to mitigation costs. We recognize that this is not the whole story, but it is an important part. Article 3 of the Framework Convention states that "policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible costs."⁵ Identifying least-cost mitigation strategies can free up valuable resources for addressing alternative uses.

2. The model

The analysis is based on MERGE -- a model for evaluating the regional and global effects of greenhouse gas reduction policies. MERGE provides a bottom-up representation of the energy supply system. For a given scenario, a least-cost choice is made among specific technologies for the generation of electricity and for the production of nonelectric energy. As fossil fuels (coal, oil and gas) are exhausted, their prices rise and carbon-free alternatives become more competitive. To allow for inertia in the energy supply system, decline and expansion constraints are placed on existing and new technologies, respectively.

A top-down perspective is taken for the balance of the economy. These sectors are modeled through nested constant elasticity of substitution production functions. The production functions determine how aggregate output depends upon the inputs of capital, labor, electric and nonelectric energy. In

this way, the model allows for both price-induced and autonomous (non-price) energy conservation and also for interfuel substitution. A "putty-clay" formulation is used to allow for the lags in adapting to changes in energy prices.

In MERGE, the savings and investment process is affected by intertemporal and interregional forces. Each region is represented as though it maximizes discounted utility (the logarithm of consumption) subject to an intertemporal budget constraint. Its wealth includes not only capital, labor, and exhaustible resources, but also its negotiated share in global carbon emission rights. With this objective function, the costs of abatement are defined as the losses in the discounted value of consumption associated with alternative carbon constraints.

In previous versions of MERGE, the world was subdivided into five geopolitical regions.^{6,7} The present version of the model, known as MERGE 3.0, divides the world into nine regions: 1) the USA, 2) OECD (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). The further disaggregation provides better alignment with the Annex 1/non-Annex 1 structure of the Framework Convention. It provides more details concerning winners and losers under alternative burden sharing schemes, and it distinguishes between the major oil importing and exporting regions.

Population trends for each region are taken as exogenous. Per capita incomes are determined primarily by the rate of labor force productivity. Between 1990 and 2020, our projections are consistent with the conventional wisdom median values of the International Energy Workshop poll.⁸ For the world as a whole, GDP growth is projected at an average annual rate of 2.5% between 1990 and 2100. It is assumed that there are ultimate limits to economic growth, and that there will eventually be convergence between the per capita incomes in the OECD countries and those in the rest of the world. Figure 2.1 shows our specific projections of per capita GDP in each of the nine regions.

MERGE is based on a general equilibrium formulation of the global energy-economic system. This enables us to model trade in oil, gas and carbon emission rights. The model does not, however, account for the effect of an economic slowdown in one region on the full range of exports of another. It may therefore be ignoring some important "spillover" effects. MERGE is not designed to address short-run macroeconomic issues such as unemployment and inflation. The employment level is exogenous, and there are instantaneous adjustments to policy shocks. As a result, the model may overlook some costly short-term dislocations.

Figure 2.1 Per Capita GDP

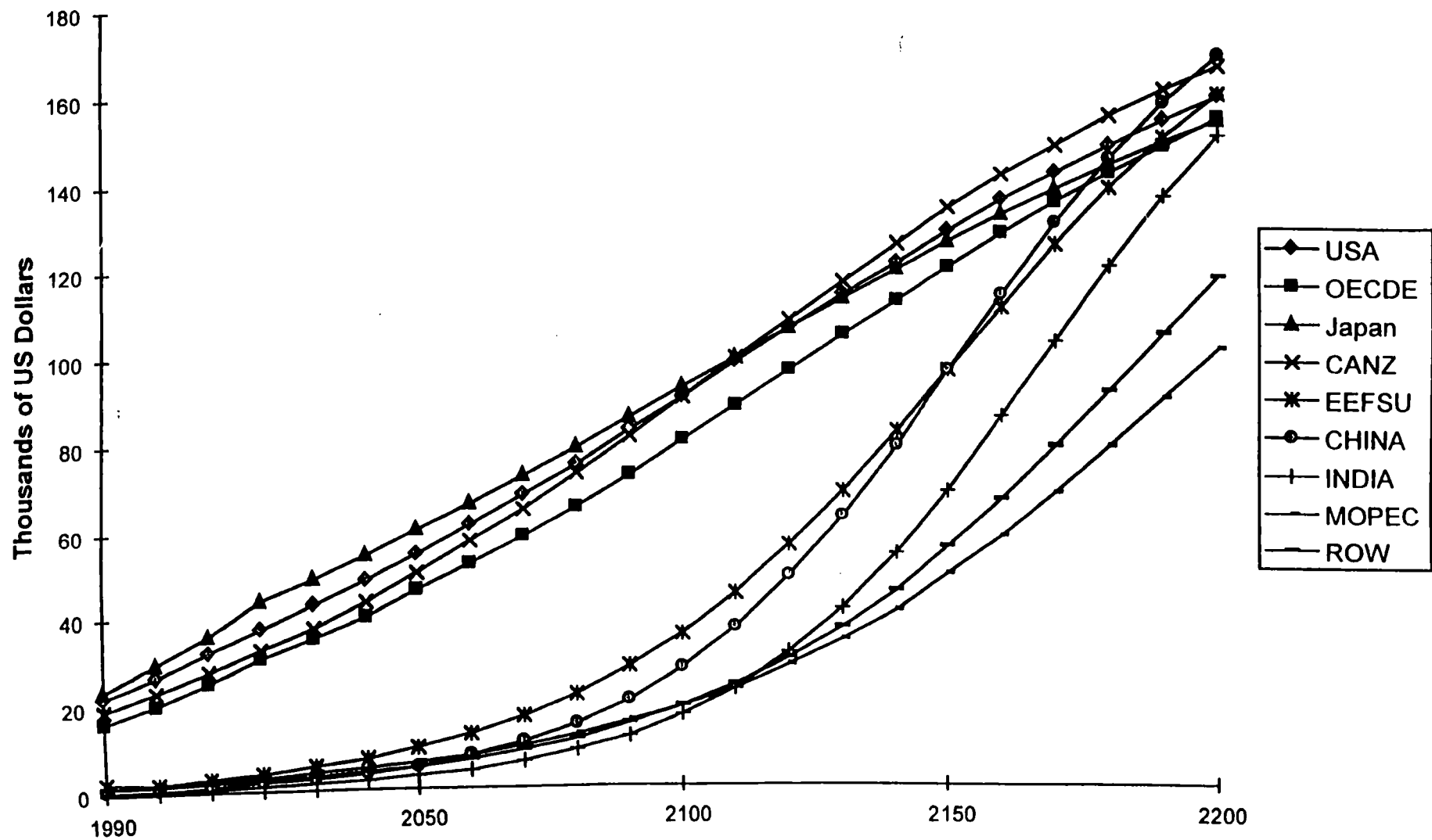


Figure 2.2 Regional Carbon Emissions - Basecase

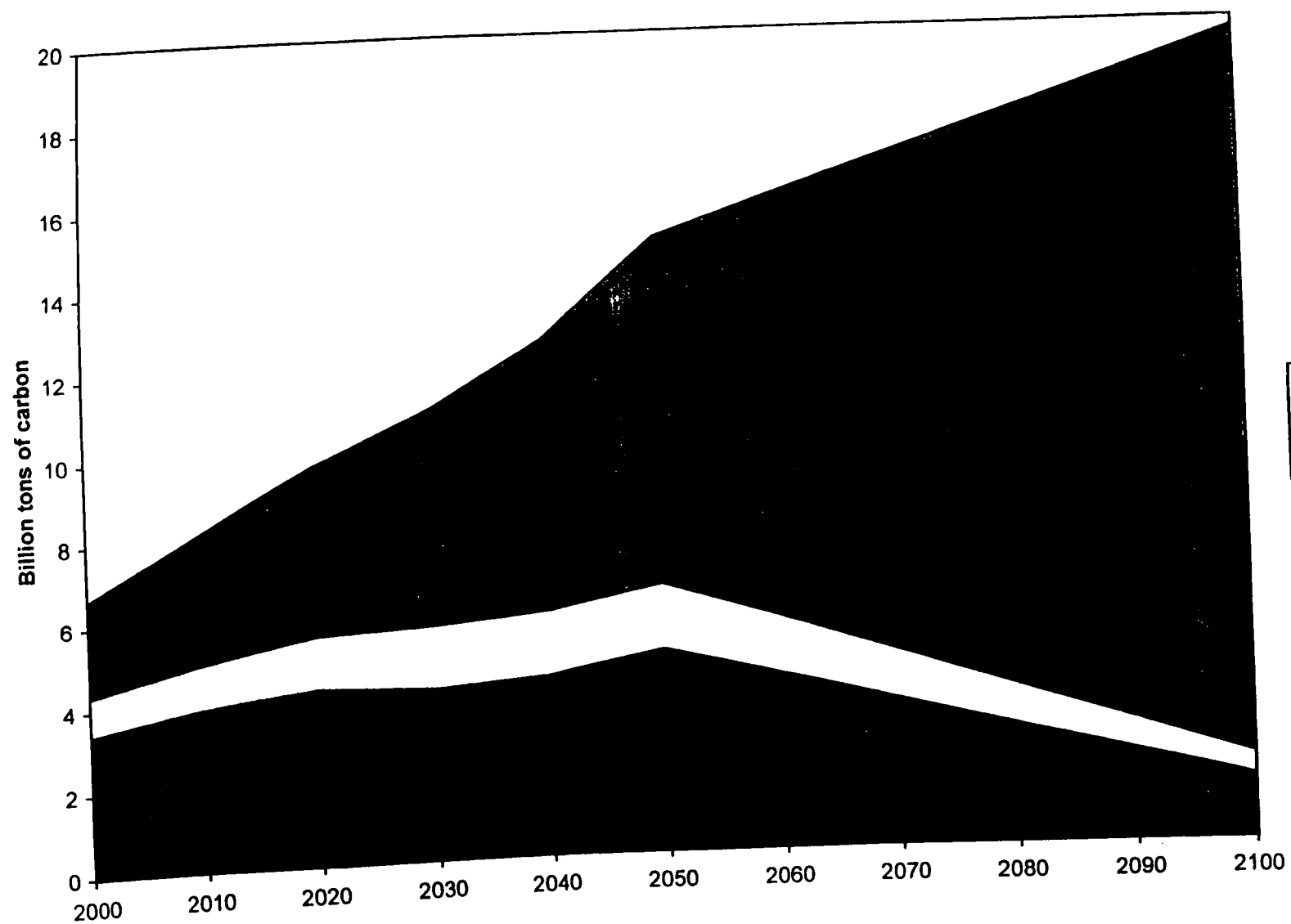
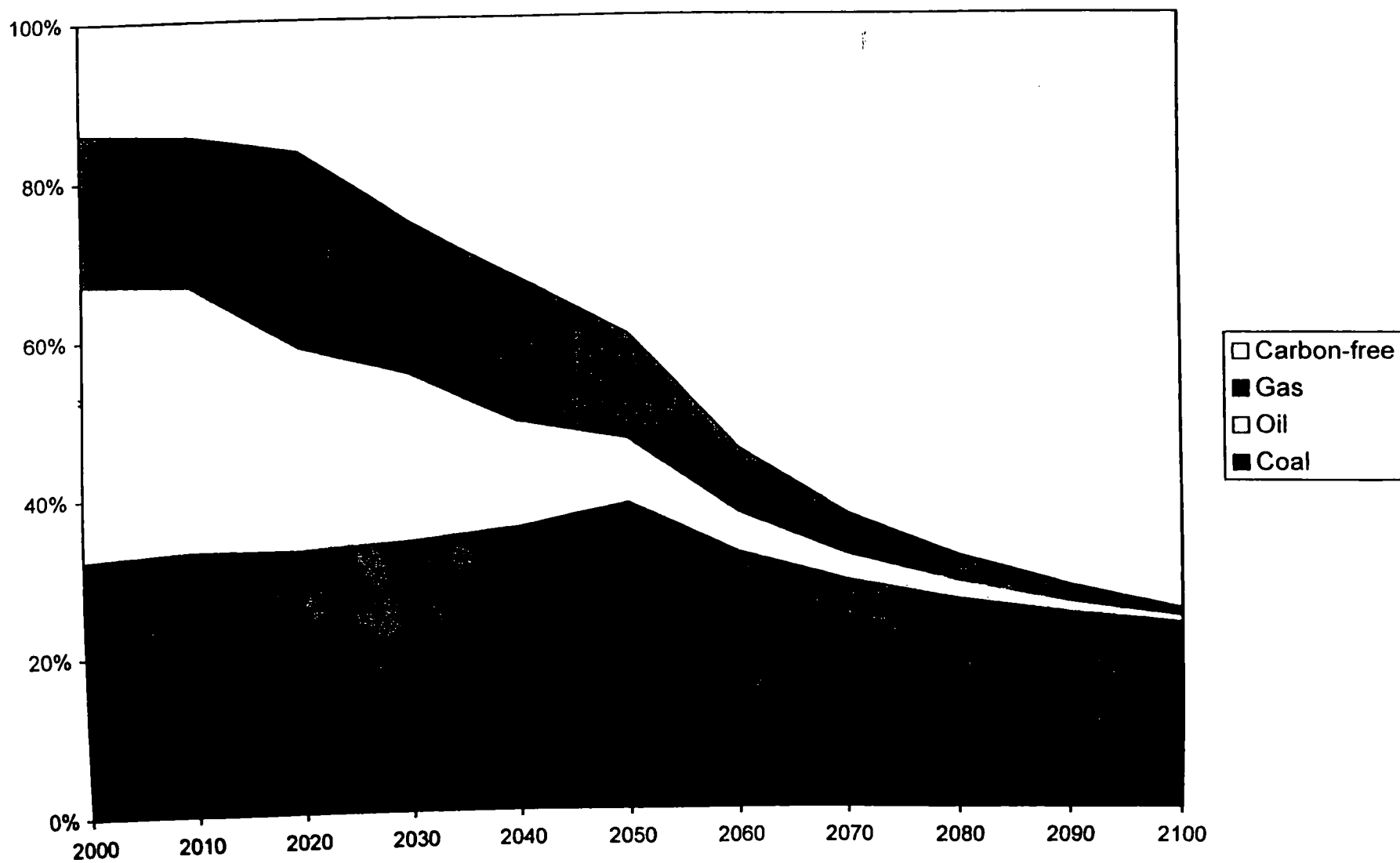


Figure 2.3 Total Primary Energy Use - Basecase



CO₂ mitigation costs are determined by 1) the emissions baseline -- i.e., how emissions are apt to grow in the absence of policy interventions, 2) the cost and availability of alternative supply and demand-side options, and 3) the magnitude of the CO₂ constraint. For the present analysis, several supply and demand parameters of the energy-economy submodel have been adjusted so that the baseline tracks the IPCC IS92a⁹ scenario through the year 2100. Figure 2.2 shows carbon emissions for the OECD, EEFSU and non-Annex 1. Figure 2.3 shows the corresponding total primary energy use by fuel type. It is supposed that conventional oil and gas resources will be depleted in the late 21st century but that coal, tar sands and shale oil will continue to be available.

Some observers have suggested that the exogenous specification of technical change will overstate the costs of a carbon constraint. They argue that an international carbon abatement agreement will automatically induce innovations in carbon-saving technologies. We do not share their optimism on the automatic nature of such innovations. (Consider, for example, the history of both fission and fusion technologies.) We do believe, however, that carbon constraints might speed up the process of technology *diffusion*.

MERGE 3.0 incorporates the notion of "endogenous technology diffusion". Specifically, in the electric power sector, the near-term adoption of high cost carbon-free substitutes makes it possible to introduce low-cost alternatives more rapidly in the future. Upon request, the authors will supply computer files that document the numerical assumptions underlying the model.¹

3. Scenario design

We focus on three factors critical to determining the costs of stabilizing concentrations at a particular level: the choice of global emissions pathway, the degree of international cooperation and the burden sharing scheme. In this section, we describe our assumptions with regard to each.

The global emissions path to stabilization. As noted by the IPCC (1996), to a first approximation a concentration target depends more upon cumulative emissions than year-by-year emissions. Indeed, a variety of emission pathways can be followed to meet a particular concentration target. In this paper, we compare mitigation costs for emission pathways involving a rapid transition away from the emissions baseline with those involving a more gradual transition.

In 1994, Working Group I (WG1) of the Intergovernmental Panel on Climate Change (IPCC) published a set of concentration profiles for stabilizing

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atmospheric CO₂ at 350, 450, 550, 650 and 750ppmv.¹⁰ The purpose of their estimates was to illustrate what might be required in terms of global CO₂ emissions reductions in order to stabilize concentrations at these different levels. Subsequently, Wigley, Richels and Edmonds (WRE) published an alternative set of emission profiles for achieving the WG1 concentration targets.¹¹ Although WG1 and WRE are identical in terms of the prescribed stabilization levels and attainment dates, they differ in the routes to stabilization (Figure 3.1a). The IPCC, while not taking a position on the desirability of one set over another, published both in their 1995 scientific assessment.¹²

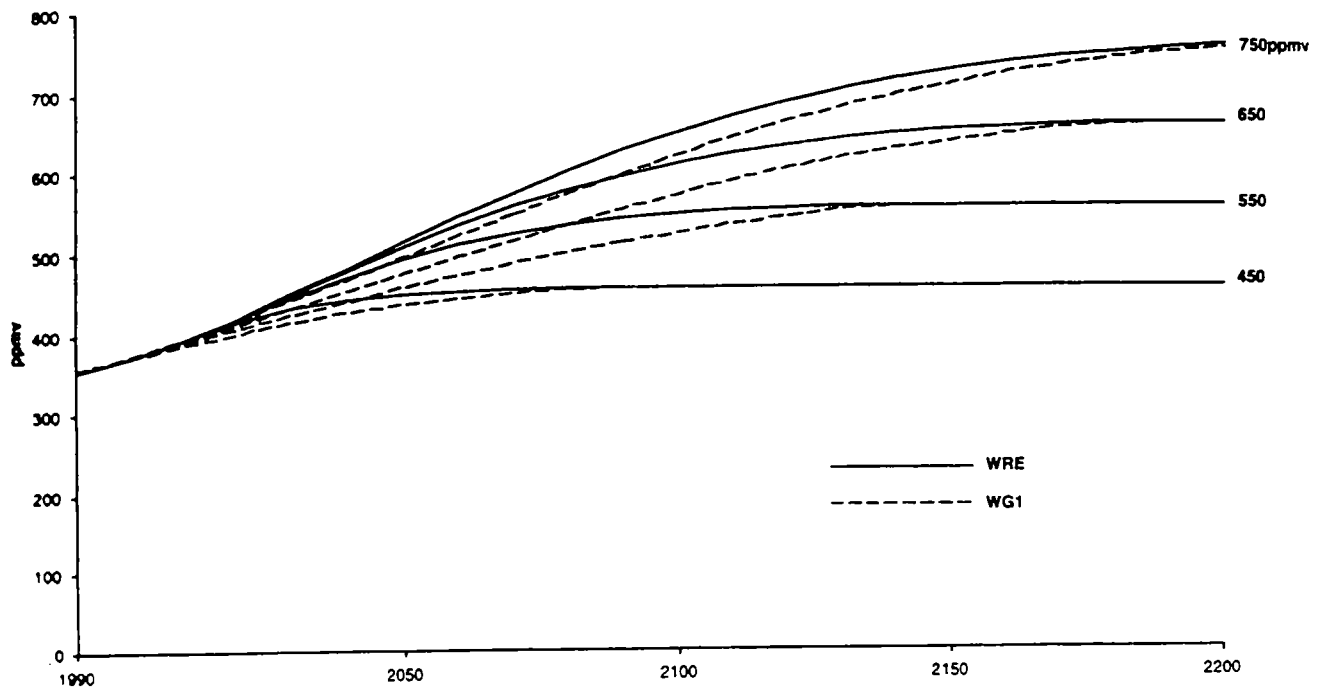
Figure 3.1b shows the emission rates required to achieve stabilization via the WG1 concentration profiles (the dashed lines) and the WRE concentration profiles (the solid lines). The calculations were made using the Wigley carbon cycle model. The WRE curves were constructed so that they would follow the central IPCC "existing policies" or "baseline" emissions scenario (IS92a) in the early years. The higher the stabilization target, the longer the adherence to IS92a. In contrast, the WG1 curves depart from IS92a immediately.

WRE assert that concentration pathways with higher near-term emissions are apt to have lower mitigation costs. They cite several economic studies that have examined how mitigation costs might vary with the timing of emission reductions.^{13,14,15,16} These studies suggest that the time path to stabilization may be as important as the concentration target itself in determining the overall discounted costs. They conclude that emission pathways that provide for a gradual transition away from fossil fuels are apt to be less expensive in terms of mitigation costs.

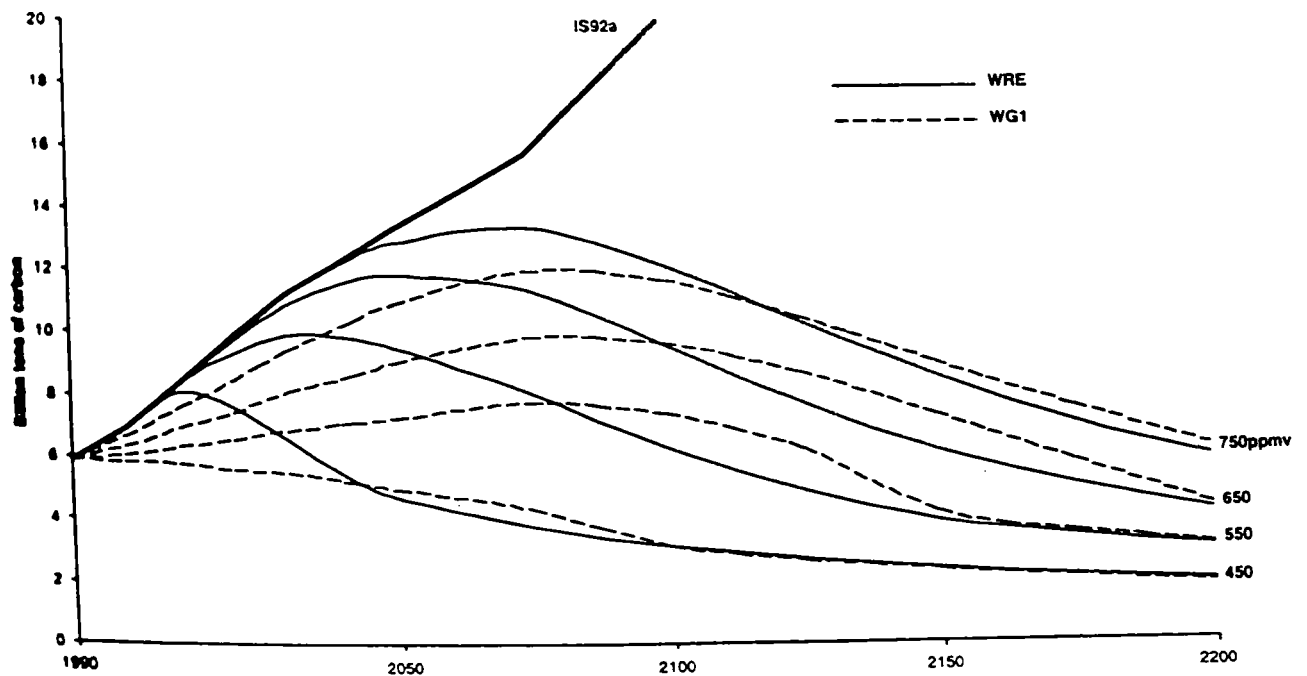
The WRE analysis is primarily qualitative. While drawing upon other studies to make their points, no explicit analysis is made of the mitigation costs associated with either the WG1 or WRE pathways. This is the issue to which we now turn. In this paper, we examine the costs of stabilizing concentrations at 450, 550, 650, and 750ppmv, first following the WG1 emissions pathway and then those suggested by WRE. In each case, we examine the costs to Annex 1 and non-Annex 1 countries under alternative burden sharing schemes.

The extent of international cooperation. A number of studies have shown that the marginal costs of emissions abatement might vary considerably among regions.¹⁷ This will be particularly the case in those periods when emission reductions are confined to Annex 1 countries. Clearly, it is inefficient to incur high marginal domestic abatement costs in Annex 1 countries when the marginal cost of emissions abatement is lower in non-Annex 1 countries. It is equally clear that it would be unrealistic to expect the non-Annex 1 countries to bear the burden of domestic reductions so as to achieve a globally cost-effective result.

Figure 3.1 Alternative Routes to CO₂ Stabilization



a) Alternative concentration profiles



b) Alternative fossil fuel emission paths

This suggests opportunities for efficiency gains through various forms of "joint implementation". This could be done on a bilateral project-by-project basis during the early years of an international agreement. Over the long term, however, it is more promising to explore market mechanisms such as a system of international allocations of tradeable carbon emission rights. Here we first examine mitigation costs when emission reductions are confined to the region of origin. We then calculate the benefits from international cooperation using trade in emission rights as a proxy for other forms of cooperative mechanisms with side payments.

When we assume that reductions take place wherever it is cheapest to do so (regardless of the geographical location), we refer to this as "interregional" or "where" flexibility. When there is a choice in the timing of emission reductions, we refer to this as "intertemporal" or "when" flexibility.

The burden sharing rule. Region-specific mitigation costs will also depend upon how emission reductions are allocated among regions. Few issues are likely to be as contentious for international negotiators. In this paper, we examine the implications of one particular set of burden sharing schemes. Although the choice is purely arbitrary, it nevertheless provides some insight into how the allocation of emission rights might affect the distribution of wealth among regions.

Consistent with the Berlin Mandate, we assume that the burden will fall on Annex 1 countries during the initial decades of an agreement. During this period, Annex 1 countries would be required to limit their emissions to amounts proportional to their 1990 levels.

Even if the Annex 1 countries were to reduce their emissions to zero, this would not be sufficient to limit global concentrations. Eventually, the non-Annex 1 countries will also have to limit their emissions. The ultimate concentration target will affect the date at which these non-Annex 1 countries must begin to participate in a global agreement. The more ambitious the target, the sooner they will have to participate in such an agreement. Once the non-Annex 1 countries do agree to a constraint, however, it is plausible to assume that there will be a gradual transition to equal per capita emission rights. (For one such scheme, see Table 3.1.)

Table 3.1 Structure of Burden Sharing Scheme

Concentration target (ppmv)	Date at which non-Annex 1 countries must begin to limit emissions	Date by which transition to equal per capita emission rights is achieved
450	2020	2040
550	2030	2050
650	2040	2060
750	2050	2070

With "where" flexibility, global mitigation costs are independent of the burden sharing scheme. That is, reductions will take place wherever it is cheapest to do so regardless of the geographical location. This is not the case, however, when emission reductions are restricted to the region of origin. With this type of restriction, the burden sharing scheme will affect both the global and the regional costs.

4. Global costs of stabilization at 550ppmv

Mitigation costs are incurred when the imposition of a carbon constraint leads to a reallocation of resources from the pattern that would be preferred in the absence of the constraint. A carbon constraint will lead to more expensive price-induced conservation activities and to fuel switching. There are changes in both domestic and international prices. In most cases, these forced adjustments lead to a reduction in economic performance. The tighter the constraint, the greater the effect.

With MERGE, we can calculate how mitigation costs vary with the choice of concentration profile. At the present time, there is little consensus on what constitutes an appropriate concentration target. There is even less consensus on the choice of a pathway to stabilization. We shall begin by focusing on a concentrations target of 550ppmv – approximately twice the preindustrial level. Later, we will explore the implications of adopting alternative concentration targets.

Figure 3.1b shows two sets of emission pathways for stabilizing concentrations at 550ppmv. The burden sharing rule (Table 3.1) will determine how emissions might be apportioned between regions. The results are summarized for three broad groups of countries: 1) the OECD (USA, Western Europe, Japan, Canada, Australia and New Zealand), 2) EEFSU (Eastern Europe and the former Soviet Union) and 3) developing countries. In the

language of the Framework Convention, the first two groups are described as Annex 1 countries. All others (the developing countries) are non-Annex 1 countries.

Figure 4.1 shows the implications of the burden sharing rule for these three regional groupings. The figure provides some insight into both global and regional costs. Under the WRE scenario, Annex 1 countries have some room for emissions growth, at least during the early decades of the 21st century. This is not the case, however, under the WG1 scenario. Here, Annex 1 emission reductions must begin immediately. This decline would be inconsistent with post-1990 trends in all but a few countries.

(Note that if non-Annex 1 emissions were to grow at a faster rate in the early decades, the proposed burden sharing scheme could prove infeasible in the absence of emission trading. That is, the residual emissions rights under the WG1 scenario (those available to Annex 1) could turn out to be negative.)

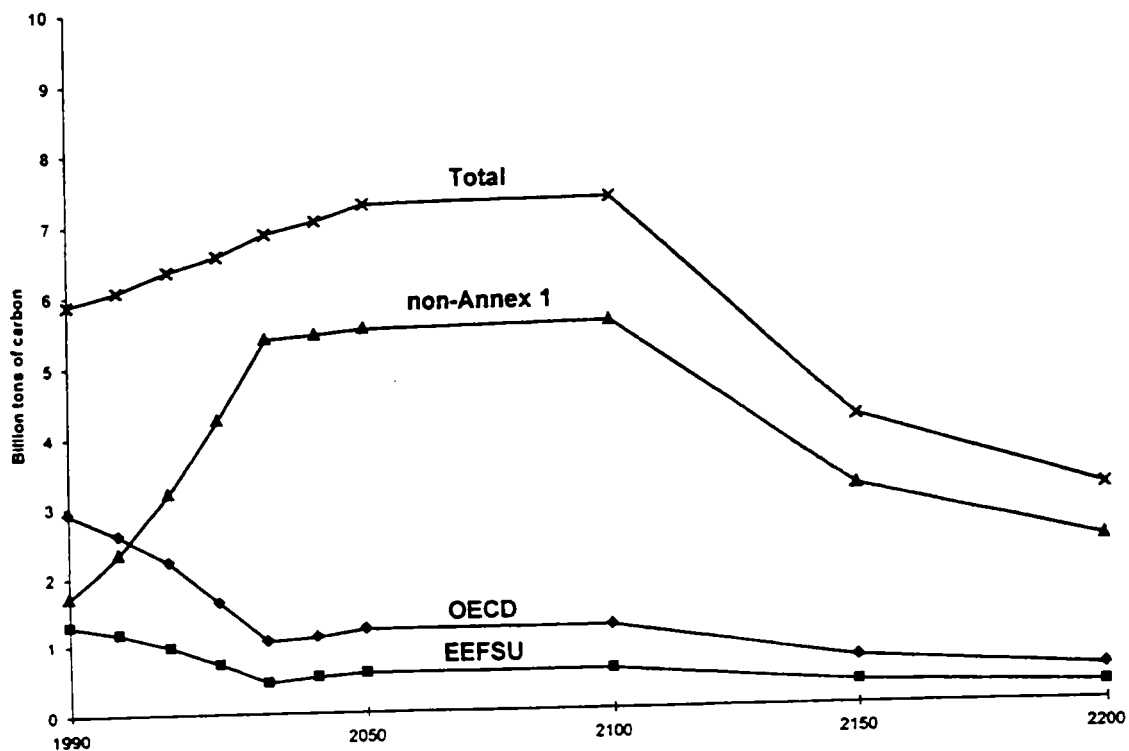
Figure 4.2 compares mitigation costs over the 21st century. Consumption losses are expressed in constant dollars, discounted to 1990 at 5% per year. Notice that costs are considerably lower for the WRE pathway. There are several reasons why this turns out to be the case. A concentration target defines an emissions budget, i.e., an allowable amount of carbon to be released between now and the date at which the target is to be achieved. A cost-effectiveness analysis is focused upon how this global budget might be allocated over time.

Shifting emission reductions into the future provides valuable time for: 1) adapting the energy using and energy producing capital stock, 2) developing low cost substitutes to carbon intensive fuels, and 3) removing carbon from the atmosphere via the carbon cycle. In addition, with the economy yielding a positive return on capital, future reductions can be made with a smaller commitment of today's resources. For a more detailed discussion of these factors, see ref. (11).

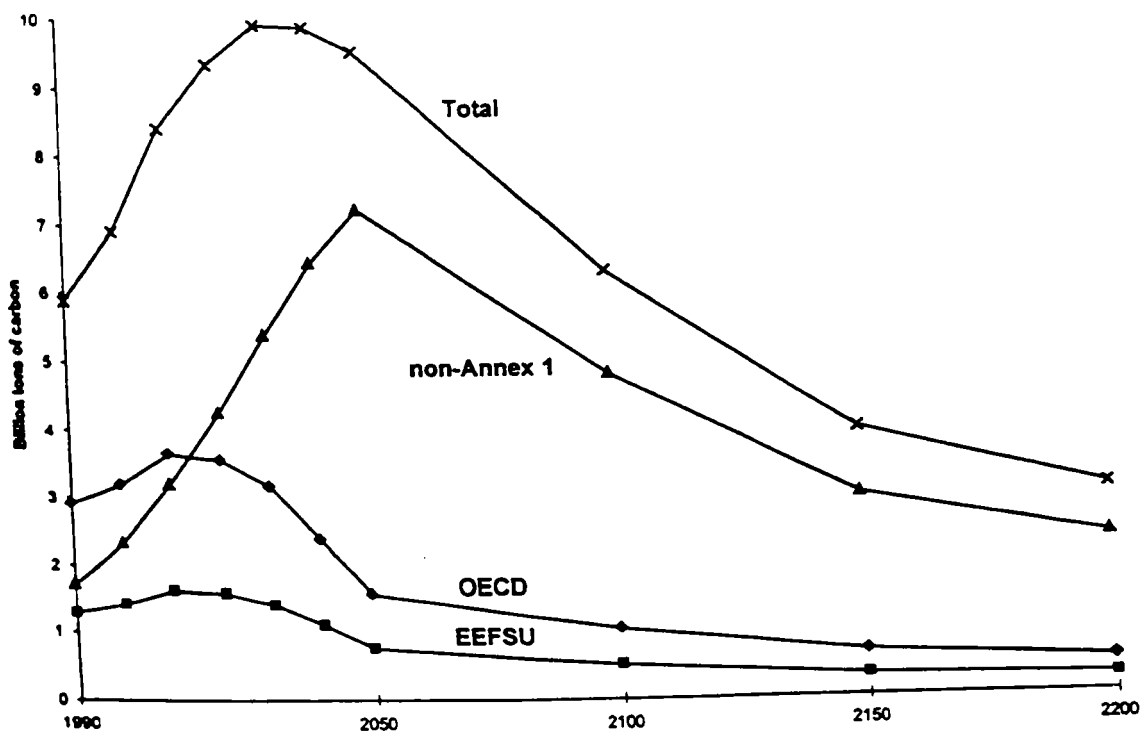
Figure 4.2 also estimates the benefits from international cooperation. Without "where" flexibility, the immediate emission reductions are confined directly to Annex 1. The more countries that participate in an international agreement, the greater become the opportunities for cost-effective trades. It then becomes possible for countries with high marginal abatement costs to purchase emission rights from countries with low marginal abatement costs.

From a global perspective, combining "where" flexibility with a more gradual transition away from fossil fuels substantially reduces the present value of mitigation costs. It turns out that there can be cost reductions as high as 90% when we combine both types of flexibility. (Compare the leftmost to the

Figure 4.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

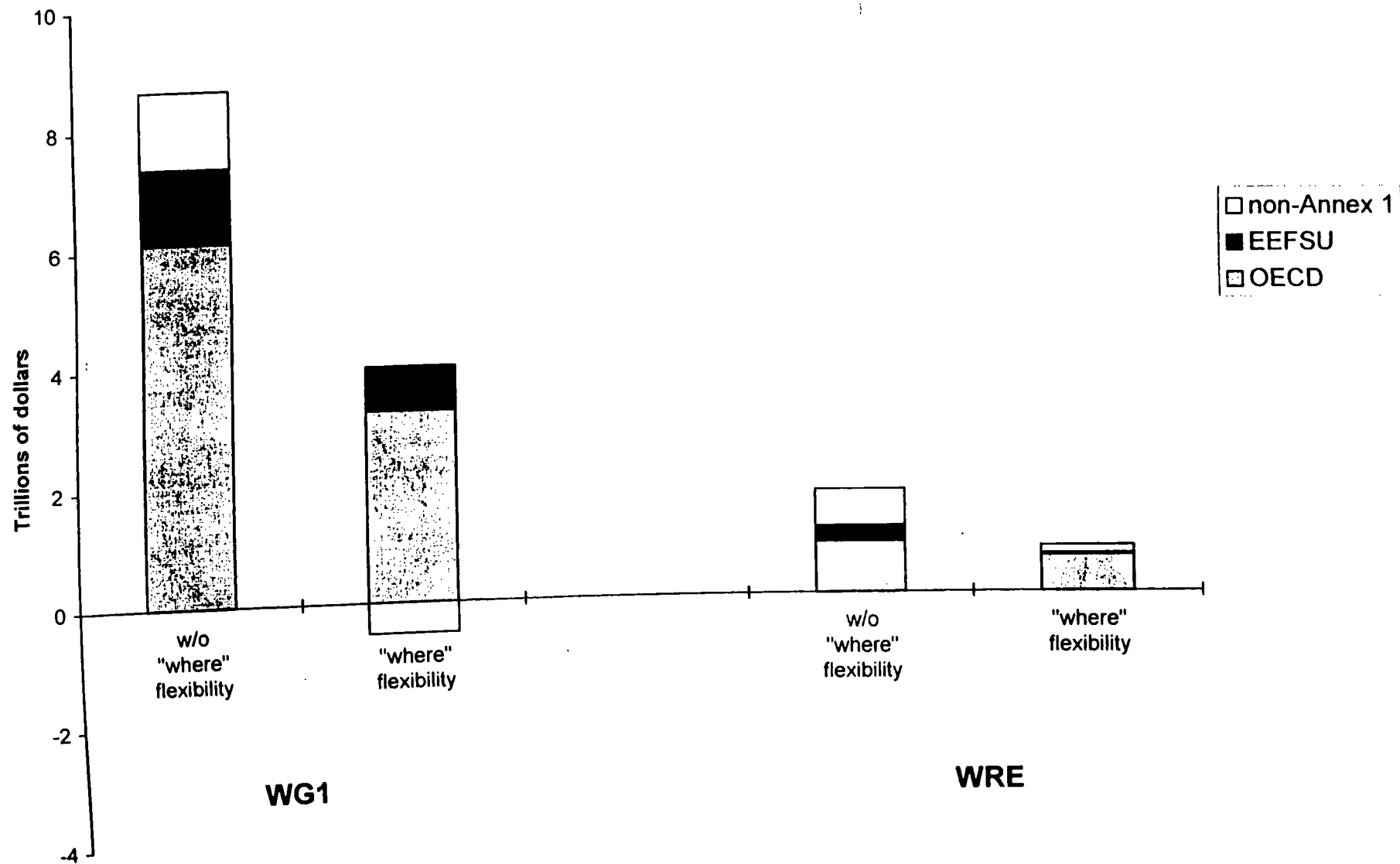


a) WG1



b) WRE

Figure 4.2 Regional Costs of Stabilizing Concentrations at 550ppmv
-- discounted to 1990 at 5%



rightmost bar in Figure 4.2.) The discounted cost savings to the international community appear to be of the order of trillions of dollars over the 21st century. This is consistent with earlier studies which focused exclusively on near-term targets and timetables.^{18,19}

Table 3.1 describes a burden sharing rule that is particularly favorable to the non-Annex 1 countries during the early decades of the next century. This is why the mitigation costs are lowest for non-Annex 1 countries under the WG1 pathway when we allow for "where" flexibility. Indeed, the WG1 emission constraints creates a sufficiently high price for emission rights and high wealth transfers during the early decades of the coming century so that the non-Annex 1 countries are actually better off in the presence of a carbon constraint than in its absence. This particular result should not, however, obscure the fact that from a global perspective, costs are far lower under the WRE pathway.

5. Annual losses when stabilizing concentrations at 550ppmv

Figure 4.2 summarizes abatement costs in terms of discounted present value -- summing over all time periods. Additional insights can be gained by looking at how losses might evolve over time. In MERGE, we adopt consumption as our welfare measure. Relative impacts are more apparent when we measure annual losses in percentage rather than absolute dollar terms.

In order to explain the pattern of annual losses, it is first necessary to say something about the impact of a carbon constraint on world oil prices. A carbon constraint would have roughly the same consequence as monopsonistic cartel behavior on the part of oil importing nations.

Figure 5.1 shows the international price of oil for the reference case and under the alternative pathways for stabilizing concentrations at 550ppmv. Note that oil prices are quite sensitive to the pathway to stabilization. With a tight near-term constraint, there is a drop in the international demand for crude oil. This has a dramatic effect on oil prices. There can be a differential of as much as \$20 per barrel between the reference and the WG1 cases. This has important implications for the costs of a carbon constraint to both oil exporting and oil importing countries.

Figure 5.2 compares annual welfare losses across scenarios for each of the three broad regional groupings. Under WG1, the Annex 1 countries must begin reducing emissions immediately. Losses are highest when there is no opportunity for trading emission rights. Losses rise to more than 3% and 6% of annual consumption for the OECD and EEFSU, respectively. As a major importer of oil, the OECD benefits from the decline in world oil prices. Hence,

Figure 5.1 International Price of Crude Oil

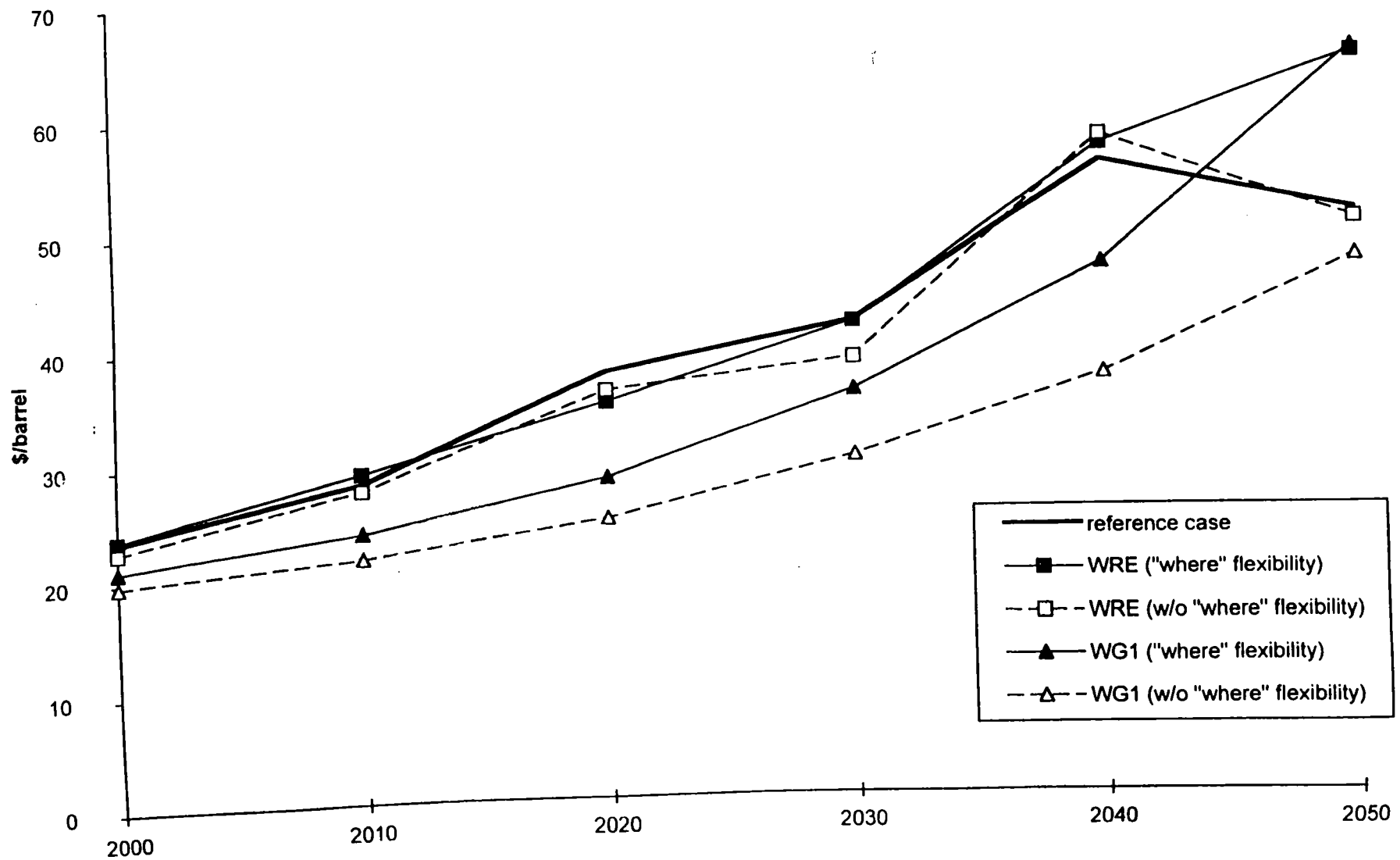
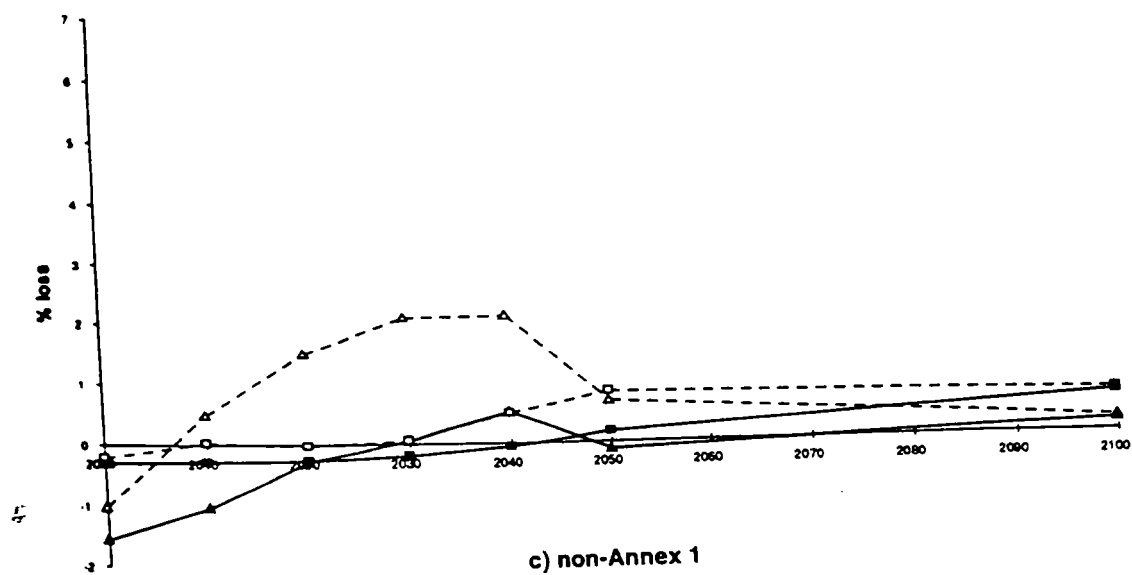
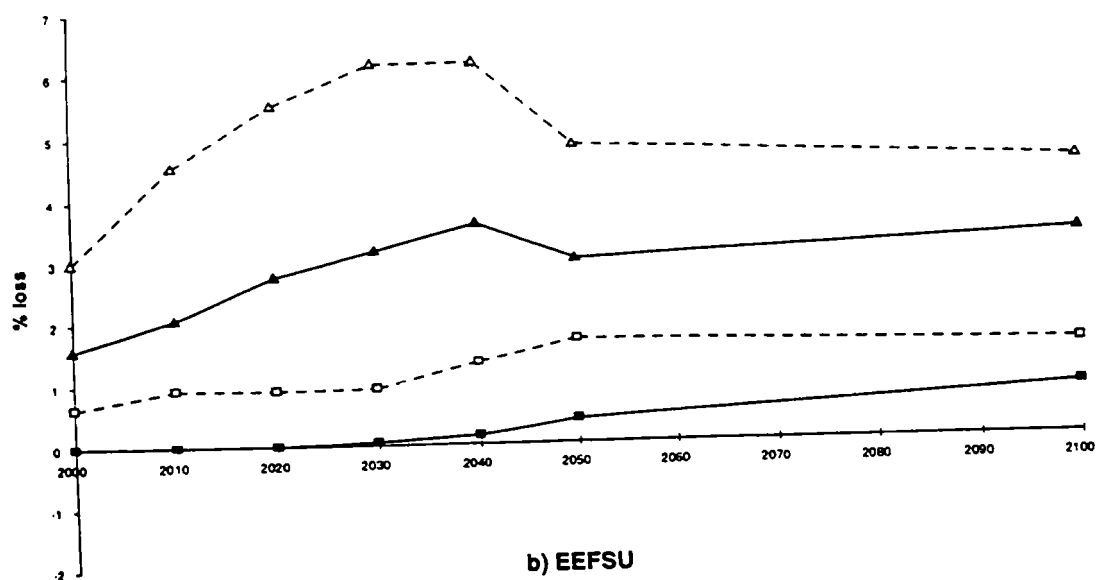
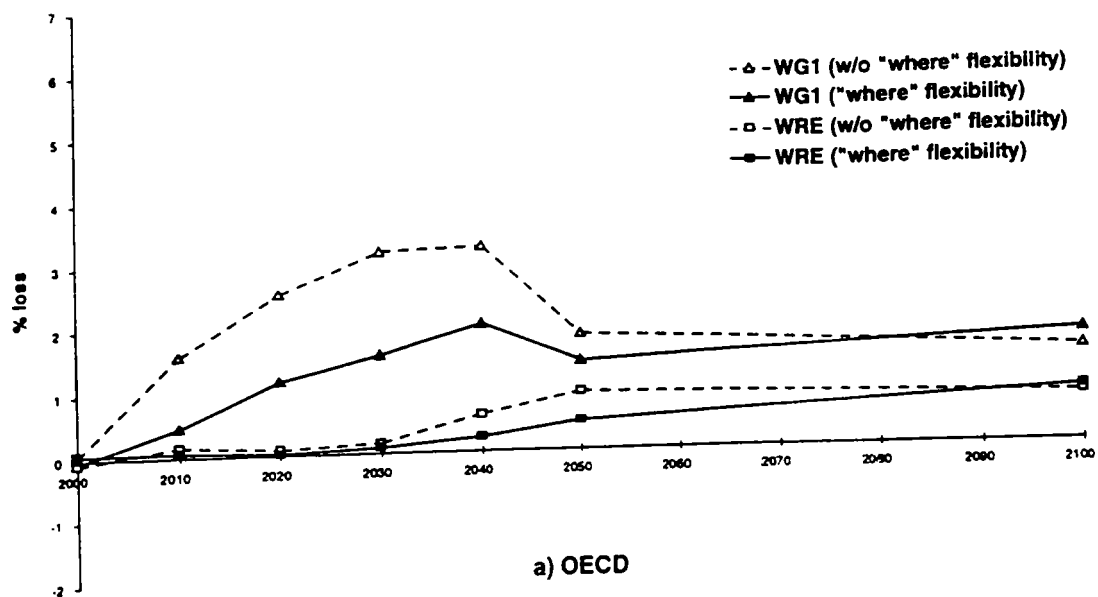


Figure 5.2 Annual % Consumption Losses



its losses are partially mitigated. EEFSU, on the other hand, is a substantial exporter. As a result, it will be adversely affected by a drop in world oil prices, and this compounds its losses from a near-term carbon constraint.

The non-Annex 1 region consists of both oil exporting and oil importing countries. Under the burden sharing scheme described in Table 3.1, the WG1 proposal leads to substantial net benefits in the early years, particularly with "where" flexibility. A tight near-term global emissions constraint would create a large demand for emission rights in Annex 1 countries. Since non-Annex 1 countries have carbon allocations up to their baseline emissions, it is in their interest to engage in domestic abatement, and to sell some of their rights to Annex 1 countries.

With the parameters employed in this version of MERGE, there is a net benefit to the non-Annex 1 countries, even without "where" flexibility. The oil importers gain more than the oil exporters lose from the decline in world oil prices. Eventually, however, the region will become a net loser unless it is able to sell emission rights to Annex 1 countries.

6. The least-cost mitigation pathway -- 550ppmv

The WG1 emission pathways were meant to be purely illustrative. No attempt was made to determine whether they represented an efficient transition away from fossil fuels. WRE, on the other hand, drew upon the insights of earlier studies in constructing their emission pathways. They argued that allowing more time for the transition would lower mitigation costs. They did not attempt to quantify the savings from choosing one path over another. Nor did they try to identify the least-cost mitigation pathway.

In the preceding sections, we analyzed the mitigation costs associated with the WG1 and WRE pathways. We now turn to the question of what might constitute a least-cost mitigation pathway for stabilizing concentrations at 550ppmv. For these calculations, we use MERGE 3.0. Rather than apply a carbon constraint derived through inverse calculations with the Wigley carbon cycle model, we now place a constraint on atmospheric concentrations and use the model to identify the least-cost mitigation pathway.

Note from Figure 6.1 that the least-cost and WRE pathways for stabilizing concentrations at 550ppmv lie fairly close together, at least in the early years. That is, they tend to follow the emissions baseline during the first decade of the next century and then depart gradually. Figure 6.2 shows the results in terms of discounted present value. In each case, we assume trade among all regions. As would be expected from the previous figure, the WRE and least-cost cases are also close in terms of costs.

Figure 6.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

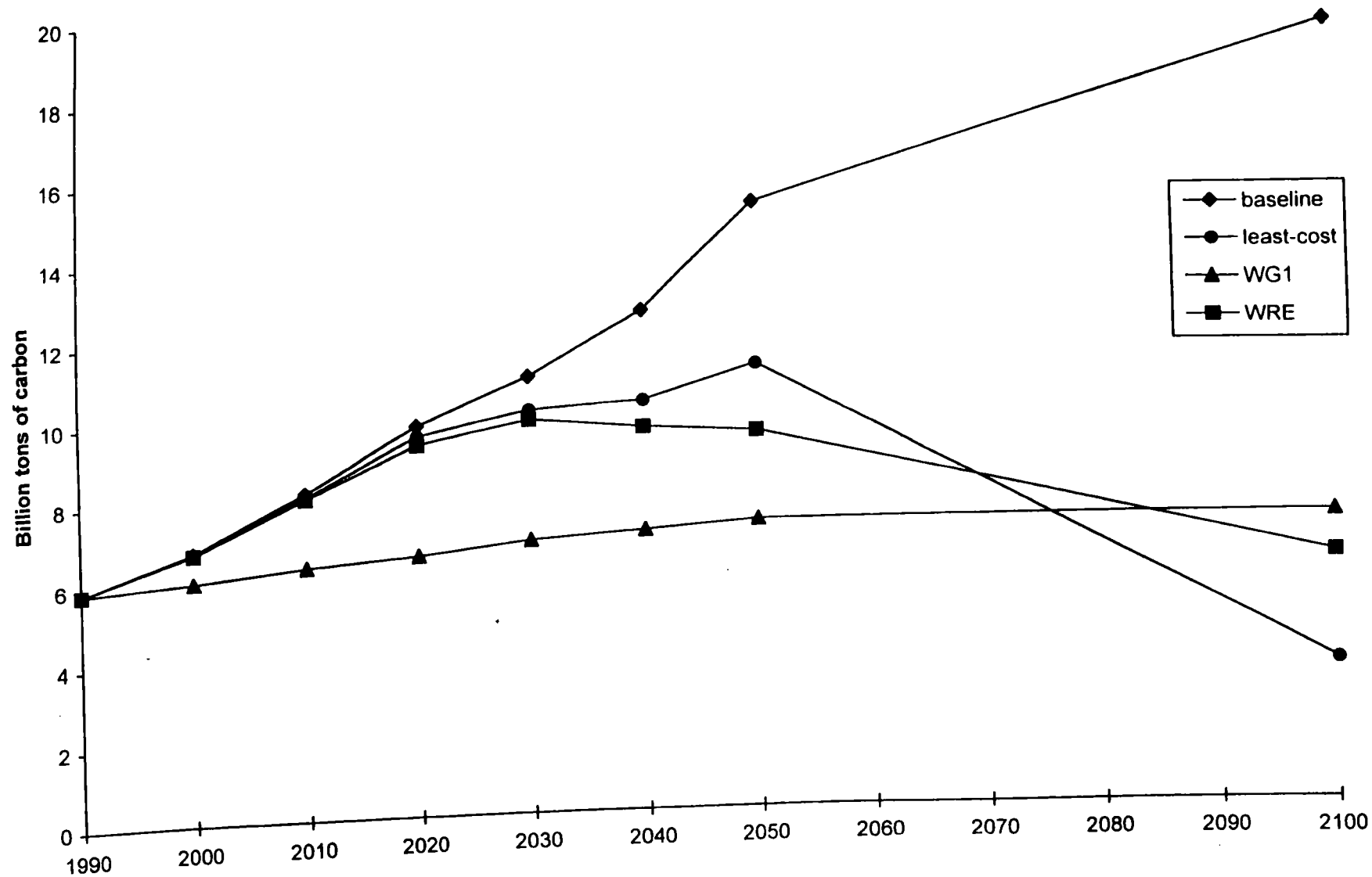


Figure 6.2 Global Costs of Stabilizing Concentrations at 550ppmv
-- discounted to 1990 at 5%

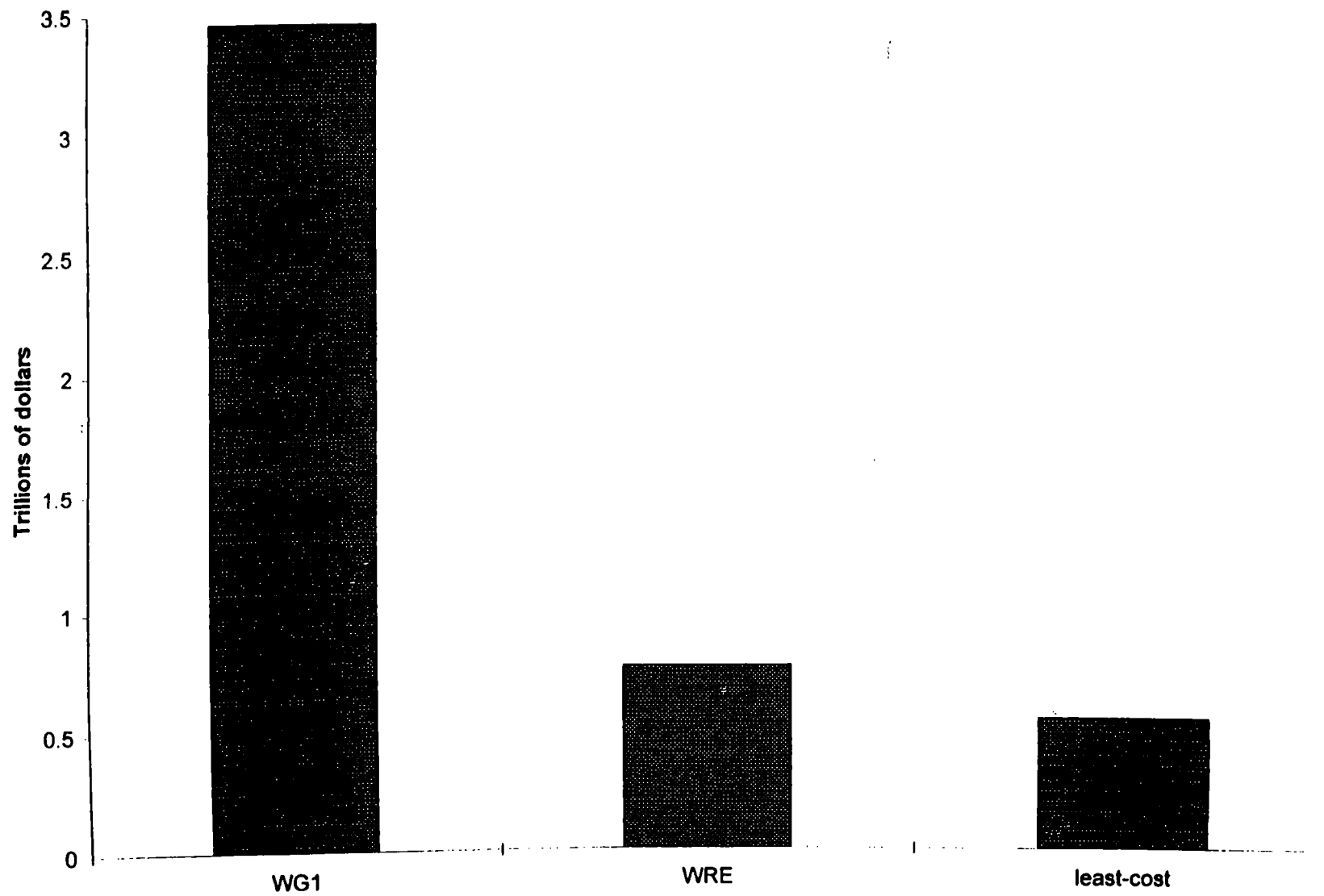
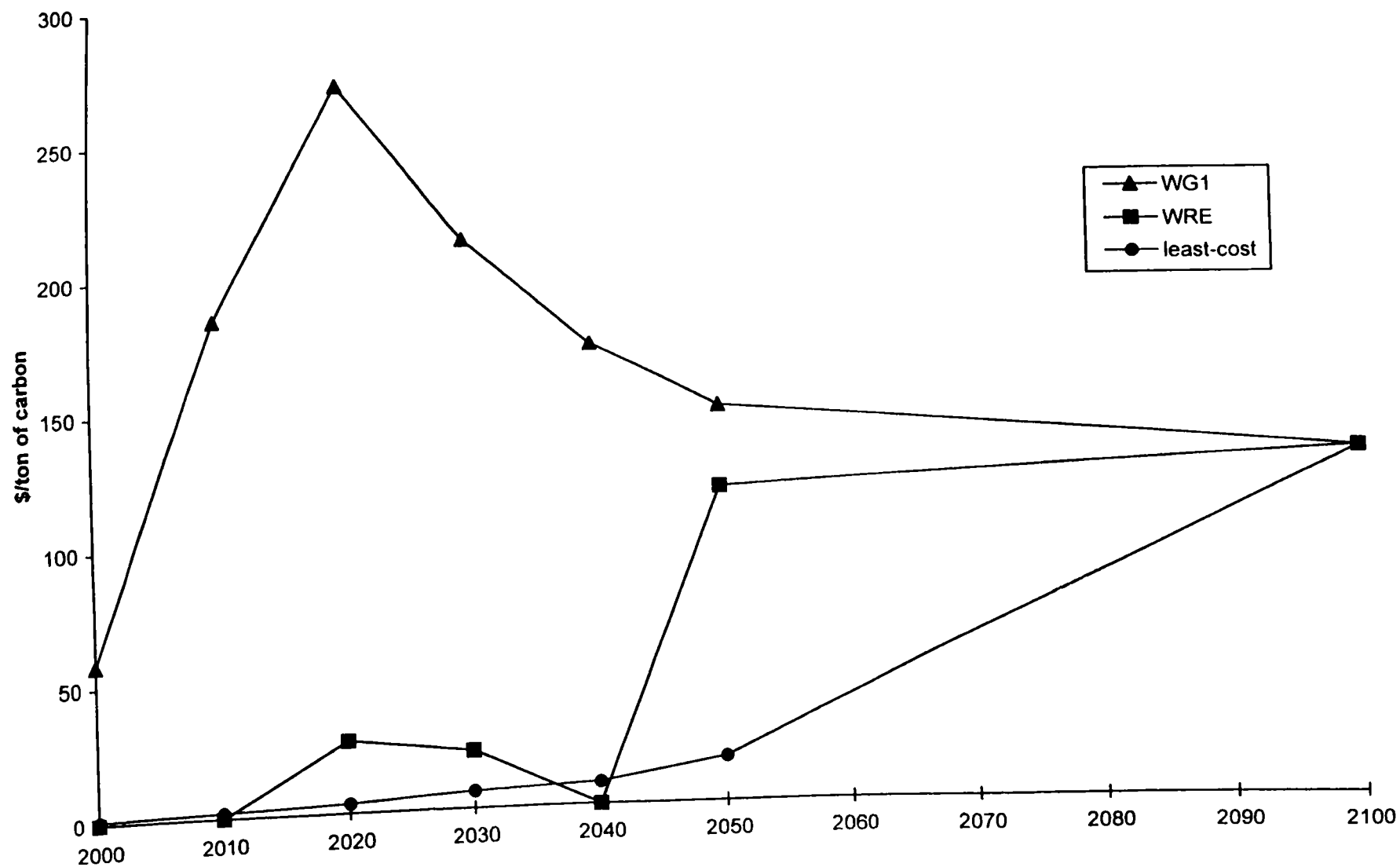


**Figure 6.3 Value of Carbon Emission Rights with Alternative Pathways
for Stabilizing Concentrations at 550ppmv**



The cases differ dramatically, however, in terms of the value of carbon emission rights. From Figure 6.3, we see that the least-cost path starts off at a low price (approximately \$2/ton of carbon) and rises gradually over time. The WRE case leads to an erratic time path of carbon prices. Indeed, in some years there is an excess of emission rights. As a result, their value falls to zero. In other years, their value exceeds that of the least-cost optimal emissions reduction path.

7. The costs of stabilizing concentrations at alternative levels

The selection of the 550ppmv target was purely arbitrary and not meant to imply an optimal concentration level. Given the present lack of consensus on what constitutes "dangerous" interference with the climate system, it is important to understand how mitigation costs might vary with alternative concentration targets.

Figure 7.1 summarizes the results of the MERGE analysis. As would be expected, mitigation costs are a declining function of the stabilization target. Recall that a concentration target places an upper limit on the amount of CO₂ to be released into the atmosphere between now and the date at which the target is to be achieved. This in effect defines an emissions budget. The lower the target, the smaller the emissions budget.

Figure 7.2a shows the constraint on Annex 1 emissions during the initial decades of the next century under the WG1 scenario. In the absence of "where" flexibility, this becomes an effective upper bound on emissions. The figure provides useful insights into the shape of the abatement cost curve. Relative to higher targets, 450ppmv implies that: 1) more carbon must be removed from the energy system, 2) there is greater need to reconfigure the existing energy using and energy producing capital stock, 3) low-cost substitutes are likely to be available in a less timely manner, and 4) there is a shorter time window for discounting to reduce the present value of mitigation costs with a concentration constraint above 450ppmv, each of these factors acts to lower costs.

The costs of complying with WG1 are substantially reduced when we allow for "where" flexibility. Annex 1 countries are able to purchase lower marginal cost abatement alternatives from non-Annex 1 countries. As a result, the need is not as intense for early reductions.

WRE produces the lowest mitigation cost possibilities. The asymmetry in the cost function between 450 and 550ppmv suggests that even with WRE, the low target will provide insufficient time to adapt the existing capital stock. From Figure 7.2b, note that a 450ppmv target would require a departure from the baseline during the first decade of the next century, and there would be an

Figure 7.1 Mitigation Cost for Stabilizing Concentrations at Alternative Levels
-- discounted to 1990 at 5%

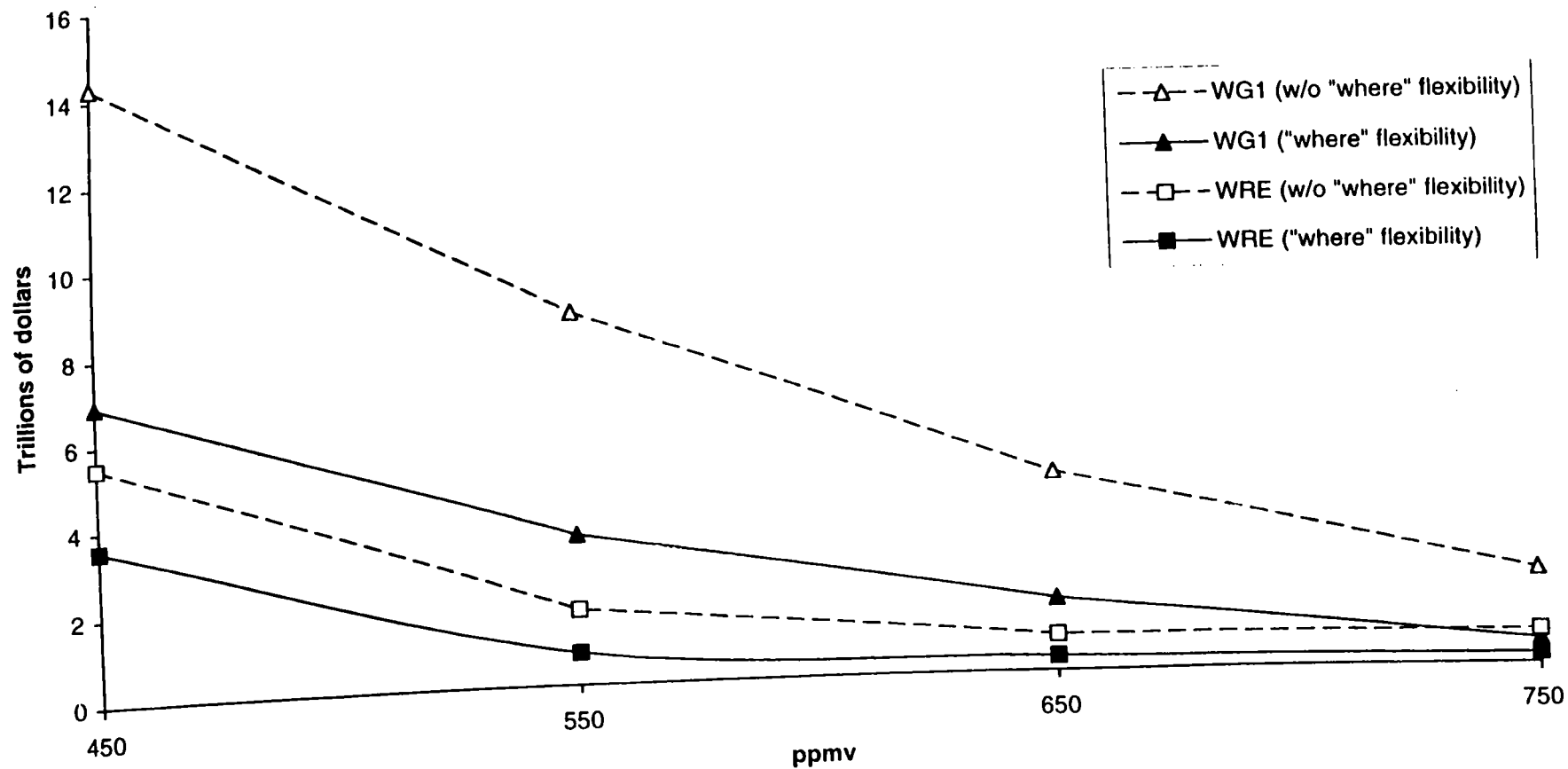
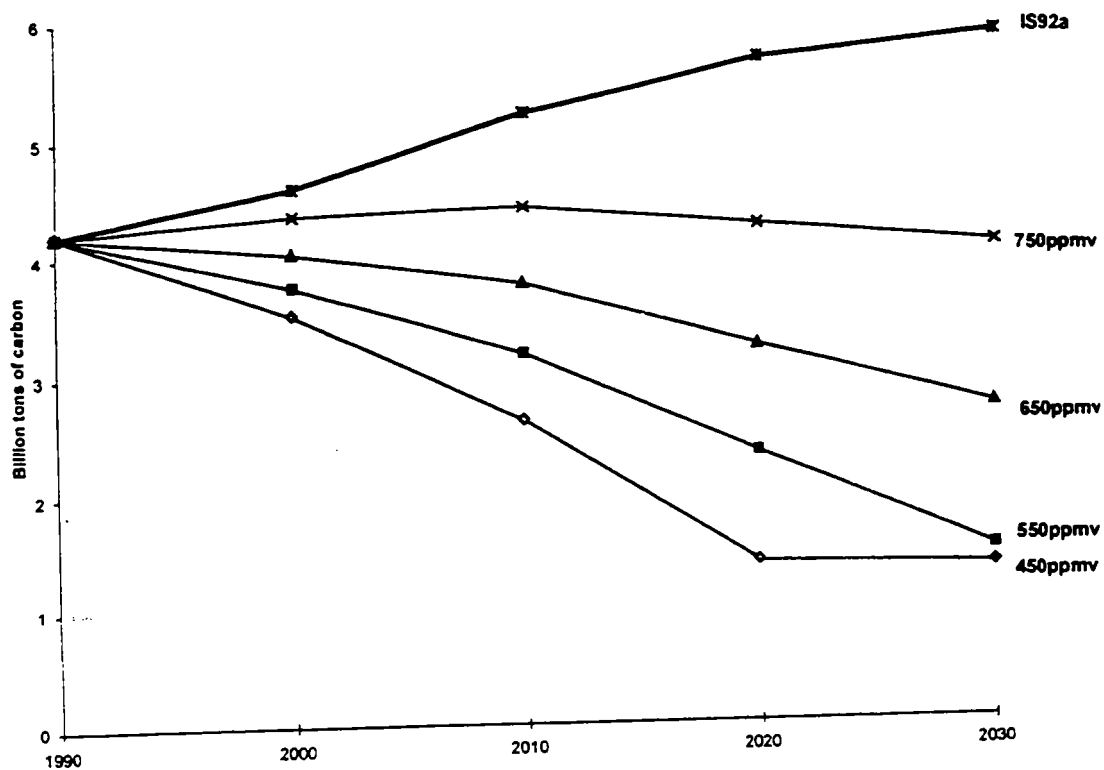
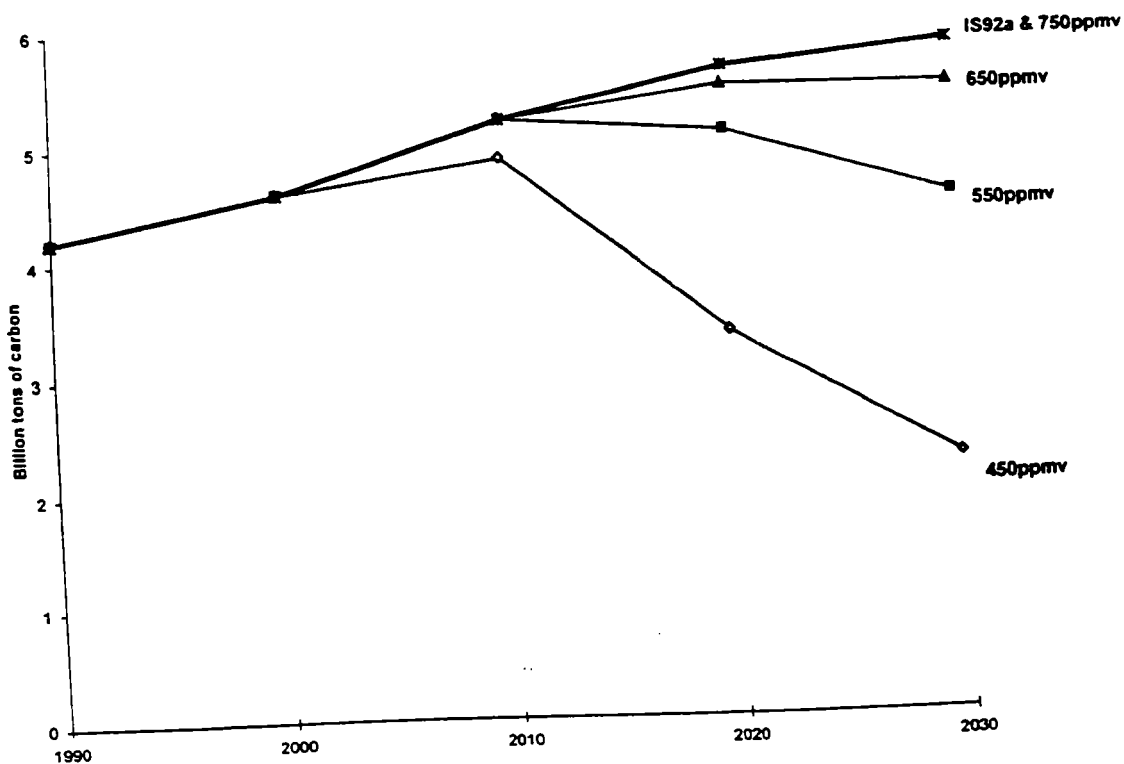


Figure 7.2 Annex 1 Emission Constraints under Alternative Concentration Targets



a) WG1



b) WRE

even more rapid departure thereafter. With targets of 550ppmv and above, there is time for a more gradual transition away from carbon-intensive fuels.

8. The choice of near-term mitigation strategy

Figure 7.2b provides some useful guidance for the design of near-term emission strategies. If it is certain that the target is 550ppmv or above, the near-term emissions path appears to be quite robust. That is, it adheres fairly closely to the emissions baseline through 2010. It should be noted, however, that even in this case, there is some transition away from the world's current heavy dependence on carbon-intensive technologies prior to 2010. That is, inexpensive alternatives (e.g., renewables and cost-effective conservation) are introduced in increasing amounts - both on the supply and demand sides of the energy sector. However, if these alternatives are economically attractive in their own right, they will be adopted even in the absence of climate policy.

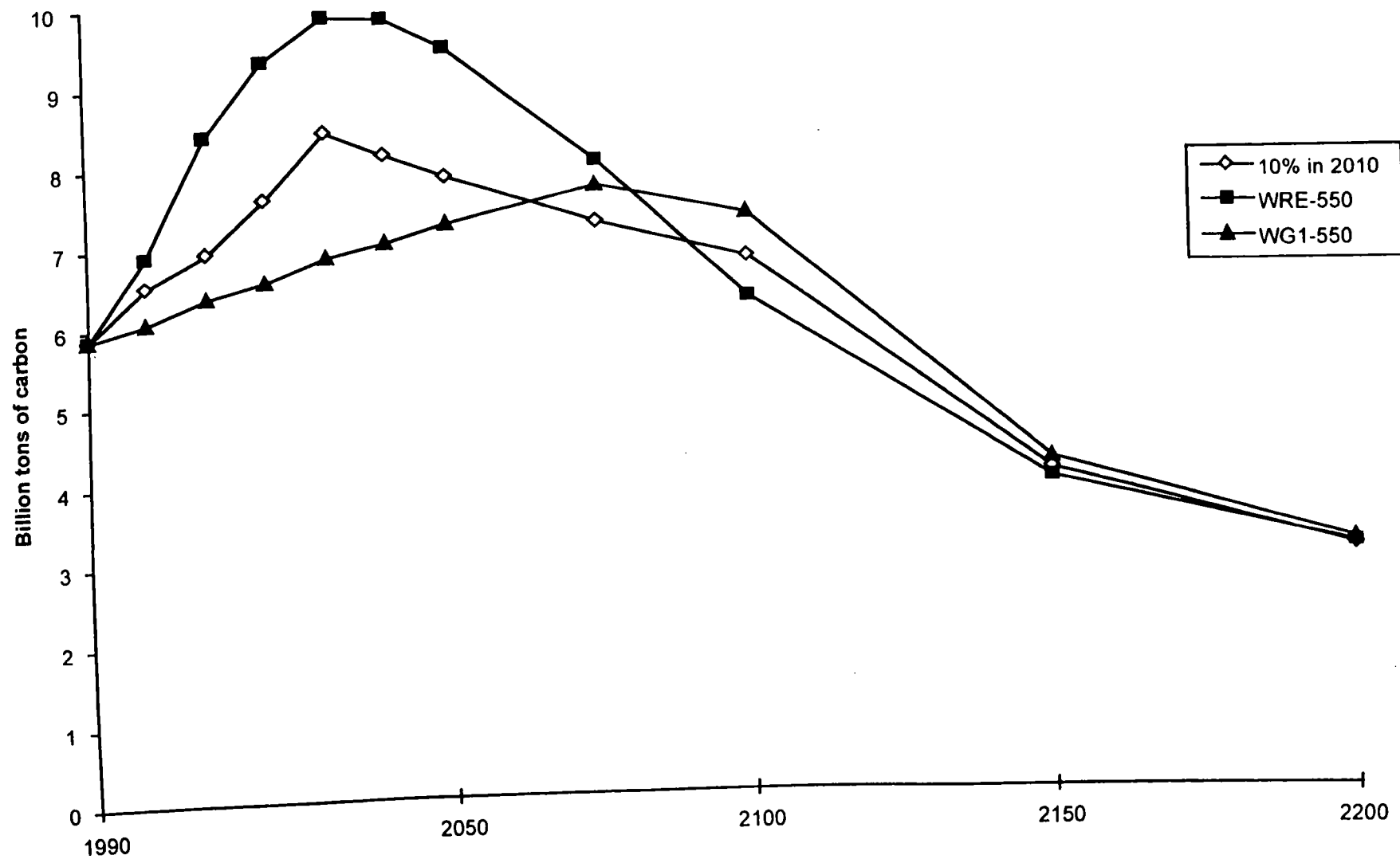
Suppose, on the other hand, that one believes there is some probability that the target is in the 450 to 550ppmv range. A more aggressive departure from the emissions baseline will be required. The degree of hedging depends upon the probabilities and the relative costs of two types of errors in the design of future capital stocks. That is, one must balance the risks of investing in capital stocks that lead to carbon emissions that are either too high or too low.

Of course, the choice of emission pathway for meeting a prescribed concentration target must also involve consideration of the environmental consequences of adopting one emission trajectory over another. The WRE emission pathways result in higher concentrations in the years preceding the date by which the target is to be achieved. For the 550ppmv case, the higher concentrations lead to pathway related differentials of up to .2 degrees C in global mean temperature and 4cm in global mean sea level change (ref. 11). To the extent that this leads to higher environmental damages, these need to be balanced against the benefits from reduced mitigation cost.

9. A framework for analyzing alternative proposals

The WG1 and WRE emissions pathways are likely to bound the majority of proposed pathways for stabilizing concentrations at a particular level. Figure 9.1 shows three emission pathways for stabilizing concentrations at 550ppmv in 2150. In addition to WG1 and WRE, we include a third pathway that has some common characteristics with several proposals being put forward under the Berlin Mandate. Here we assume that Annex 1 countries agree to return emissions to 1990 levels by 2000, with further reductions of 10% per decade through 2030. At that point, all countries would begin moving to equal per

Figure 9.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv



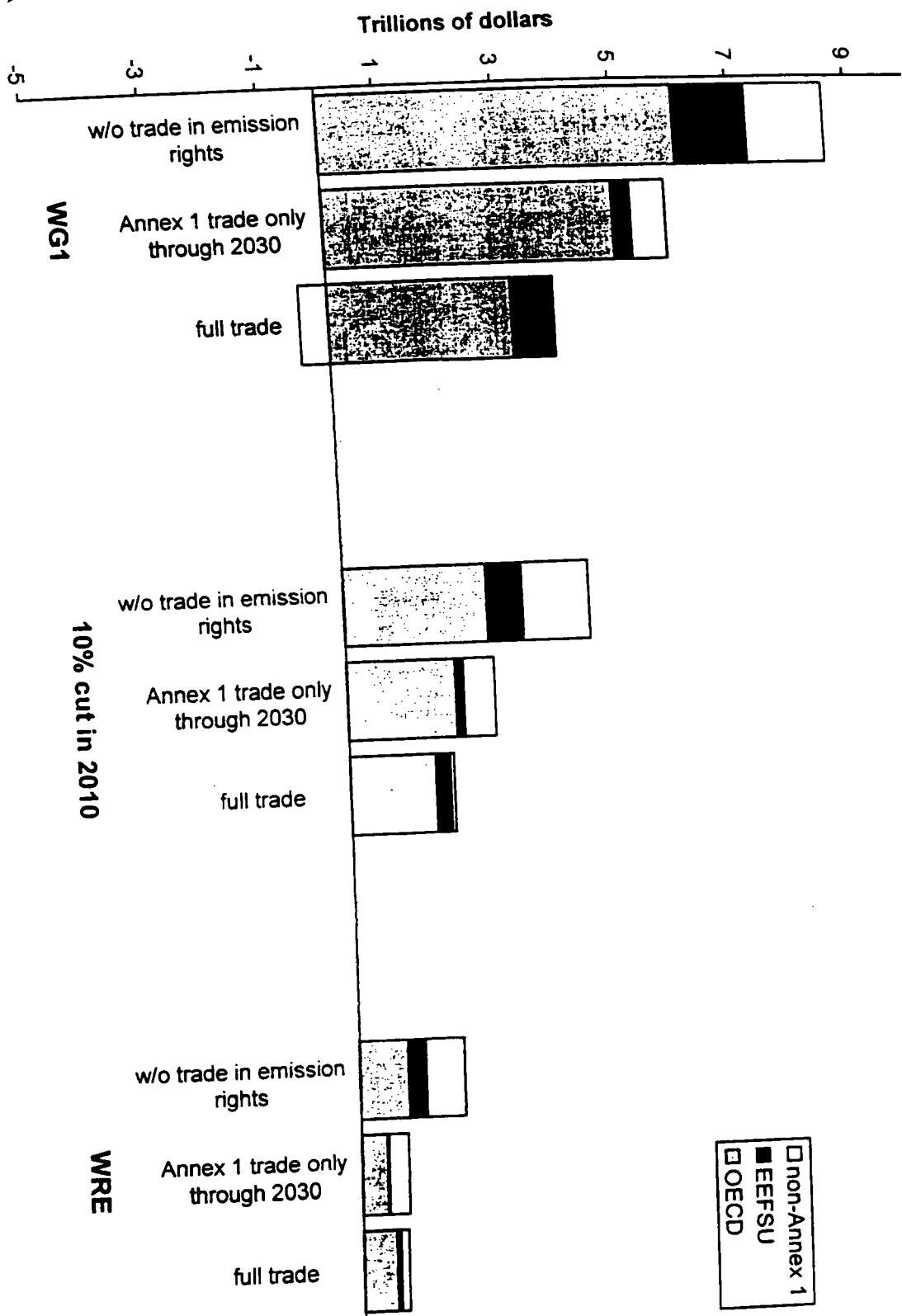


Figure 9.2 Regional Costs of Stabilizing Concentrations at 550ppmv
 -- discounted to 1990 at 5%

capita emissions (based on 1990 population). The transition would be completed by 2050.

We also use this opportunity to explore a variant on our emission trading scheme. Thus far, we have assumed that, if there is to be trading, all countries will participate. As an alternative, some have suggested that trading be confined to those countries which have agreed to adopt emission constraints. The following calculations explore the implications for stabilization costs. For the partial trading scenario, we assume that trading is confined to Annex 1 countries through 2030. Non-Annex 1 countries are permitted to participate thereafter.

Figure 9.2 summarizes our results. Discounted mitigation costs for the new scenario lie between those of WG1 and WRE. Also notice that the difference between partial trading and full trading is greatest under WG1. With a tight near-term constraint, Annex 1 has the highest demand for emission rights. EEFSU can help, but cannot satisfy the needs of the OECD. Full global trading is necessary. Conversely, under WRE, there are negligible costs of limiting trading to Annex 1 countries through 2030. This is because the looser constraint on near-term emissions postpones the need for emission rights.

10. Some concluding comments

The above analysis suggests that a more gradual transition away from fossil fuels is likely to be less expensive than a more aggressive policy in terms of mitigation costs. This should not be interpreted as suggesting a "do nothing" or "wait and see" strategy. Mitigation may mean action, but action does not necessarily mean mitigation. As pointed out in the IPCC 1995 Report²⁰, climate policy requires a portfolio of responses. The challenge facing today's policy makers is to arrive at a prudent hedging strategy in the face of climate-related uncertainties. Among the options are

- immediate reductions of greenhouse gas emissions,
- investments in actions to assist human and natural systems adapt to climate change should it occur,
- continued research to reduce uncertainties about how much change will occur and what effects it will have, and
- R&D on energy supply and end-use technologies to reduce the costs of limiting greenhouse gas emissions.

The issue is not one of either-or but one of finding the right blend of options. Policy makers must decide how to divide greenhouse insurance dollars among these competing needs.

The present analysis has provided some useful insights bearing on this decision. Deep near-term reductions are apt to be costly. They provide less time to adapt the existing capital stock. There will be more opportunities for reducing emissions cheaply as the current capital equipment turns over. Indeed, the 1995 IPCC report states that "implementing emission reductions at rates that can be absorbed in the course of normal capital stock turnover is likely to be cheaper than forcing premature retirement now."²¹

Fortunately, with regard to carbon dioxide, the issue is one of cumulative rather than year-by-year emissions. This means that we can allow for an economical turnover of the existing capital stock if we are prepared to make sharper reductions in the future.

This brings us to the issue of R&D. Sharper reductions in the future will be less problematic if we can lower the costs of fuel switching and conservation. Indeed, studies by Stanford University's Energy Modeling Forum suggest that the development of economically competitive alternatives to conventional fossil fuels could substantially reduce the costs of a carbon constraint.²²

Although virtually all parties in the debate recognize the value of R&D, we have yet to develop a technology strategy for dealing with global climate change. How much should we be investing today to ensure ample supplies of low-cost alternatives in the future? What should be the nature of these investments, who would make them, and how would they be managed? Given the size of the stakes, surprisingly little attention has been devoted to these questions.

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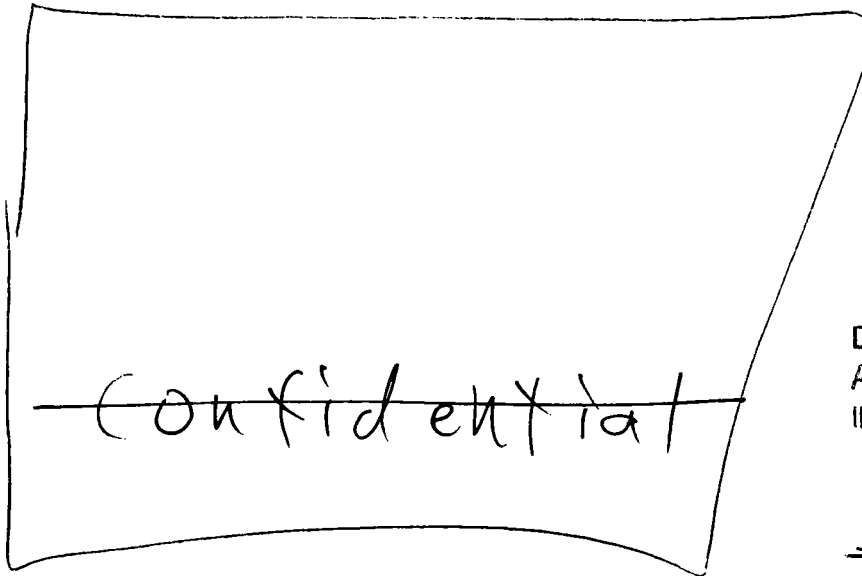
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To: Rich Richels

8/29/94

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415 855-2950



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ADMINISTRATIVE MARKING
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Thanks!!

Rich

Let's talk in la
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results right, ~~the fact?~~
now?)

★ If you could write up your new
results yourself, so I had something to cite,
that would be great!

OF

On Stabilizing CO₂ Concentrations - Cost-Effective Emission Reduction Strategies

Alan Manne, Stanford University

Richard Richels, Electric Power Research Institute

February 25, 1997

This research results from our involvement in Stanford University's Energy Modeling Forum 14 Study. For presentation at the IPCC Asia-Pacific Workshop on Integrated Assessment Models, the United Nations University, Tokyo, Japan, 10-12 March 1997. We are indebted to David Chang and Robert Parkin for research assistance. We have benefited from discussions with Sharmila Barathan, Jae Edmonds, Howard Gruenspecht, Eric Haites, Henry Jacoby, William Nordhaus, Stephen Peck, Leo Schrattenholzer, John Weyant, Tom Wigley, and ZhongXiang Zhang. Funding was provided by the Electric Power Research Institute. The views presented here are solely those of the individual authors.

Abstract

With the adoption of the Berlin Mandate, developed countries are being asked to set emission limits for the early decades of the next century. The size of the reductions is currently the subject of international negotiations. This paper is intended to contribute to the analysis and assessment phase leading up to the adoption of new targets and timetables. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO₂ concentrations to alternative levels. We then explore the implications for near-term mitigation decisions and for long-term participation by the developing countries.

1. Introduction

In recent years, global climate change has become one of the most contentious environmental issues facing the international community. The UN Framework Convention calls for the "stabilization of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."¹ Yet the issue of what constitutes "dangerous anthropogenic interference" is likely to remain the subject of intense scientific and political debate for some time. For the present, international negotiations must remain an ongoing process -- with ample opportunities for learning and for midcourse corrections.

We are currently in the midst of one such review cycle. When initially put forward at the "Earth Summit" in 1992, the Framework Convention called upon developed countries to aim to return emissions to 1990 levels by the year 2000. At the first meeting of the Conference of the Parties in 1995, these commitments were deemed inadequate. As a result, the so-called "Berlin Mandate" was adopted. This called upon developed countries to set "quantified limitation and reduction objectives" for the post-2000 time frame.²

Although the Berlin Mandate is explicit in its call for additional reductions, it does not specify how large the reductions should be. Rather it specifies an "analysis and assessment" phase to help inform the decision making process. The deadline for new commitments is December 1997. A wide variety of proposals have been put forward in anticipation of this deadline. These proposals range from sharp cuts in near-term emissions to a more gradual transition away from carbon-intensive fuels. The international research community is actively engaged in trying to understand the environmental and economic implications of these policy proposals.

This paper is intended to contribute to the process of analysis and assessment. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO₂ concentrations to alternative levels. We then explore the implications for near-term mitigation decisions and for long-term participation by the developing countries.

There are several reasons why a broader perspective is desirable. The Intergovernmental Panel on Climate Change (IPCC) has demonstrated that if CO₂ concentrations were to be stabilized at any of the levels it examined, this would require an eventual and sustained reduction in emissions to

substantially below current levels.³ Developed countries cannot do the job by themselves. Nor can the transition be accomplished overnight. Cost-effective strategies will require both a global and a long-term perspective.

Any analysis of stabilization must confront the divisive issue of burden sharing. With trade in carbon emission rights, emission reductions can be made where it is cheapest to do so, regardless of their geographical location. The allocation of permits will have little impact on the least-cost global strategy.⁴ It will, however, have profound affects on who pays. Consistent with the Framework Convention, we adopt a burden sharing scheme that initially places the onus on developed countries. We then discuss the implications for international negotiations.

Economic analysis can play an important role in the climate debate. It can help policy makers identify least-cost mitigation strategies from a global perspective. In doing so, this helps to minimize the size of the overall burden. It can shed light on the implications of alternative burden sharing schemes at the regional level. Economic analysis, however, cannot tell us how a given burden *should* be allocated. Fairness and equity issues must necessarily be left to the international negotiation process.

Finally, we emphasize that our analysis is confined to mitigation costs. We recognize that this is not the whole story, but it is an important part. Article 3 of the Framework Convention states that "policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible costs."⁵ Identifying least-cost mitigation strategies can free up valuable resources for addressing alternative uses.

2. The model

The analysis is based on MERGE -- a model for evaluating the regional and global effects of greenhouse gas reduction policies. MERGE provides a bottom-up representation of the energy supply system. For a given scenario, a least-cost choice is made among specific technologies for the generation of electricity and for the production of nonelectric energy. As fossil fuels (coal, oil and gas) are exhausted, their prices rise and carbon-free alternatives become more competitive. To allow for inertia in the energy supply system, decline and expansion constraints are placed on existing and new technologies, respectively.

A top-down perspective is taken for the balance of the economy. These sectors are modeled through nested constant elasticity of substitution production functions. The production functions determine how aggregate output depends upon the inputs of capital, labor, electric and nonelectric energy. In

this way, the model allows for both price-induced and autonomous (non-price) energy conservation and also for interfuel substitution. A "putty-clay" formulation is used to allow for the lags in adapting to changes in energy prices.

In MERGE, the savings and investment process is affected by intertemporal and interregional forces. Each region is represented as though it maximizes discounted utility (the logarithm of consumption) subject to an intertemporal budget constraint. Its wealth includes not only capital, labor, and exhaustible resources, but also its negotiated share in global carbon emission rights. With this objective function, the costs of abatement are defined as the losses in the discounted value of consumption associated with alternative carbon constraints.

In previous versions of MERGE, the world was subdivided into five geopolitical regions.^{6,7} The present version of the model, known as MERGE 3.0, divides the world into nine regions: 1) the USA, 2) OECD (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). The further disaggregation provides better alignment with the Annex 1/non-Annex 1 structure of the Framework Convention. It provides more details concerning winners and losers under alternative burden sharing schemes, and it distinguishes between the major oil importing and exporting regions.

Population trends for each region are taken as exogenous. Per capita incomes are determined primarily by the rate of labor force productivity. Between 1990 and 2020, our projections are consistent with the conventional wisdom median values of the International Energy Workshop poll.⁸ For the world as a whole, GDP growth is projected at an average annual rate of 2.5% between 1990 and 2100. It is assumed that there are ultimate limits to economic growth, and that there will eventually be convergence between the per capita incomes in the OECD countries and those in the rest of the world. Figure 2.1 shows our specific projections of per capita GDP in each of the nine regions.

MERGE is based on a general equilibrium formulation of the global energy-economic system. This enables us to model trade in oil, gas and carbon emission rights. The model does not, however, account for the effect of an economic slowdown in one region on the full range of exports of another. It may therefore be ignoring some important "spillover" effects. MERGE is not designed to address short-run macroeconomic issues such as unemployment and inflation. The employment level is exogenous, and there are instantaneous adjustments to policy shocks. As a result, the model may overlook some costly short-term dislocations.

Figure 2.1 Per Capita GDP

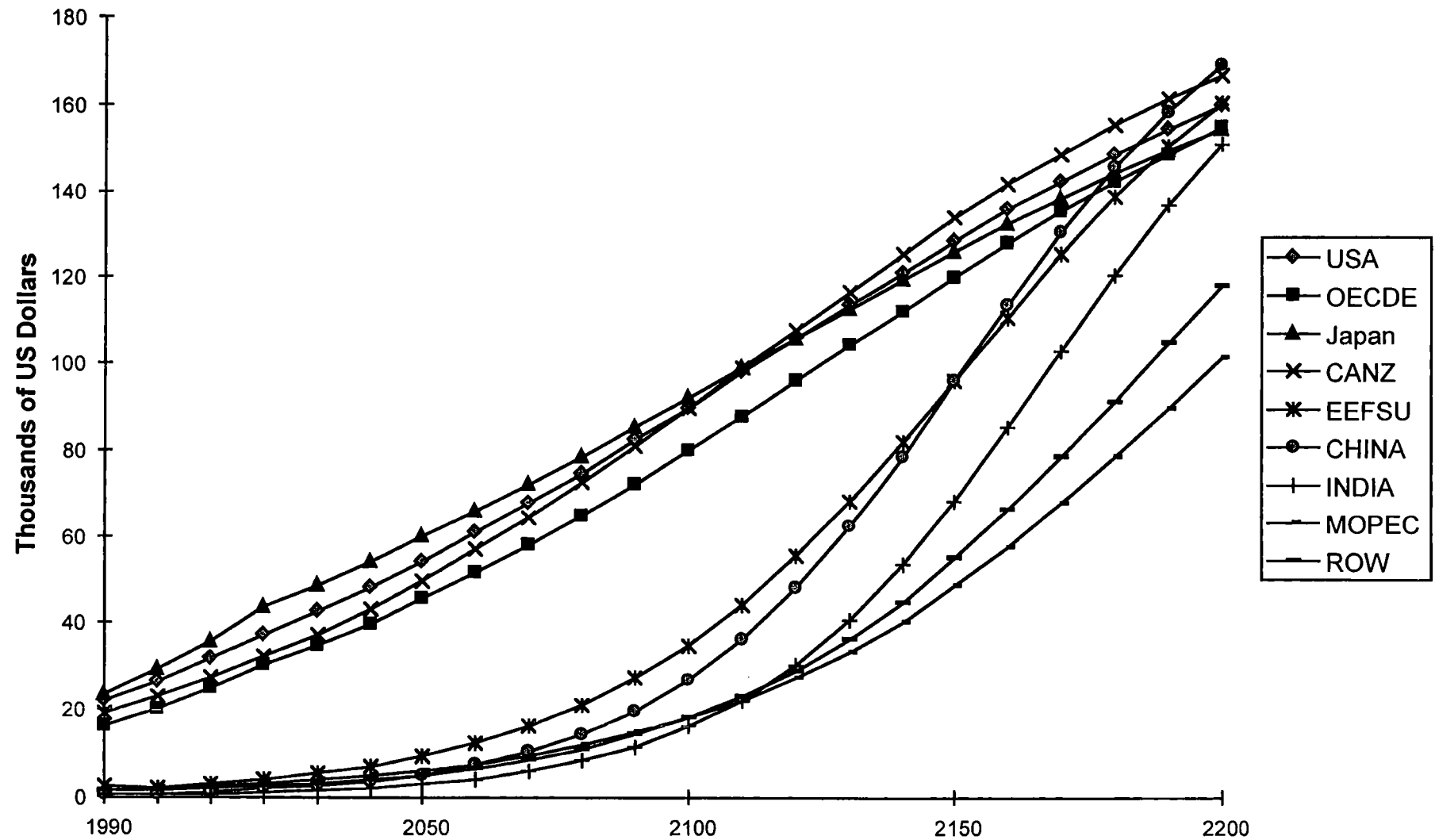


Figure 2.2 Regional Carbon Emissions

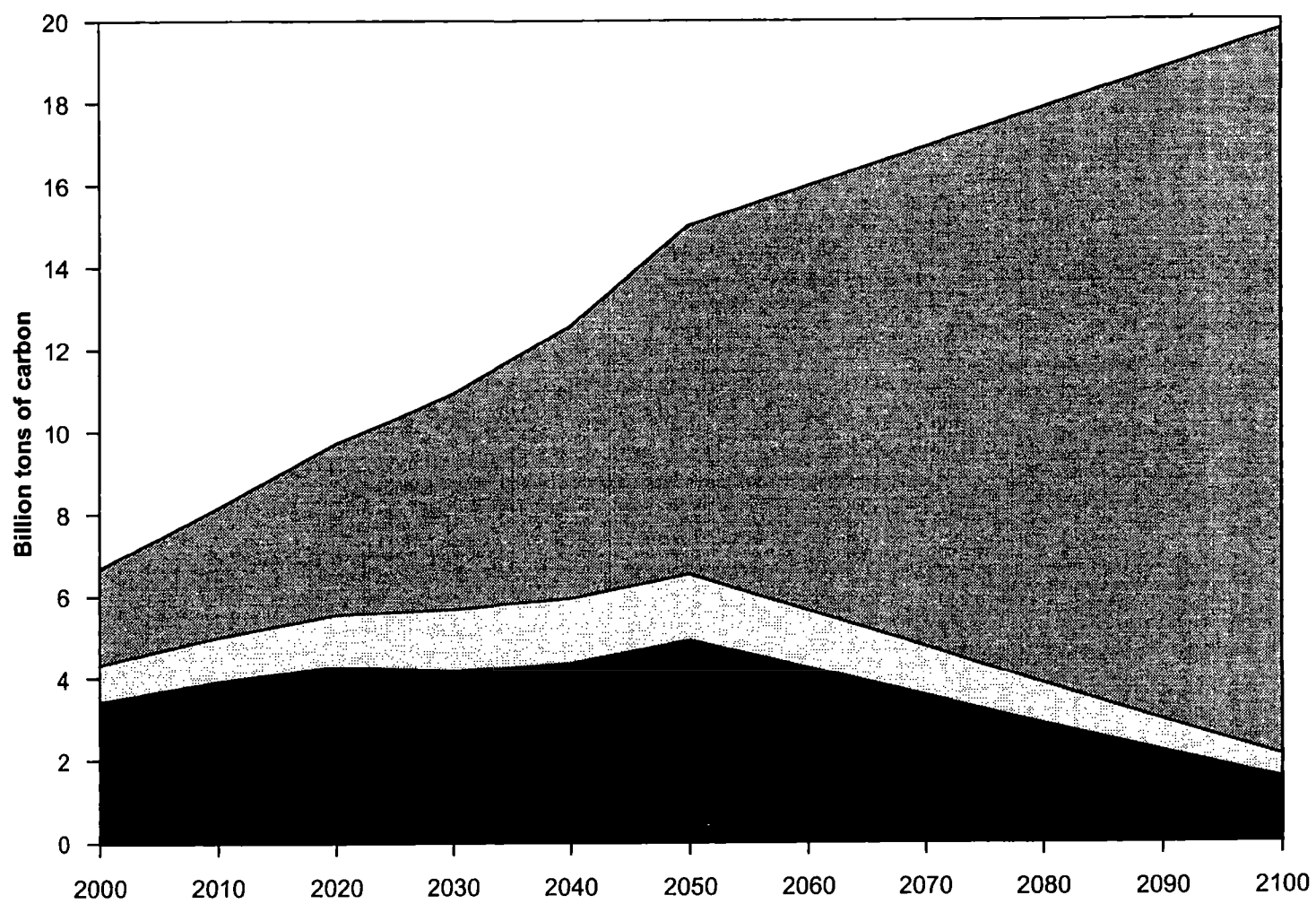
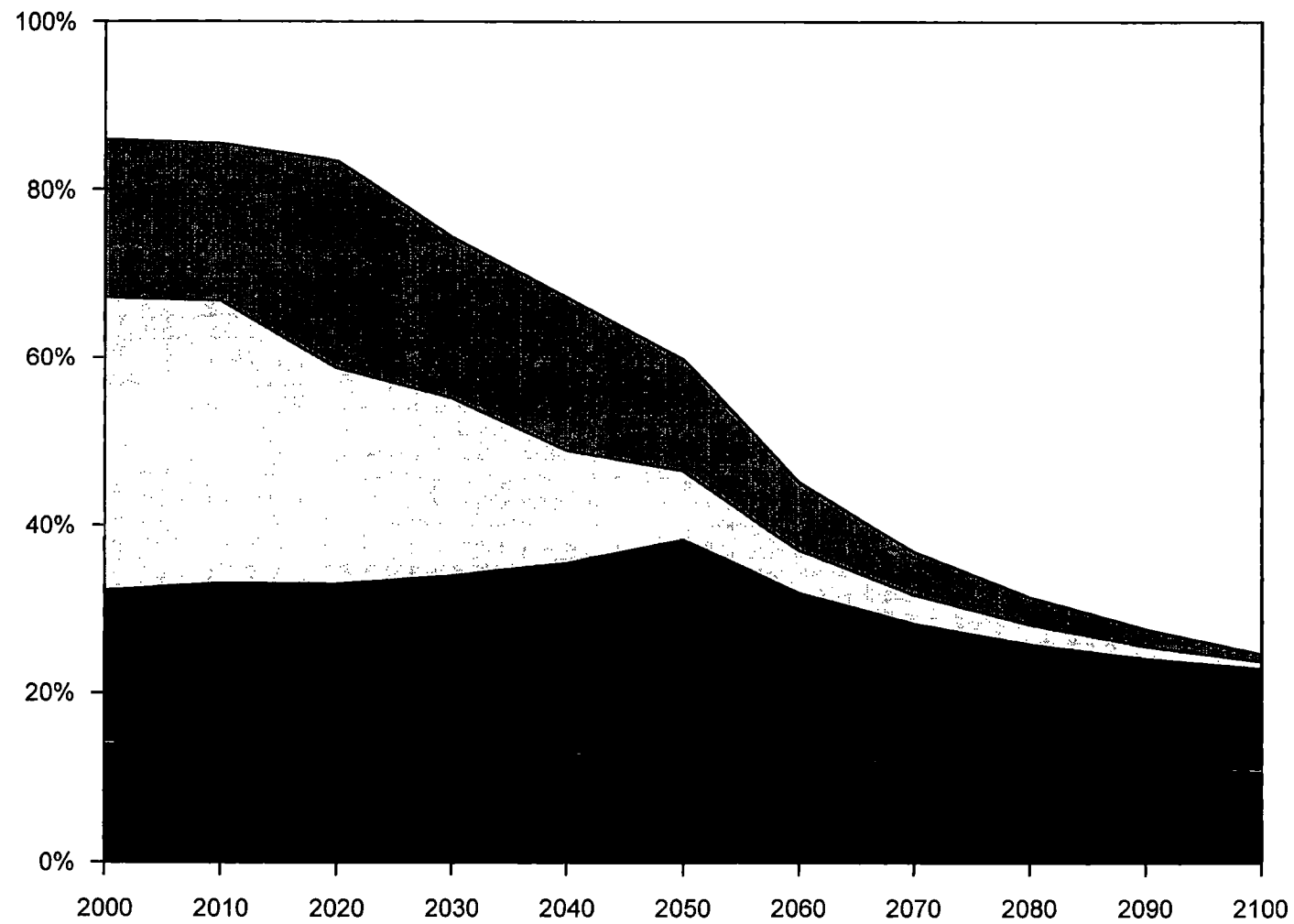


Figure 2.3 Total Primary Energy Use - Basecase



CO2 mitigation costs are determined by 1) the emissions baseline -- i.e., how emissions are apt to grow in the absence of policy interventions, 2) the cost and availability of alternative supply and demand-side options, and 3) the magnitude of the CO2 constraint. For the present analysis, several supply and demand parameters of the energy-economy submodel have been adjusted so that the baseline tracks the IPCC IS92a⁹ scenario through the year 2100. Figure 2.2 shows carbon emissions for the OECD, EEFSU and non-Annex 1. Figure 2.3 shows the corresponding total primary energy use by fuel type.

Some observers have suggested that the exogenous specification of technical change will overstate the costs of a carbon constraint. They argue that an international carbon abatement agreement will automatically induce innovations in carbon-saving technologies. We do not share their optimism on the automatic nature of such innovations. (Consider, for example, the history of both fission and fusion technologies.) We do believe, however, that carbon constraints might speed up the process of technology *diffusion*.

MERGE 3.0 incorporates the notion of "endogenous technology diffusion". Specifically, in the electric power sector, the near-term adoption of high cost carbon-free substitutes makes it possible to introduce low-cost alternatives more rapidly in the future. Upon request, the authors will supply computer files that fully document the assumptions underlying the model.¹

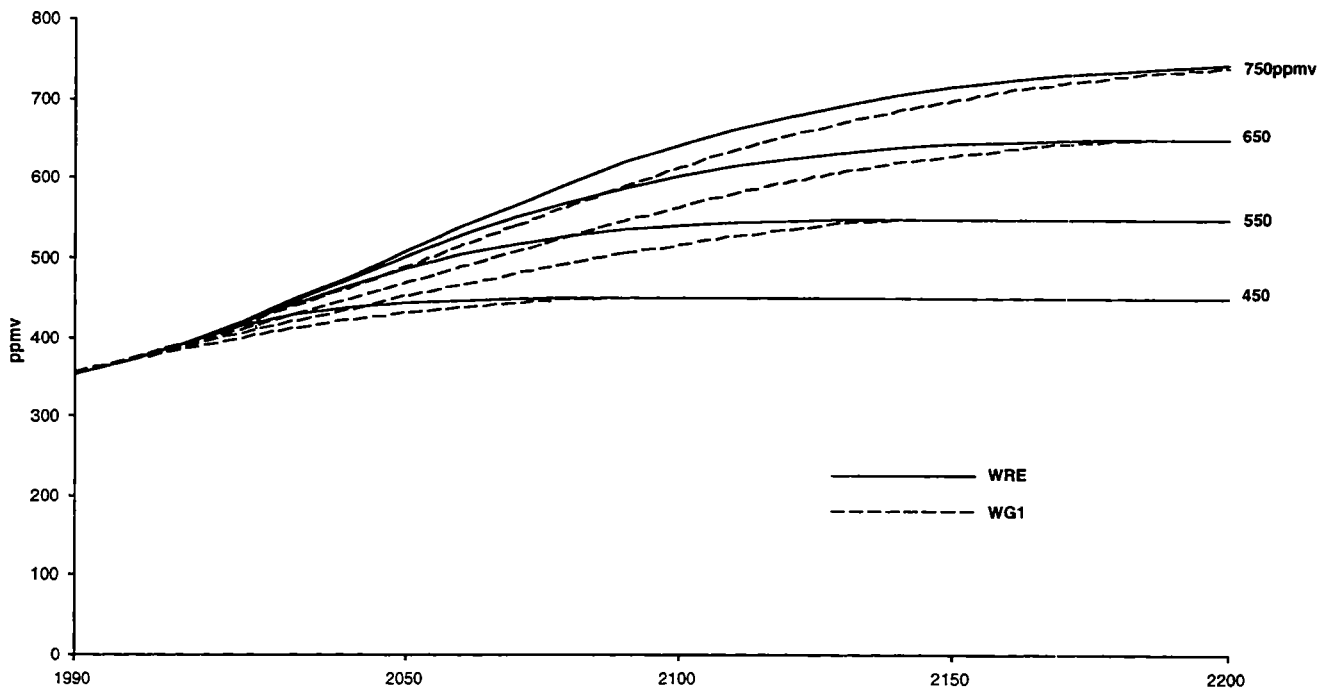
3. Scenario design

We focus on three factors critical to determining the costs of stabilizing concentrations at a particular level: the choice of global emissions pathway, the degree of international cooperation and the burden sharing scheme. In this section, we describe our assumptions with regard to each.

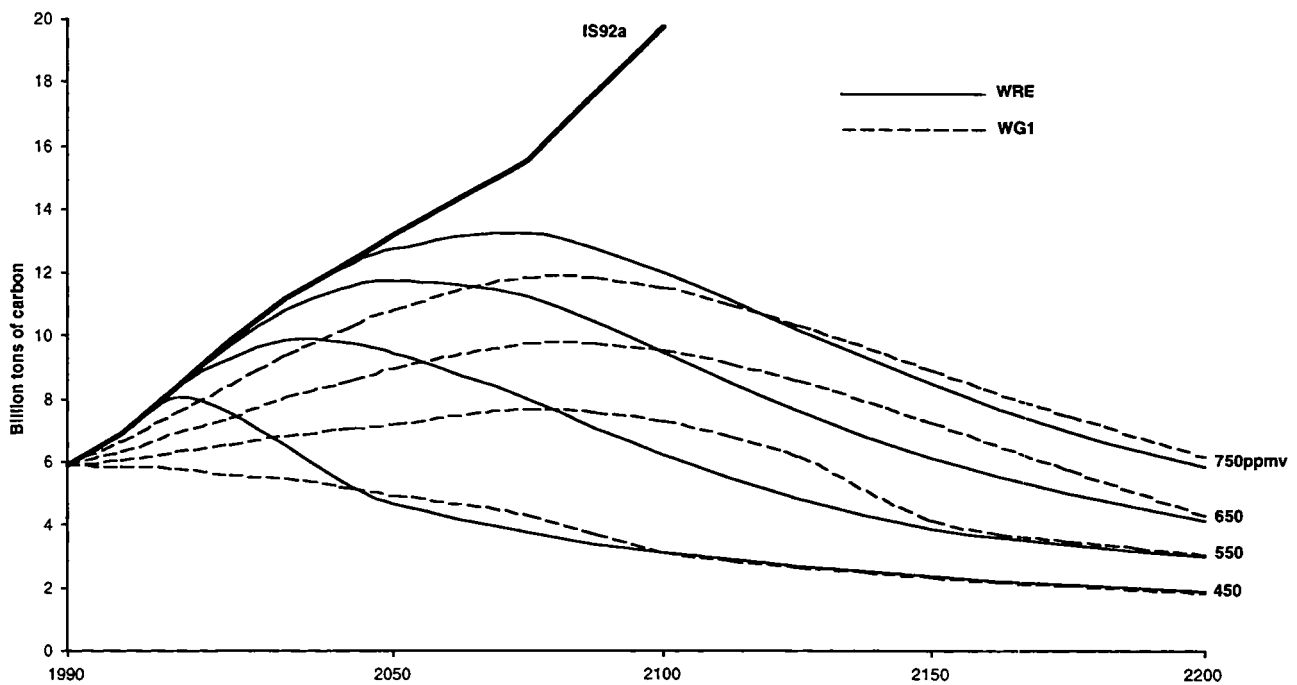
The global emissions path to stabilization. In 1994, Working Group I (WG1) of the Intergovernmental Panel on Climate Change (IPCC) published a set of concentration profiles for stabilizing atmospheric CO2 at 350, 450, 550, 650 and 750ppmv.¹⁰ The purpose of their estimates was to illustrate what might be required in terms of global CO2 emissions reductions in order to stabilize concentrations at these different levels. Subsequently, Wigley, Richels and Edmonds (WRE) published an alternative set of emission profiles for achieving the WG1 concentration targets.¹¹ Although WG1 and WRE are identical in terms of the prescribed stabilization levels and attainment dates, they differ in the routes to stabilization (Figure 3.1a). The IPCC, while not taking a position on the desirability of one set over another, published both in their 1995 scientific assessment.¹²

¹ Contact rrichels@epri.com

Figure 3.1 Alternative Routes to CO₂ Stabilization



a) Alternative concentration profiles



b) Alternative fossil fuel emission paths

Figure 3.1b shows the emission rates required to achieve stabilization via the WG1 concentration profiles (the dashed lines) and the WRE concentration profiles (the solid lines). The calculations were made using the Wigley carbon cycle model. The WRE curves were constructed so that they would follow the central IPCC "existing policies" or "baseline" emissions scenario (IS92a) in the early years. The higher the stabilization target, the longer the adherence to IS92a. In contrast, the WG1 curves depart from IS92a immediately.

WRE assert that concentration pathways with higher near-term emissions are apt to have lower mitigation costs. They cite several economic studies that have examined how mitigation costs might vary with the timing of emission reductions.^{13,14,15,16} These studies suggest that the time path to stabilization may be as important as the concentration target itself in determining the overall discounted costs. They conclude that emission pathways that provide for a gradual transition away from fossil fuels are apt to be less expensive in terms of mitigation costs.

The WRE analysis is primarily qualitative. While drawing upon other studies to make their points, no explicit analysis is made of the mitigation costs associated with either the WG1 or WRE pathways. This is the issue to which we now turn. In this paper, we examine the costs of stabilizing concentrations at 450, 550, 650, and 750ppmv, first following the WG1 emissions pathway and then those suggested by WRE. In each case, we examine the costs to Annex 1 and non-Annex 1 countries under alternative burden sharing schemes.

The extent of international cooperation. A number of studies have shown that the marginal costs of emissions abatement might vary considerably among regions.¹⁷ This will be particularly the case in those periods when emission reductions are confined to Annex 1 countries. Clearly, it is inefficient to incur high marginal domestic abatement costs in Annex 1 countries when the marginal cost of emissions abatement is lower in non-Annex 1 countries. It is equally clear that it would be unrealistic to expect the non-Annex 1 countries to bear the burden of domestic reductions so as to achieve a globally cost-effective result.

This suggests opportunities for efficiency gains through various forms of "joint implementation". This could be done on a bilateral project-by-project basis during the earlier years of an international agreement. Over the long term, however, it is more promising to explore market mechanisms such as a system of international allocations of tradable carbon emission rights. Here we first examine mitigation costs when emission reductions are confined to the region of origin. We then calculate the benefits from international cooperation using trade in emission rights as a proxy for other forms of cooperative mechanisms with side payments.

When we assume that reductions take place wherever it is cheapest to do so (regardless of the geographical location), we refer to this as “interregional” or “where” flexibility. When there is a choice in the timing of emission reductions, we refer to this as “intertemporal” or “when” flexibility.

The burden sharing rule. Region-specific mitigation costs will also depend upon how emission reductions are allocated among regions. Consistent with the Berlin Mandate, we assume that the burden will fall on Annex 1 countries during the initial decades of an agreement. During this period, Annex 1 countries would be required to limit their emissions to amounts proportional to their 1990 levels.

Even if the Annex 1 countries were to reduce their emissions to zero, this would not be sufficient to limit global concentrations. Eventually, the non-Annex 1 countries will also have to limit their emissions. The ultimate concentration target will affect the date at which these non-Annex 1 countries must begin to participate in a global agreement. The more ambitious the target, the sooner they will have to participate in such an agreement. Once the non-Annex 1 countries do agree to a constraint, however, it is plausible to assume that there will be a gradual transition to equal per capita emission rights. (For one such scheme, see Table 3.1.)

Table 3.1 Structure of Burden Sharing Scheme

Concentration target (ppmv)	Date at which non-Annex 1 countries must begin to limit emissions	Date by which transition to equal per capita emission rights is achieved
450	2020	2040
550	2030	2050
650	2040	2060
750	2050	2070

With “where” flexibility, global mitigation costs are independent of the burden sharing scheme. That is, reductions will take place wherever it is cheapest to do so regardless of the geographical location. This is not the case, however, when emission reductions are restricted to the region of origin. With this type of restriction, the burden sharing scheme will affect both the global and the regional costs.

4. Global costs of stabilization at 550ppmv

Mitigation costs are incurred when the imposition of a carbon constraint leads to a reallocation of resources from the pattern that would be preferred in the absence of the constraint. A carbon constraint will lead to more expensive conservation activities and to fuel switching. There are changes in both domestic and international prices. In most cases, these forced adjustments lead to a reduction in economic performance. The tighter the constraint, the greater the effect.

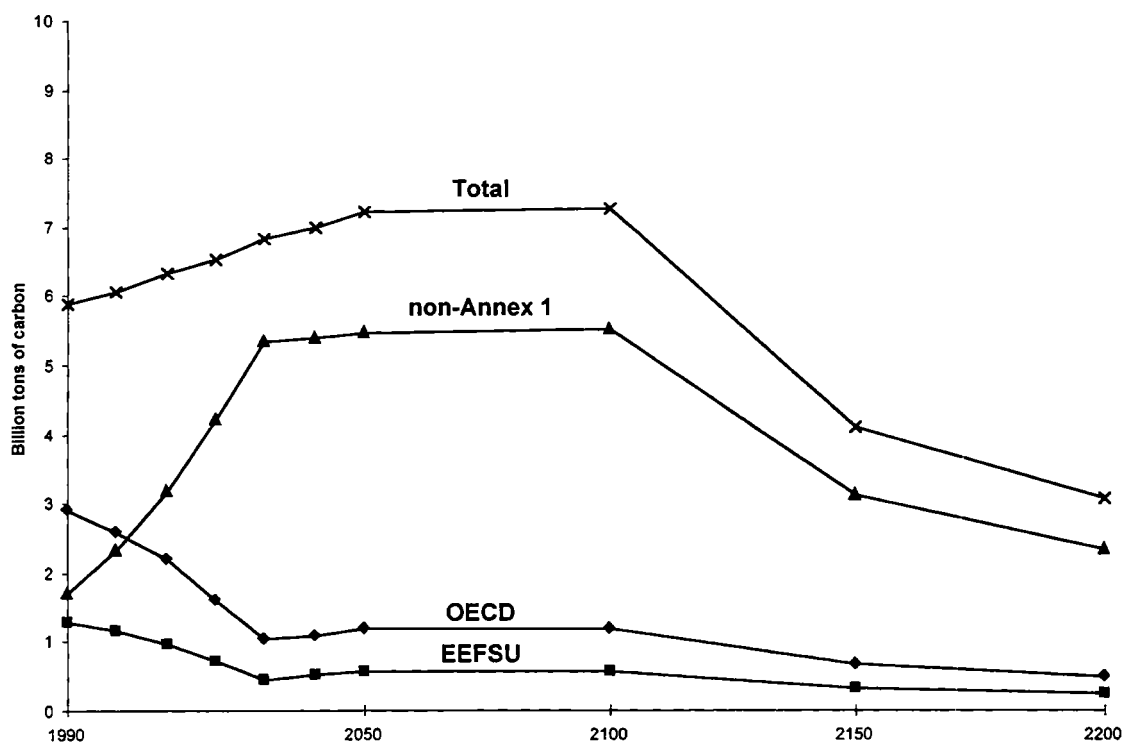
With MERGE, we can calculate how mitigation costs vary with the choice of concentration profile. At the present time, there is little consensus on what constitutes an appropriate concentration target. There is even less consensus on the choice of a pathway to stabilization. We shall begin by focusing on a concentrations target of 550ppmv -- approximately twice the preindustrial level. Later, we will explore the implications of adopting alternative concentration targets.

Figure 3.1b shows two sets of emission pathways for stabilizing concentrations at 550ppmv. The burden sharing rule (Table 3.1) will determine how emissions might be apportioned between regions. The results are summarized for three broad groups of countries: 1) the OECD (USA, Western Europe, Japan, Canada, Australia and New Zealand), 2) EEFSU (Eastern Europe and the former Soviet Union) and 3) developing countries. In the language of the Framework Convention, the first two groups are described as Annex 1 countries. All others (the developing countries) are non-Annex 1 countries.

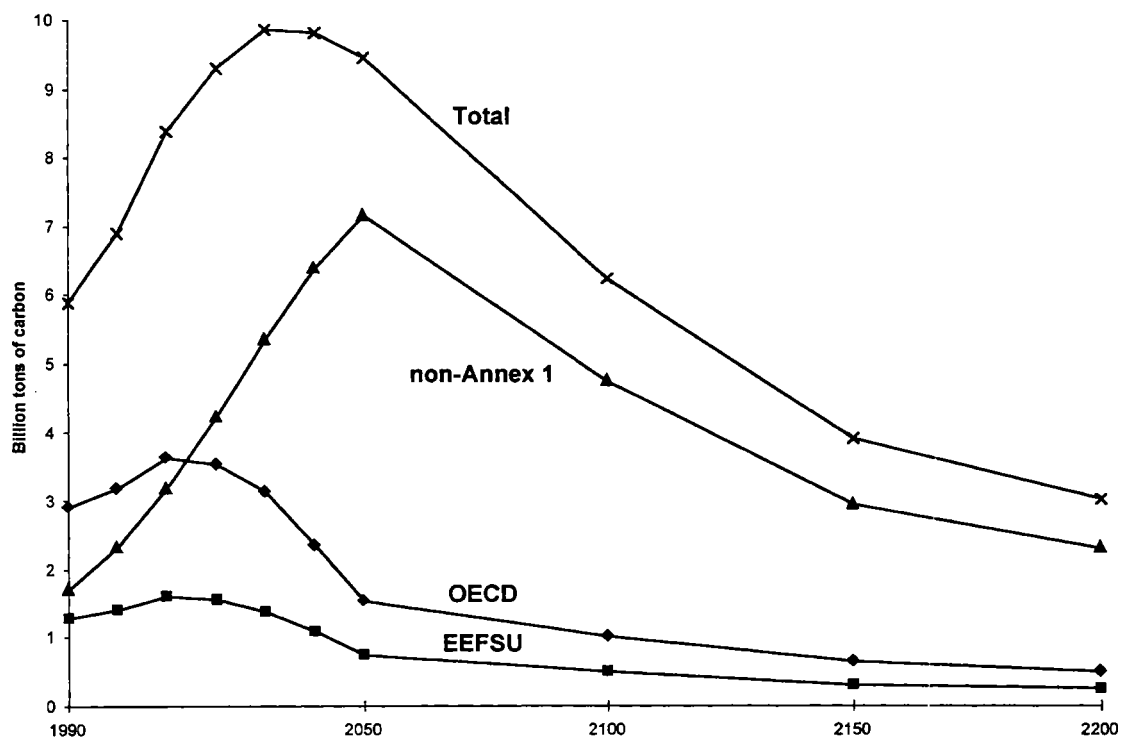
Figure 4.1 shows the implications of the burden sharing rule for these three regional groupings. The figure provides some insight into both global and regional costs. Under the WRE scenario, Annex 1 countries have some room for emissions growth, at least during the early decades of the 21st century. This is not the case, however, under the WG1 scenario. Here, Annex 1 emission reductions must begin immediately. This decline would be inconsistent with post-1990 trends in all but a few countries.

Figure 4.2 compares mitigation costs over the 21st century. Consumption losses are expressed in constant dollars, discounted to 1990 at 5% per year. Notice that costs are considerably lower for the WRE pathway. There are several reasons why this turns out to be the case. A concentration target defines an emissions budget, i.e., an allowable amount of carbon to be released between now and the date at which the target is to be achieved. A cost-effectiveness analysis is focused upon how this global budget might be allocated over time.

Figure 4.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

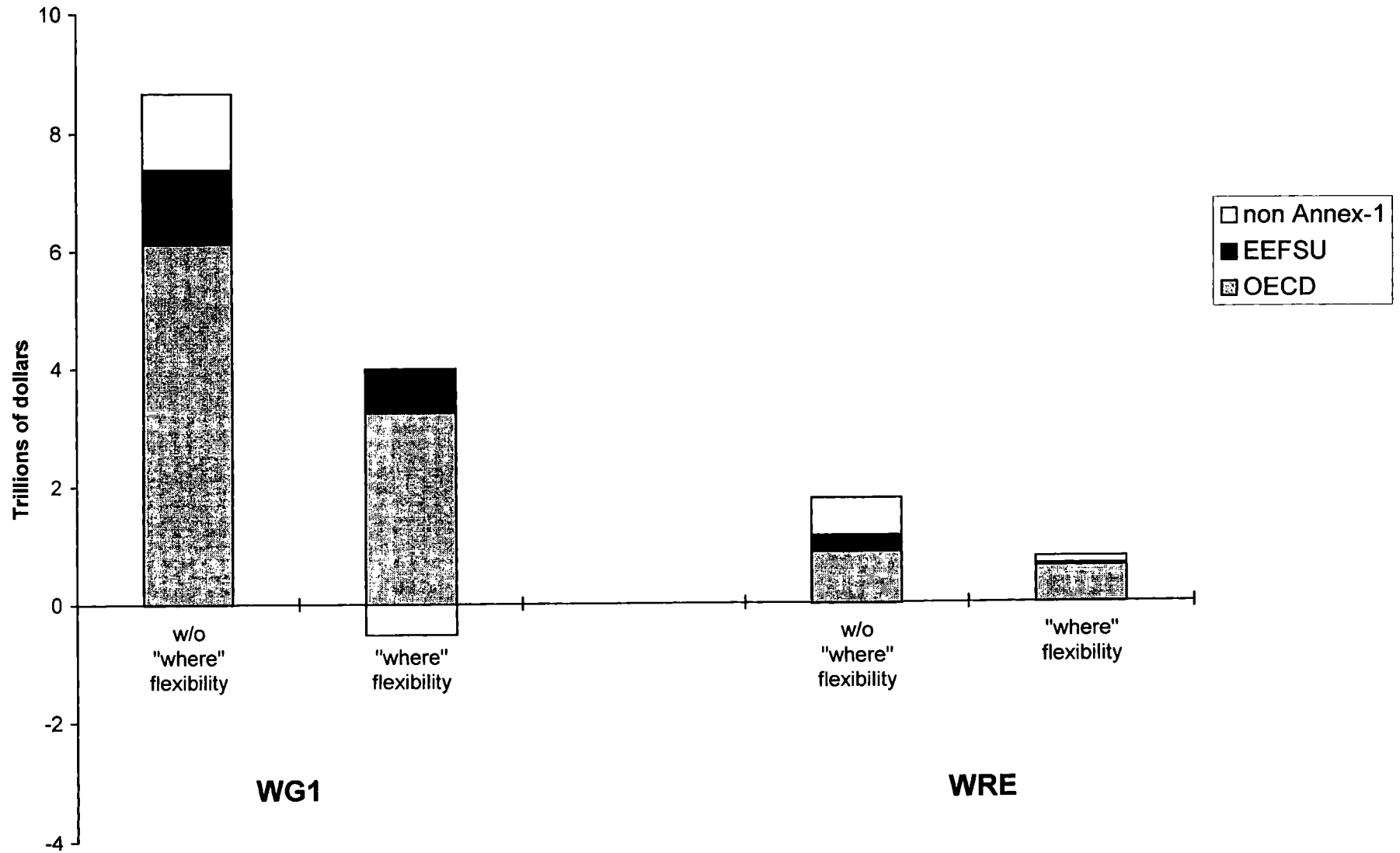


a) WG1



b) WRE

Figure 4.2 Regional Costs of Stabilizing Concentrations at 550ppmv
-- discounted to 1990 at 5%



Shifting emission reductions into the future provides valuable time for: 1) adapting the energy using and energy producing capital stock, 2) developing low cost substitutes to carbon intensive fuels, and 3) removing carbon from the atmosphere via the carbon cycle. In addition, with the economy yielding a positive return on capital, future reductions can be made with a smaller commitment of today's resources. For a more detailed discussion of these factors, see ref. (11).

Figure 4.2 also estimates the benefits from international cooperation. Without "where" flexibility, the immediate emission reductions are confined directly to the Annex 1. The more countries that participate in an international agreement, the greater become the opportunities for cost-effective trades. It then becomes possible for countries with high marginal abatement costs to purchase emission rights from countries with low marginal abatement costs.

From a global perspective, combining "where" flexibility with a more gradual transition away from fossil fuels substantially reduces the present value of mitigation costs. It turns out that there can be cost reductions as high as 90% when we combine both types of flexibility. (Compare the leftmost to the rightmost bar in Figure 4.2.) The discounted cost savings to the international community appear to be of the order of trillions of dollars over the 21st century. This is consistent with earlier studies which focused exclusively on near-term targets and timetables.^{18,19}

Table 3.1 describes a burden sharing rule that is particularly favorable to the non-Annex 1 countries during the early decades of the next century. This is why the mitigation costs are lowest for non-Annex 1 countries under the WG1 pathway when we allow for "where" flexibility. Indeed, the WG1 emission constraints creates a sufficiently high price for emission rights and high wealth transfers during the early decades of the coming century so that the non-Annex 1 countries are actually better off in the presence of a carbon constraint than in its absence. This particular result should not, however, obscure the fact that from a global perspective, costs are far lower under the WRE pathway.

5. Annual losses when stabilizing concentrations at 550ppmv

Figure 4.2 summarizes abatement costs in terms of discounted present value -- summing over all time periods. Additional insights can be gained by looking at how losses might evolve over time. In MERGE, we adopt consumption as our welfare measure. Relative impacts are more apparent when we measure annual losses in percentage rather than absolute dollar terms.

Figure 5.1 International Price of Crude Oil

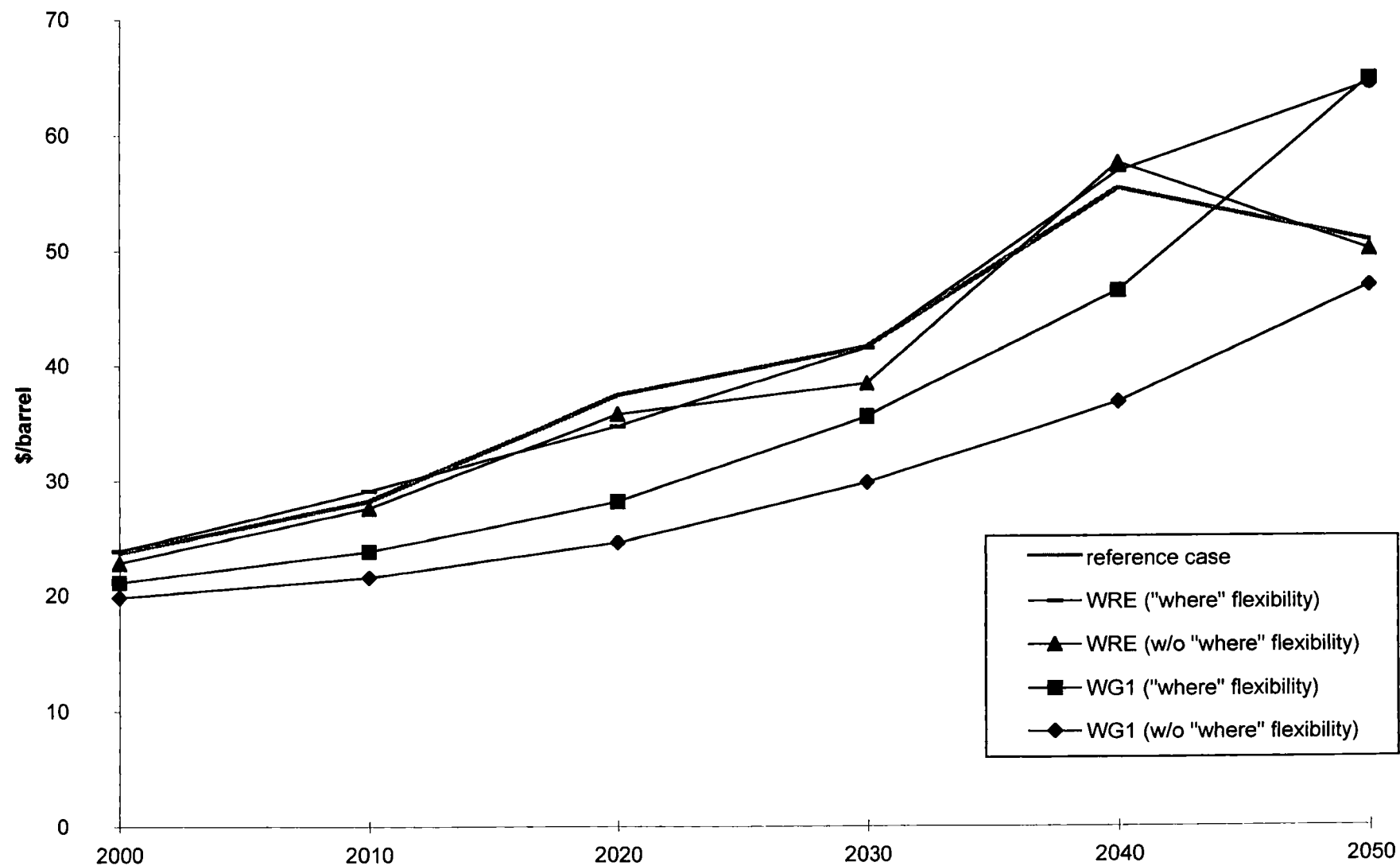
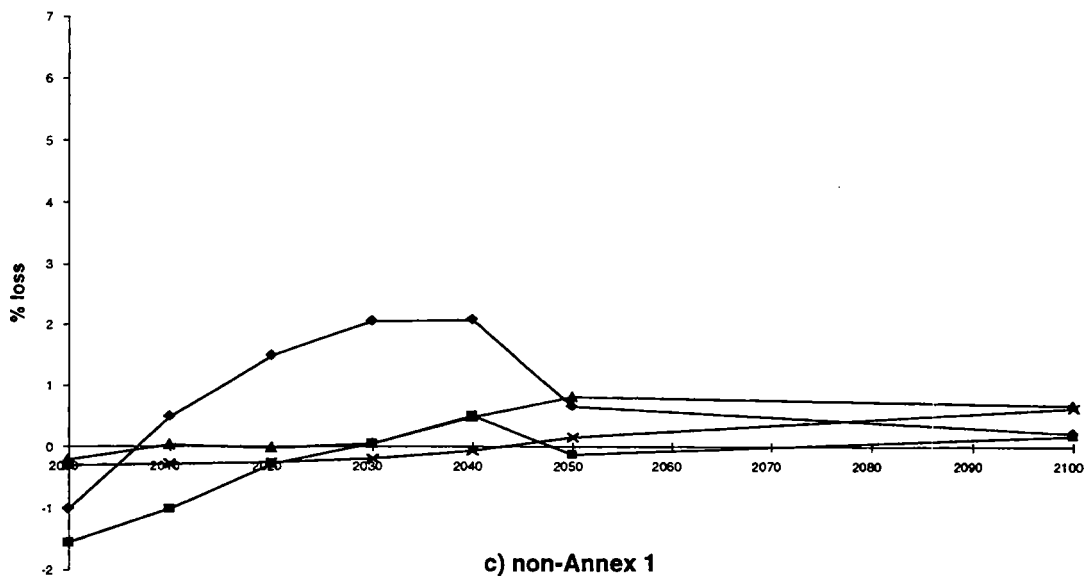
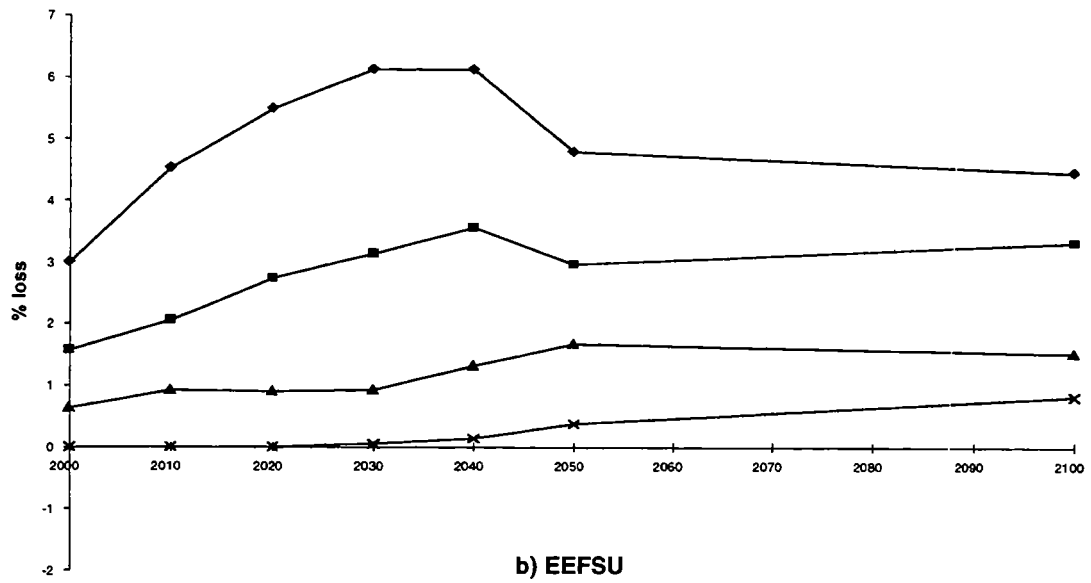
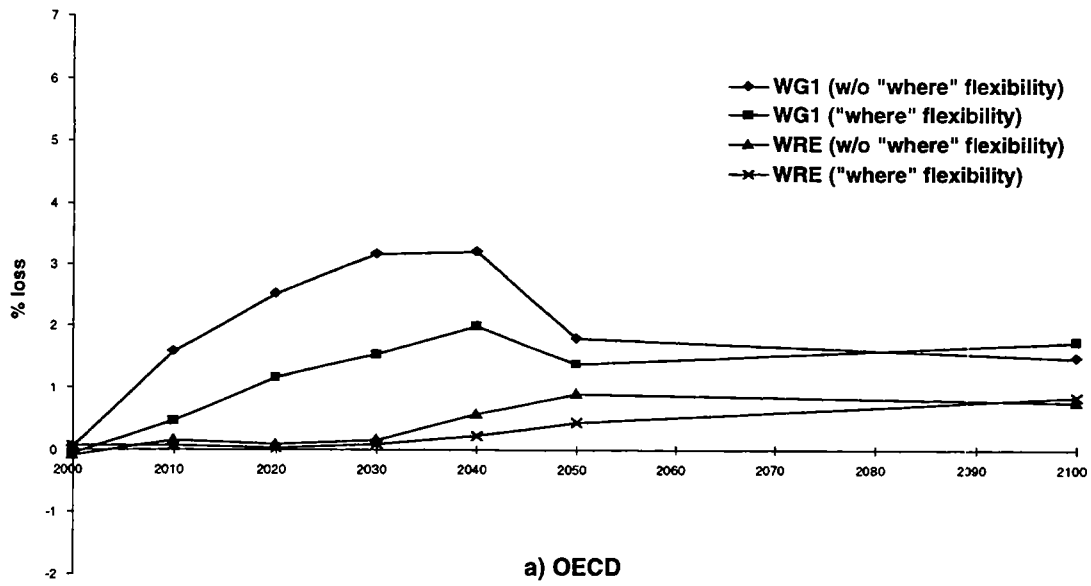


Figure 5.2 Annual % Consumption Losses



In order to explain the pattern of annual losses, it is first necessary to say something about the impact of a carbon constraint on world oil prices. A carbon constraint would have roughly the same consequence as monopsonistic cartel behavior on the part of oil importing nations.

Figure 5.1 shows the international price of oil for the reference case and under the alternative pathways for stabilizing concentrations at 550ppmv. Note that oil prices are quite sensitive to the pathway to stabilization. With a tight near-term constraint, there is a drop in the international demand for crude oil. This has a dramatic effect on oil prices. There can be a differential of as much as \$20 per barrel between the reference and the WG1 cases. This has important implications for the costs of a carbon constraint to both oil exporting and oil importing countries.

Figure 5.2 compares annual welfare losses across scenarios for each of the three broad regional groupings. Under WG1, the Annex-1 countries must begin reducing emission immediately. Losses are highest when there is no opportunity for trading emission rights. Losses rise to more than 3% and 6% of annual consumption for the OECD and EEFSU, respectively. As a major importer of oil, the OECD benefits from the decline in world oil prices. Hence, its losses are partially mitigated. EEFSU, on the other hand, is a substantial exporter. As a result, it will be adversely affected by a drop in world oil prices, and this compounds its losses from a near-term carbon constraint.

The non-Annex 1 region consists of both oil exporting and oil importing countries. Under the burden sharing scheme described in Table 3.1, the WG1 proposal leads to substantial net benefits in the early years, particularly with "where" flexibility. A tight near-term global emissions constraint would create a large demand for emission rights in Annex 1 countries. Since non-Annex 1 countries have carbon allocations up to their baseline emissions, it is in their interest to engage in domestic abatement, and to sell some of their rights to Annex 1 countries.

With the parameters employed in this version of MERGE, there is a net benefit to the non-Annex 1 countries, even without "where" flexibility. The oil importers gain more than the oil exporters lose from the decline in world oil prices. Eventually, however, the region will become a net loser unless it is able to sell emission rights to Annex 1 countries.

6. The least-cost mitigation pathway -- 550ppmv

The WG1 emission pathways were meant to be purely illustrative. No attempt was made to determine whether they represented an efficient transition away from fossil fuels. WRE, on the other hand, drew upon the insights of earlier studies in constructing their emission pathways. They

Figure 6.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

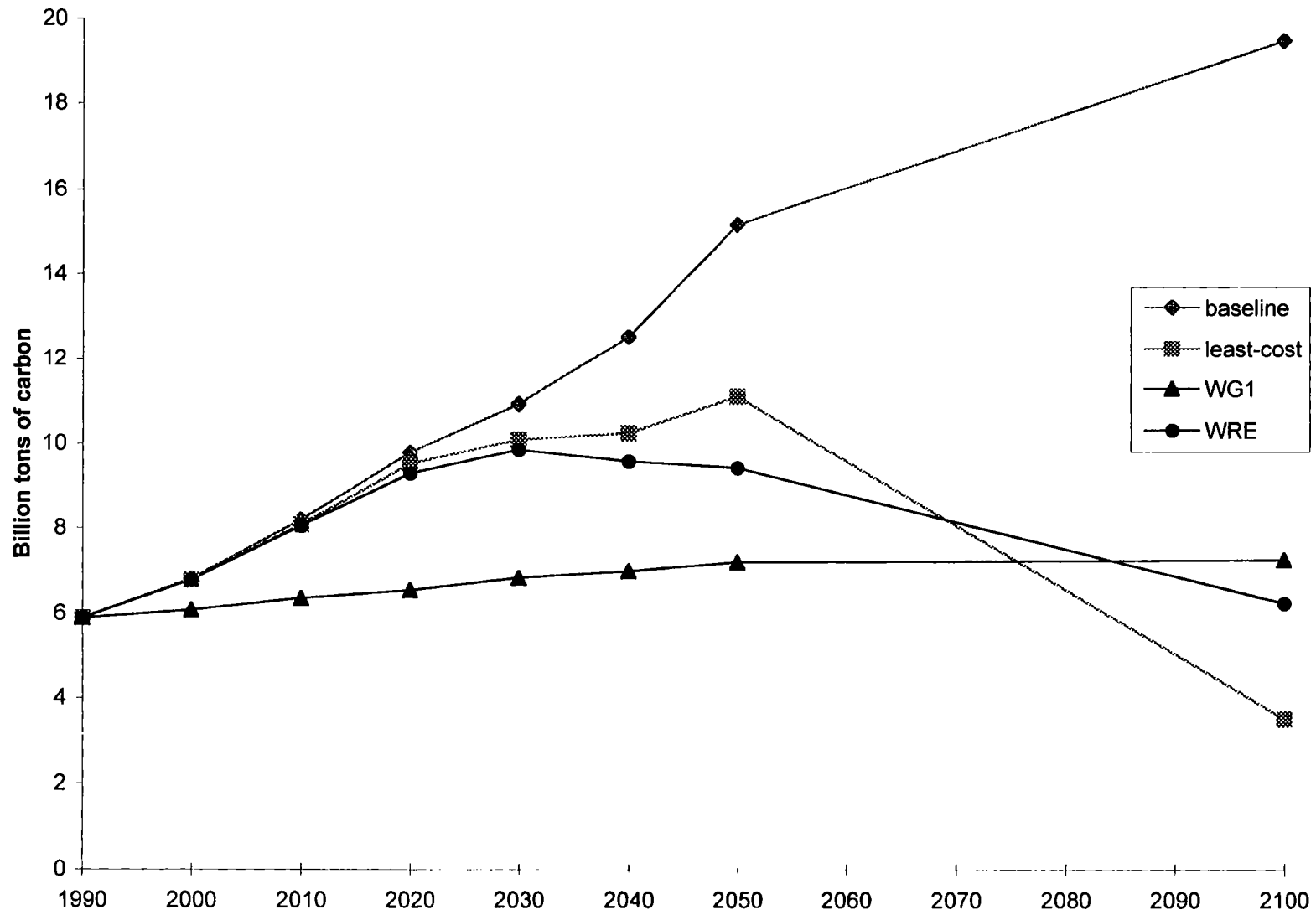


Figure 6.2 Global Costs of Stabilizing Concentrations at 550ppmv
-- discounted to 1990 at 5%

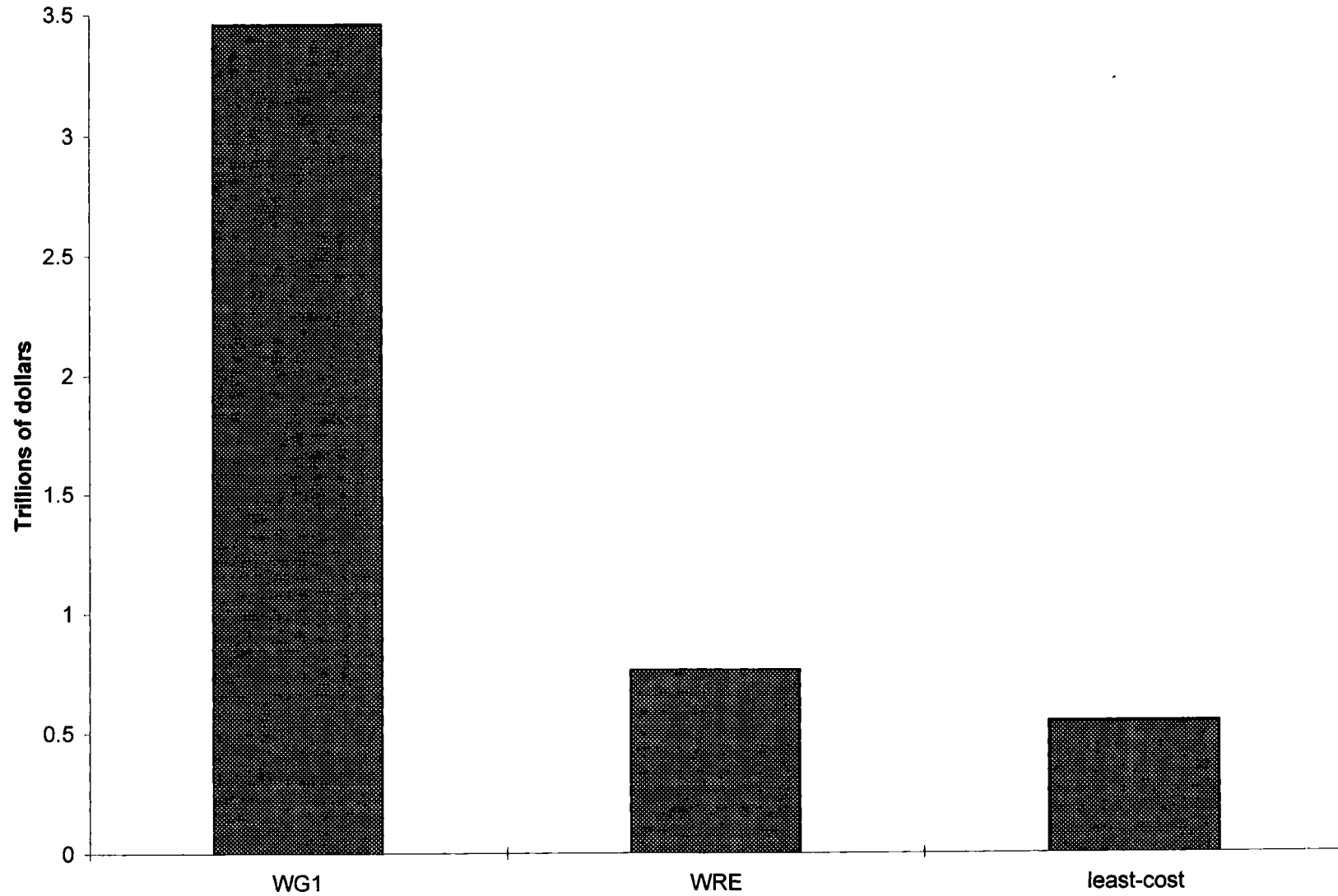
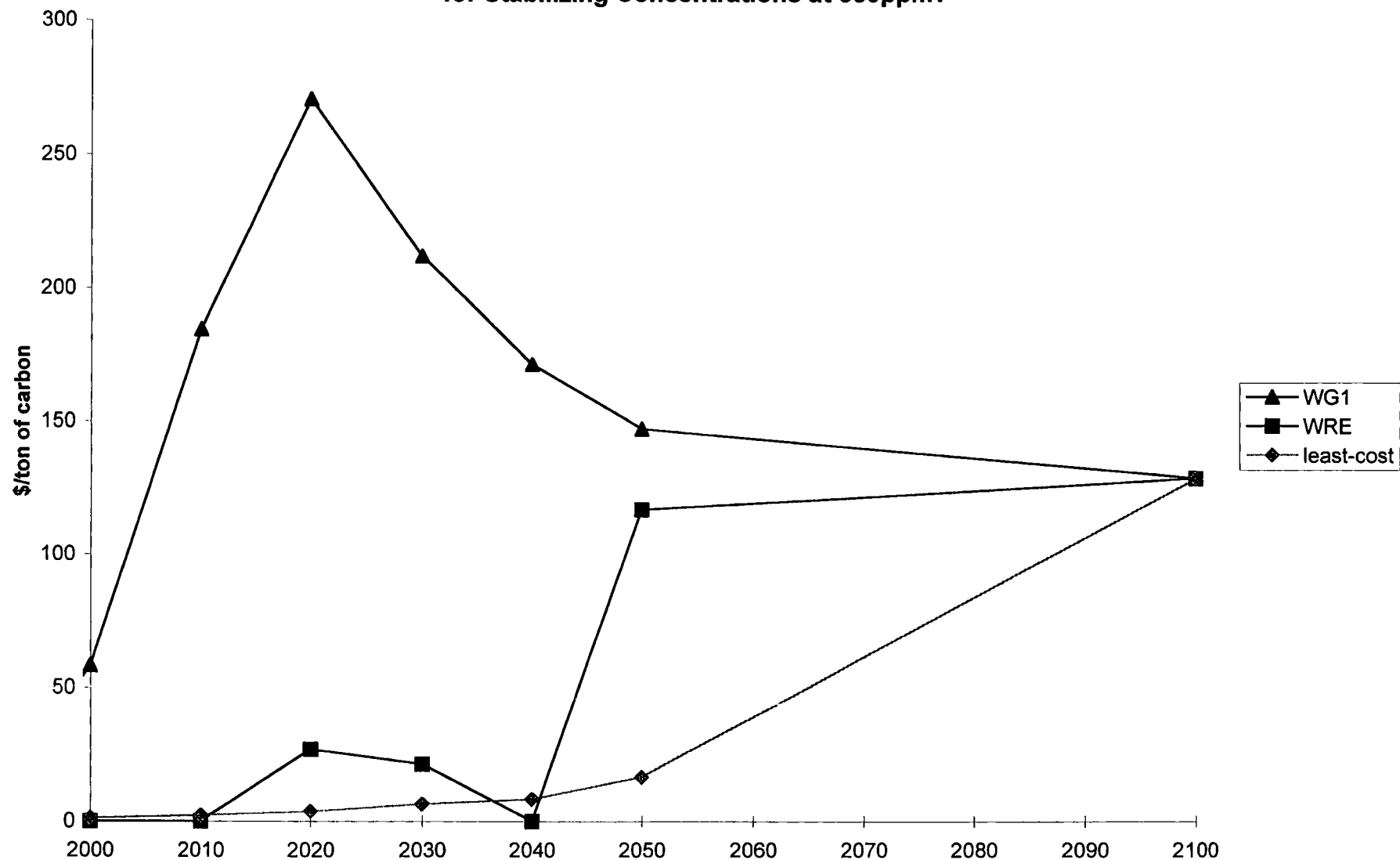


**Figure 6.3 Value of Carbon Emission Rights with Alternative Pathways
for Stabilizing Concentrations at 550ppmv**



argued that allowing more time for the transition would lower mitigation costs. They did not attempt to quantify the savings from choosing one path over another. Nor did they try to identify the least-cost mitigation pathway.

In the preceding sections, we analyzed the mitigation costs associated with the WG1 and WRE pathways. We now turn to the question of what might constitute a least-cost mitigation pathway for stabilizing concentrations at 550ppmv. For these calculations, we use MERGE 3.0. Rather than apply a carbon constraint derived through inverse calculations with the Wigley carbon cycle model, we now place a constraint on atmospheric concentrations and use the model to identify the least-cost mitigation pathway.

Note from Figure 6.1 that the least-cost and WRE pathways for stabilizing concentrations at 550ppmv lie fairly close together, at least in the early years. That is, they tend to follow the emissions baseline during the first decade of the next century and then depart gradually. Figure 6.2 shows the results in terms of discounted present value. In each case, we assume trade among all regions. As would be expected from the previous figure, the WRE and least-cost cases are also close in terms of costs.

The cases differ dramatically, however, in terms of the value of carbon emission rights. From Figure 6.3, we see that the least-cost path starts off at a low price (approximately \$2/ton of carbon) and rises gradually over time. The WRE case leads to an erratic time path of carbon prices. Indeed, in some years there is an excess of emission rights. As a result, their value falls to zero. In other years, their value exceeds that of the least-cost optimal emissions reduction path.

7. The costs of stabilizing concentrations at alternative levels

The selection of the 550ppmv target was purely arbitrary and not meant to imply an optimal concentration level. Given the present lack of consensus on what constitutes “dangerous” interference with the climate system, it is important to understand how mitigation costs might vary with alternative concentration targets.

Figure 7.1 summarizes the results of the MERGE analysis. As would be expected, mitigation costs are a declining function of the stabilization target. Recall that a concentration target places an upper limit on the amount of CO₂ to be released into the atmosphere between now and the date at which the target is to be achieved. This in effect defines an emissions budget. The lower the target, the smaller the emissions budget.

Figure 7.2a shows the constraint on Annex 1 emissions during the initial decades of the next century under the WG1 scenario. In the absence of

Figure 7.1 Mitigation Costs for Stabilizing Concentrations at Alternative Levels
-- discounted to 1990 at 5%

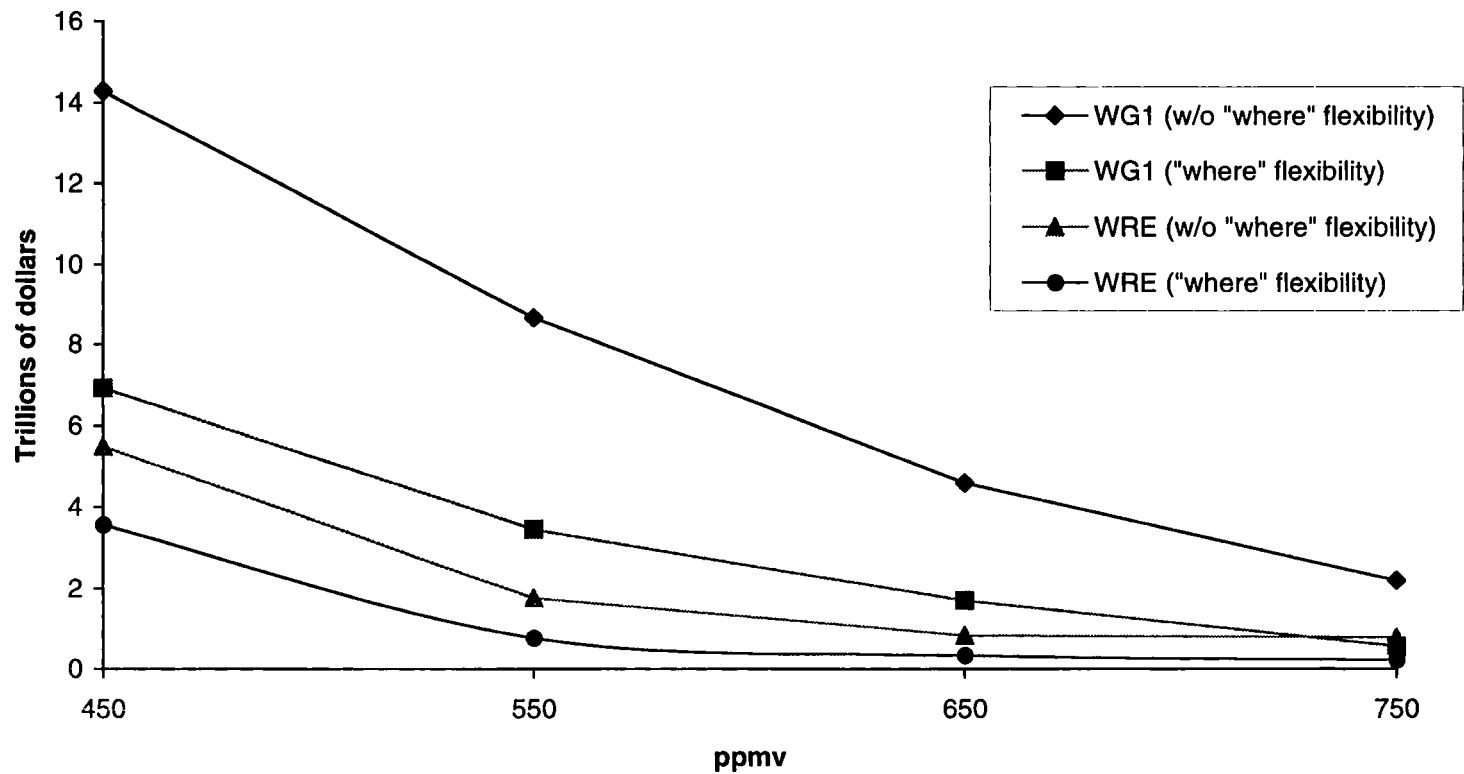
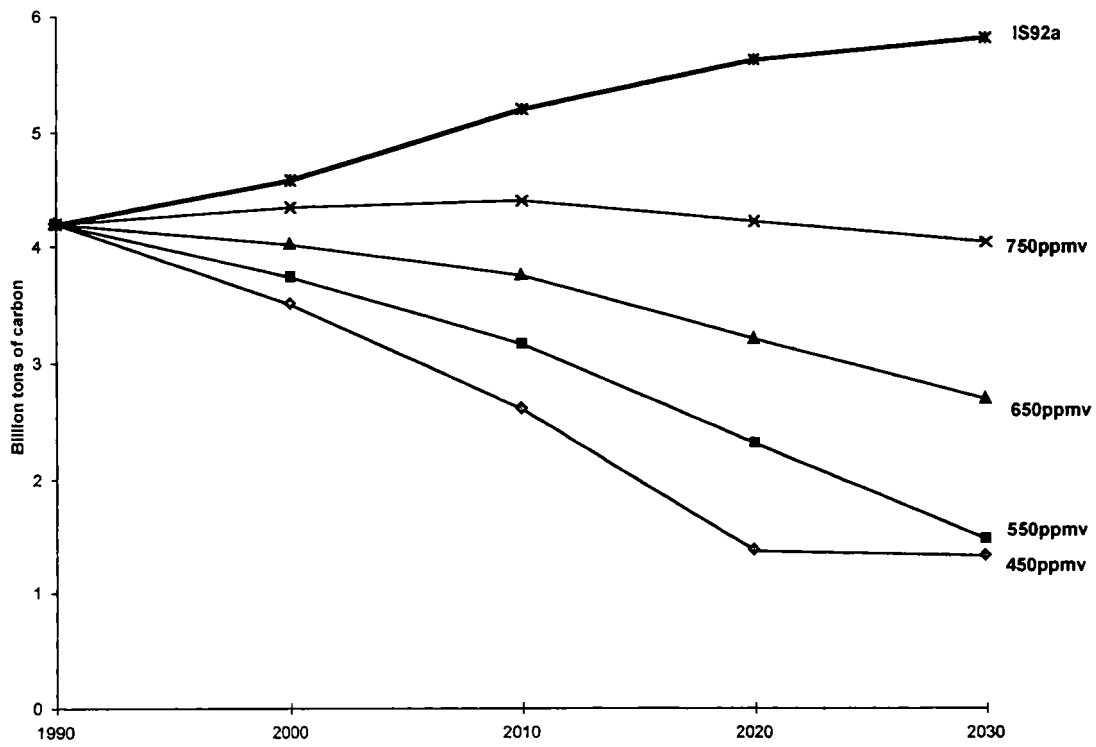
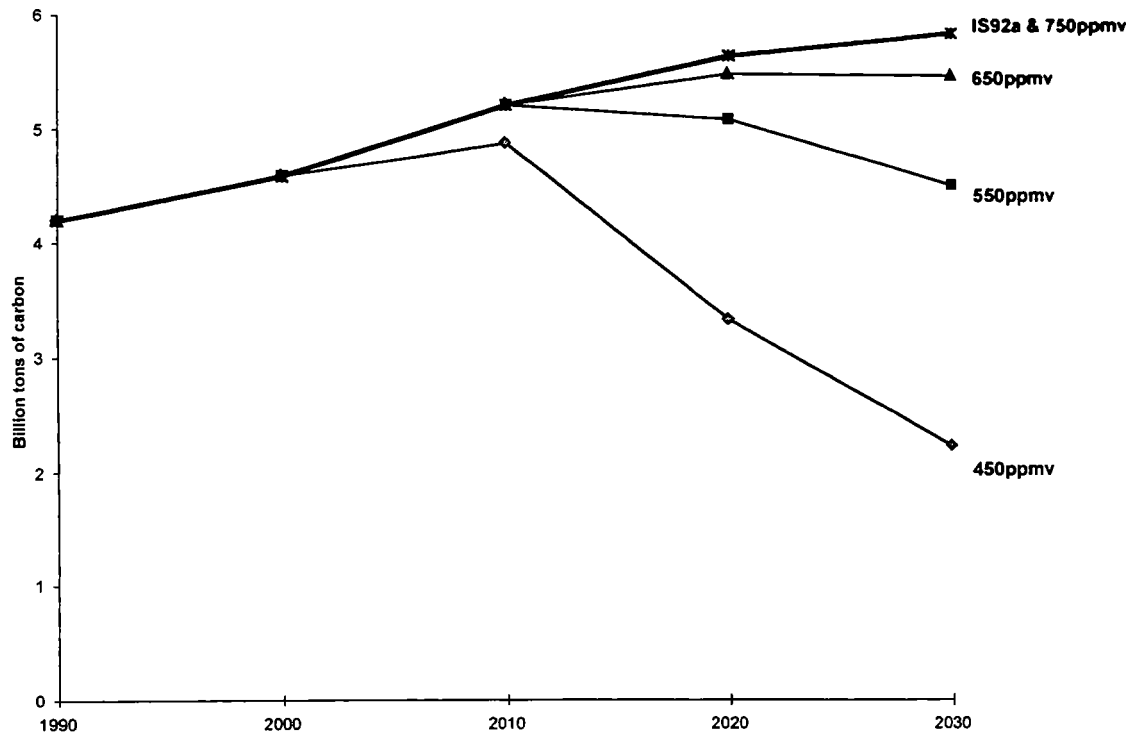


Figure 7.2 Annex 1 Emission Constraints under Alternative Concentration Targets



a) WG1



b) WRE

“where” flexibility, this becomes an effective upper bound on emissions. The figure provides useful insights into the shape of the abatement cost curve. Relative to higher targets, 450ppmv implies that: 1) more carbon must be removed from the energy system, 2) there is greater need to reconfigure the existing energy using and energy producing capital stock, 3) low-cost substitutes are likely to be available in a less timely manner, and 4) there is less opportunity for discounting to reduce the present value of mitigation costs. As the concentration constraint is relaxed, each of these factors acts to lower costs.

The costs of complying with WG1 are substantially reduced when we allow for “where” flexibility. Annex 1 countries are able to purchase lower marginal cost abatement alternatives from non-Annex 1 countries. As a result, the need is not as intense for early reductions.

WRE produces the lowest mitigation cost possibilities. The asymmetry in the cost function between 450 and 550ppmv suggests that even with WRE, the low target will provide insufficient time to adapt the existing capital stock. From Figure 7.2b, note that a 450ppmv target would require a departure from the baseline during the first decade of the next century, and there would be an even more rapid departure thereafter. With targets of 550ppmv and above, there is time for a more gradual transition away from carbon-intensive fuels.

8. The choice of near-term mitigation strategy

Figure 7.2b provides some useful guidance for the design of near-term emission strategies. If it is certain that the target is 550ppmv or above, the near-term emissions path appears to be quite robust. That is, it adheres fairly closely to the emissions baseline through 2010. It should be noted, however, that even in this case, there is some transition away from the world’s current heavy dependence on carbon-intensive technologies prior to 2010. That is, inexpensive alternatives (e.g., renewables and cost-effective conservation) are introduced in increasing amounts - both on the supply and demand sides of the energy sector. However, if these alternatives are economically attractive in their own right, they will be adopted in the absence of climate policy.

Suppose, on the other hand, that one believes there is some probability that the target is in the 450 to 550ppmv range. A more aggressive departure from the emissions baseline will be required. The degree of hedging depends upon the probabilities and the relative costs of two types of errors in the design of future capital stocks. That is, one must balance the risks of investing in capital stocks that lead to carbon emissions that are either too high or too low.

Of course, the choice of emission pathway for meeting a prescribed concentration target must also involve consideration of the environmental

consequences of adopting one emission trajectory over another. The WRE emission pathways result in higher concentrations in the years preceding the date by which the target is to be achieved. For the 550ppmv case, the higher concentrations lead to pathway related differentials of up to .2 degrees C in global mean temperature and 4cm in global mean sea level change (ref. 11). To the extent that this leads to higher environmental damages, these need to be balanced against the benefits from reduced mitigation cost.

9. Some concluding comments

The above analysis suggests that a more gradual transition away from fossil fuels is likely to be less expensive in terms of mitigation costs. This should not be interpreted as suggesting a "do nothing" or "wait and see" strategy. Mitigation may mean action, but action does not necessarily mean mitigation. As pointed out in the IPCC 1995 Report²⁰, climate policy requires a portfolio of responses. The challenge facing today's policy makers is to arrive at a prudent hedging strategy in the face of climate-related uncertainties. Among the options are

- immediate reductions of greenhouse gas emissions,
- investments in actions to assist human and natural systems adapt to climate change should it occur,
- continued research to reduce uncertainties about how much change will occur and what effects it will have, and
- R&D on energy supply and end-use technologies to reduce the costs of limiting greenhouse gas emissions.

The issue is not one of either-or but one of finding the right blend of options. Policy makers must decide how to divide greenhouse insurance dollars among these competing needs.

The present analysis has provided some useful insights bearing on this decision. Deep near-term reductions are apt to be costly. They provide less time to adapt the existing capital stock. There will be more opportunities for reducing emissions cheaply as the current capital equipment turns over. Indeed, the 1995 IPCC report states that "implementing emission reductions at rates that can be absorbed in the course of normal capital stock turnover is likely to be cheaper than forcing premature retirement now."²¹

Fortunately, with regard to carbon dioxide, the issue is one of cumulative rather than year-by-year emissions. This means that we can allow for an economical turnover of the existing capital stock if we are prepared to make sharper reductions in the future.

This brings us to the issue of R&D. Sharper reductions in the future will be less problematic if we can lower the costs of fuel switching and conservation. Indeed, studies by Stanford University's Energy Modeling Forum suggest that the development of economically competitive alternatives to conventional fossil fuels could substantially reduce the costs of a carbon constraint.²²

Although virtually all parties in the debate recognize the value of R&D, we have yet to develop a technology strategy for dealing with global climate change. How much should we be investing today to ensure ample supplies of low-cost alternatives in the future? What should be the nature of these investments, who would make them, and how would they be managed? Given the size of the stakes, surprisingly little attention has been devoted to these questions.

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