On stabilizing CO_2 concentrations – cost-effective emission reduction strategies

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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 CO_2 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" [3]. 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 [15].

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 CO_2 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 CO_2 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 [5]. 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 [1]. It will, however, have profound effects 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" [3]. 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 [8,9]. The present version of the model, known as MERGE 3.0, divides the world into nine regions:

(1) the USA,

(2) OECDE (Western Europe),

(3) Japan,

(4) CANZ (Canada, Australia and New Zealand),

(5) EEFSU (Eastern Europe and the former Soviet Union),

(6) China,

(7) India,

(8) MOPEC (Mexico and OPEC), and

(9) ROW (the rest of world).

The further disaggregation provides better alignment with the Annex 1/non-Annex 1 structure of the Framework Convention. The OECD (regions 1–4) together with EEFSU constitute Annex 1. The further disaggregation also 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 [11]. 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 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.

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 IS92a [4] scenario through the year 2100. Figure 2 shows carbon emissions for the OECD, EEFSU and non-Annex 1. Figure 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
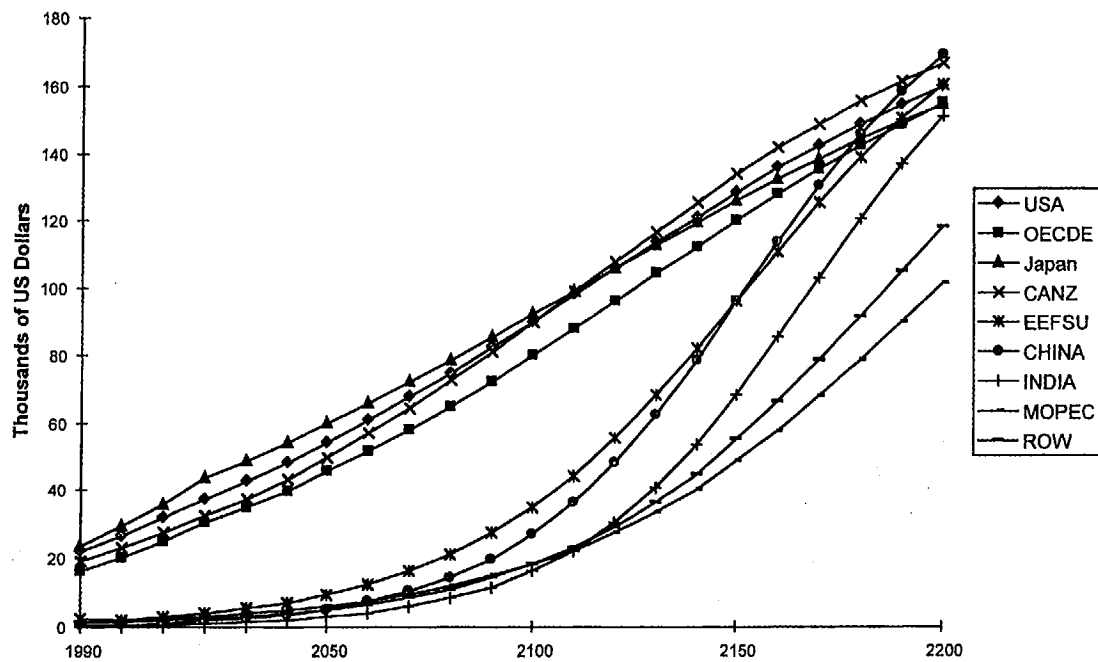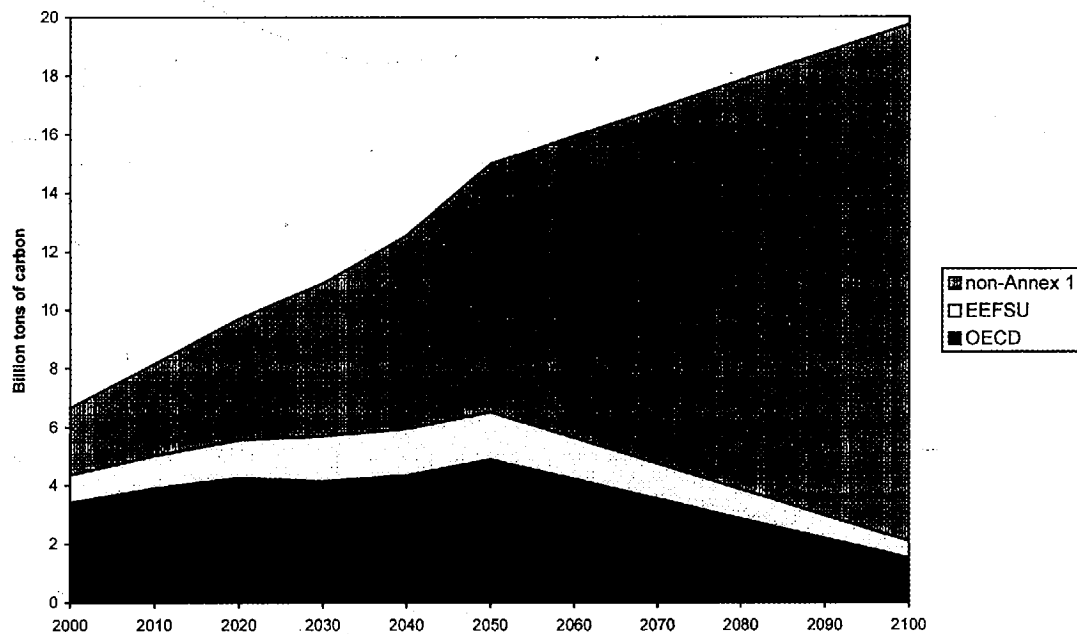
Figure 1. Per capita GDP.

Figure 2. Regional carbon emissions – basecase.

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.

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.

3.1. 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
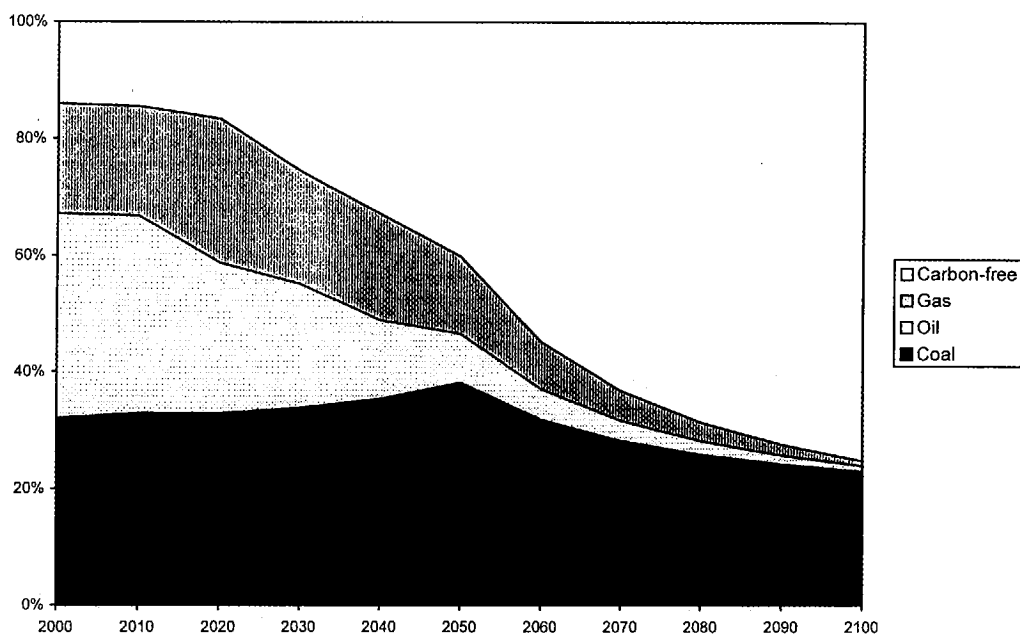
Figure 3. Total primary energy use -- basecase.

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 atmospheric CO₂ at 350, 450, 550, 650 and 750 ppmv [5]. 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 [16]. Although WG1 and WRE are identical in terms of the prescribed stabilization levels and attainment dates, they differ in the routes to stabilization (figure 4a). The IPCC, while not taking a position on the desirability of one set over another, published both in their 1995 scientific assessment [6].

Figure 4b 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 [7,9,12,13]. 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 750 ppmv, 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.

3.2. The extent of international cooperation

A number of studies have shown that the marginal costs of emissions abatement might vary considerably among regions [6]. 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 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 miti-

(a) Alternative concentration profiles

(b) Alternative fossil fuel emission paths
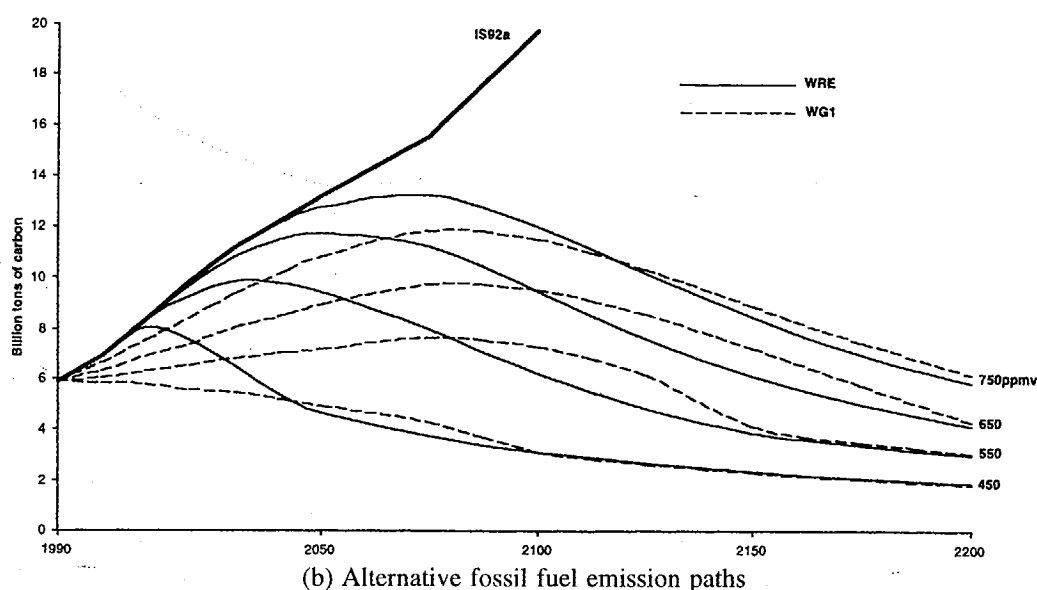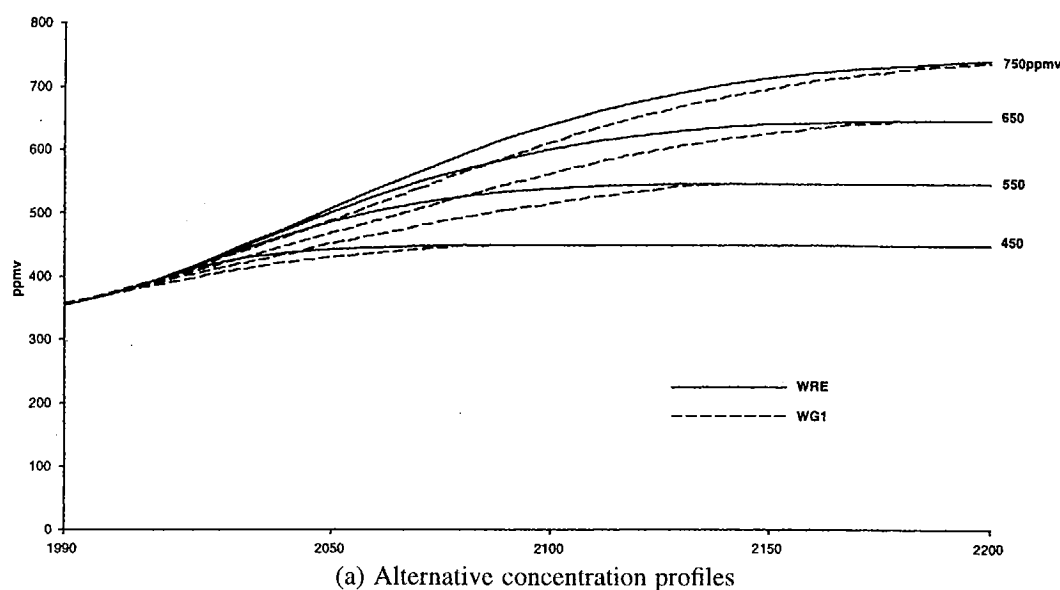
Figure 4. Alternative routes to CO_2 stabilization.

gation 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.

3.3. 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

Table 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

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 1.)

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 550 ppmv

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 550 ppmv – approximately twice the preindustrial level. Later, we will explore the implications of adopting alternative concentration targets.

Figure 4b shows two sets of emission pathways for stabilizing concentrations at 550 ppmv. The burden sharing rule (table 1) will determine how emissions might be apportioned between regions. The results are summarized for three broad groups of countries: the OECD, EEFSU and non-Annex 1.

Figure 5 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 6 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 [16].

Figure 6 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 rightmost bar in figure 6.) 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 [10,14].

Table 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 create a high price for emission rights and high wealth transfers (as high as 1.5% of GDP for the OECD countries in some periods). During the early decades of the coming century, the non-Annex 1 countries are actually better off in the presence of a carbon constraint than in its absence. This particular result
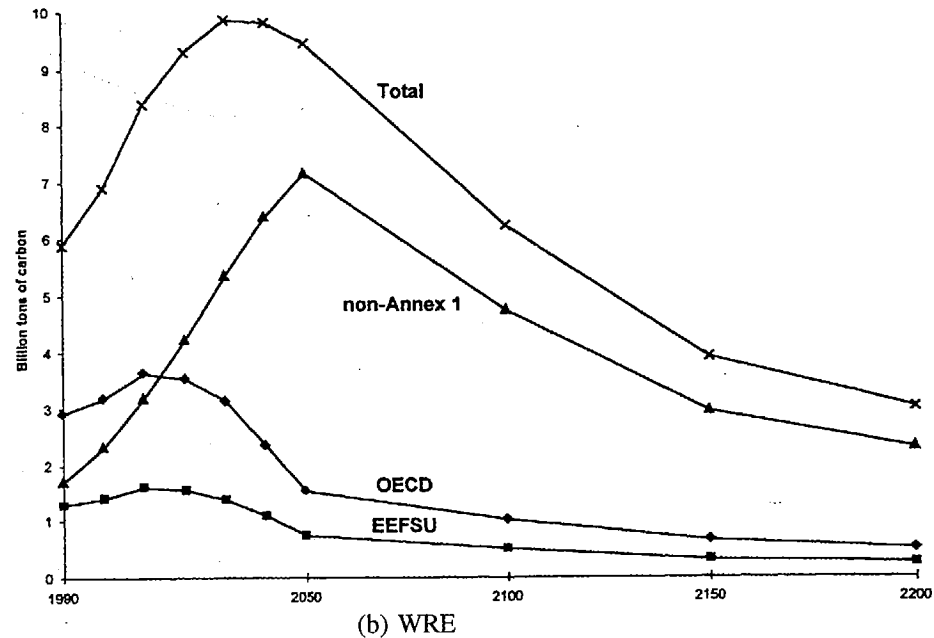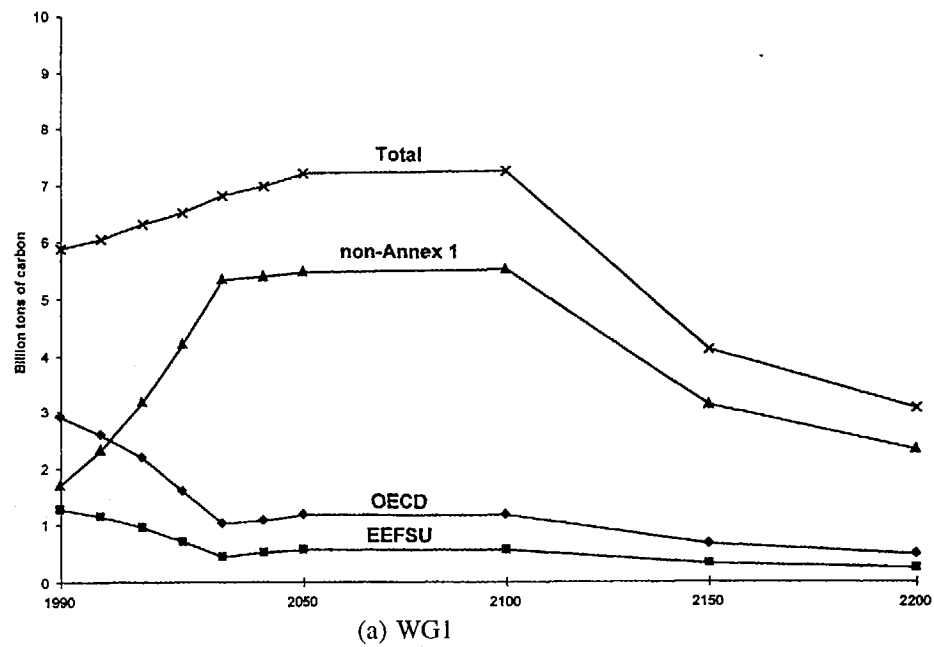
(a) WG1

(b) WRE

Figure 5. Alternative emission pathways for stabilizing concentrations at 550 ppmv.

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 550 ppmv

Figure 6 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 7 shows the international price of oil for the reference case and under the alternative pathways for stabilizing concentrations at 550 ppmv. 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
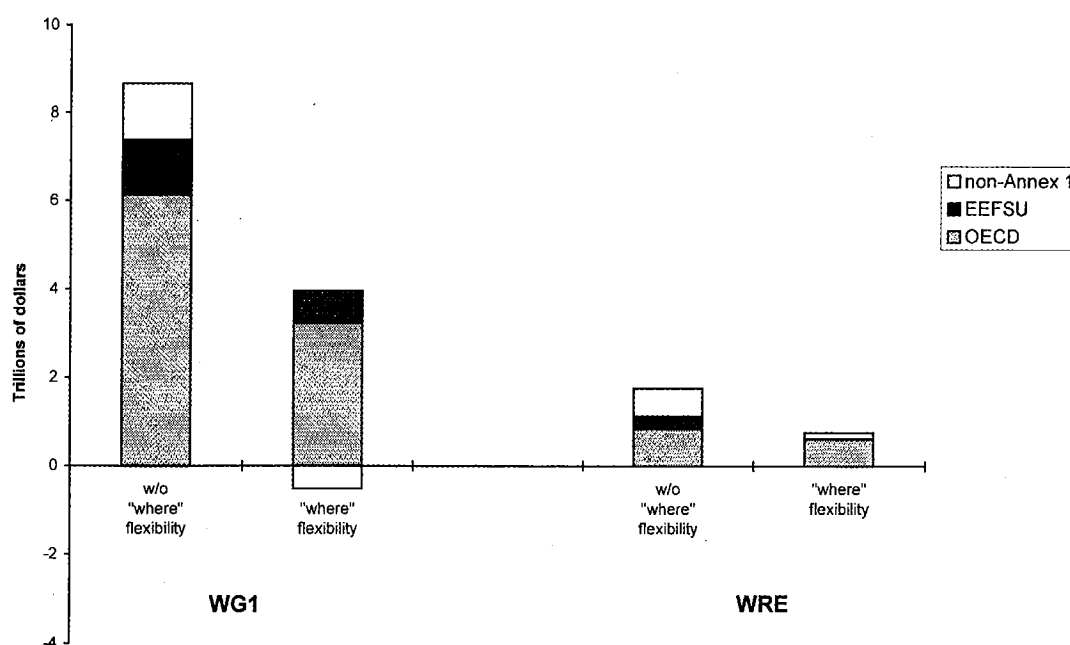
Figure 6. Regional costs of stabilizing concentrations at 550 ppmv – discounted to 1990 at 5%.
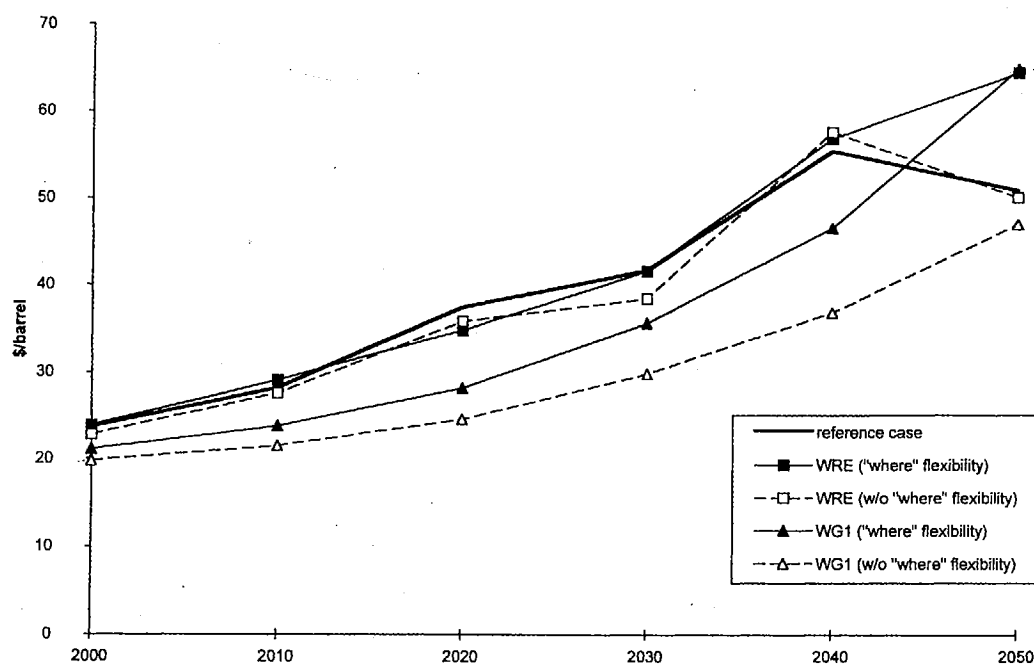

Figure 7. International price of crude oil.

constraint to both oil exporting and oil importing countries.

Figure 8 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, 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 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.
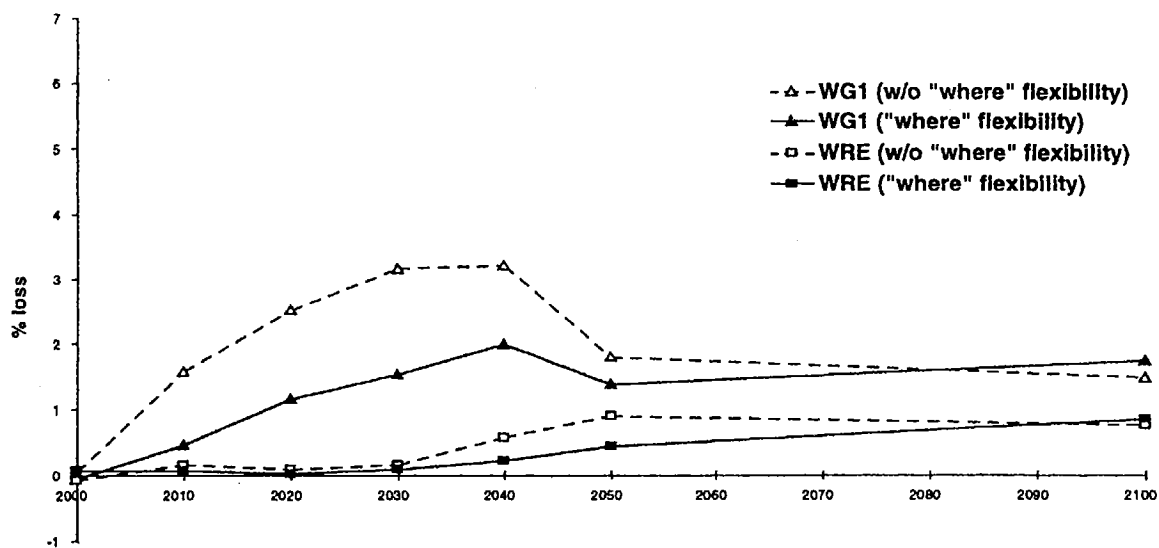
(a) OECD
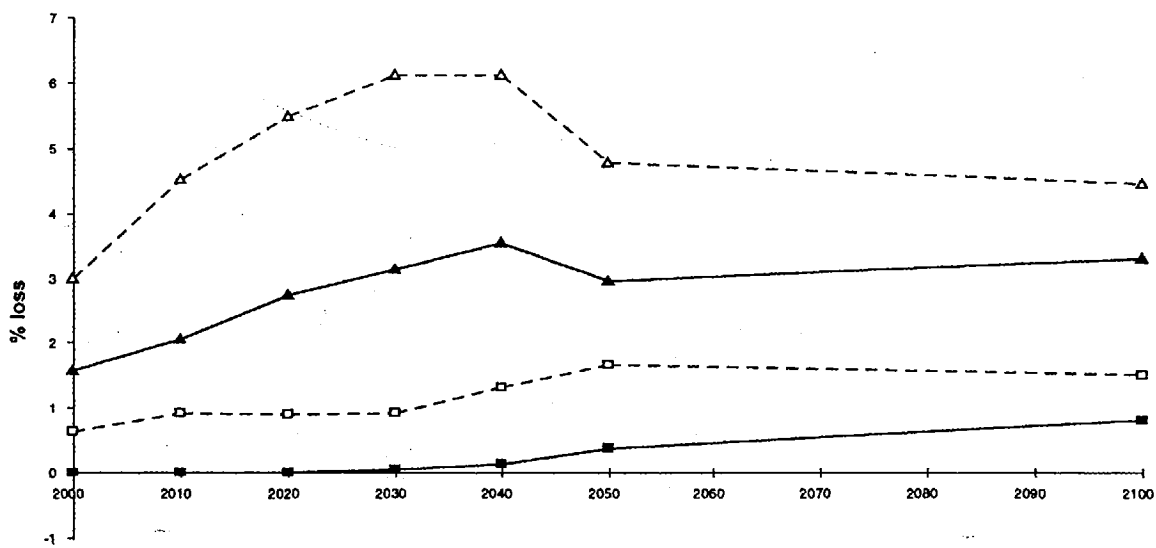
(b) EEFSU
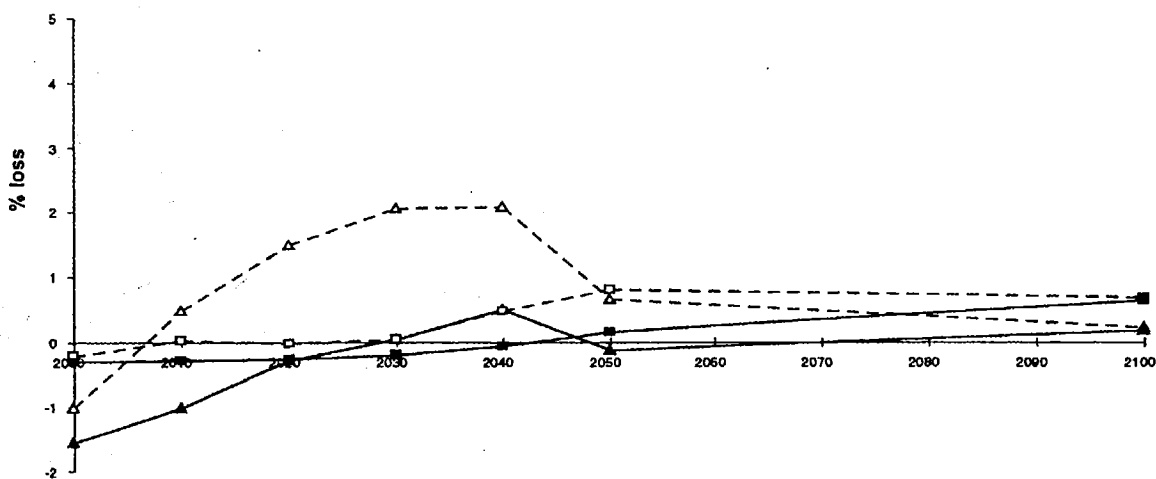
(c) non-Annex 1

Figure 8. Annual consumption losses (%).

With the parameters employed in this version of MERGE there is initially 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 – 550 ppmv

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, however. 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 550 ppmv. 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 9 that the least-cost and WRE pathways for stabilizing concentrations at 550 ppmv 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 10 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 11, 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 550 ppmv 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 12 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 CO_2 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 13 provides useful insights into the shape of the abatement cost curve. Figure 13a 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. Relative to higher targets, 450 ppmv 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 450 ppmv. Each of these factors acts to raise 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. There is a higher absolute cost reduction at 450 than at 550 ppmv. The asymmetry in the cost function suggests that even with WRE, the low target will provide insufficient time to adapt the existing capital stock. From figure 13b, note that a 450 ppmv 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 550 ppmv and above, there is time for a more gradual transition away from carbon-intensive fuels.

8. The choice of near-term mitigation strategy

Figure 13b provides some useful guidance for the design of near-term emission strategies. If it is certain that the target is 550 ppmv 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 450–550 ppmv
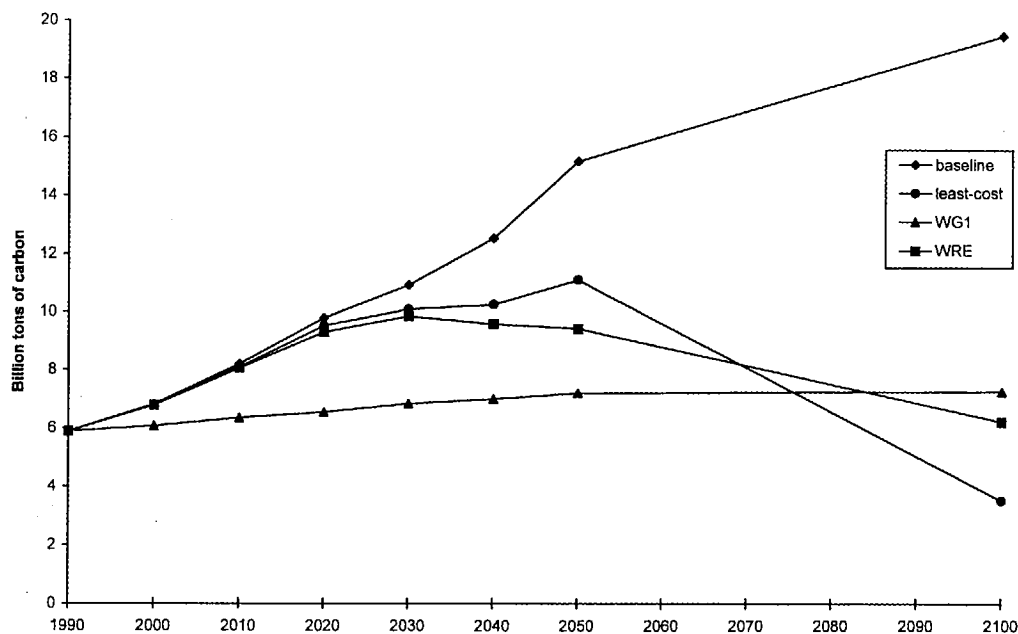
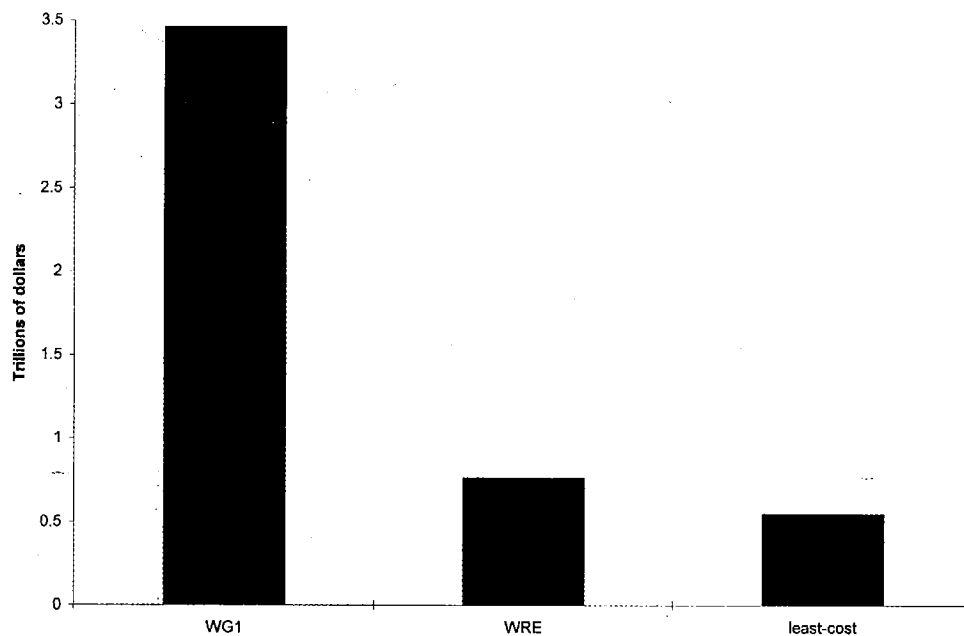Figure 9. Alternative emission pathways for stabilizing concentrations at 550 ppmv.

Figure 10. Global costs of stabilizing concentrations at 550 ppmv – discounted to 1990 at 5%.

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

550 ppmv case, the higher concentrations lead to pathway related differentials of up to 0.2°C in global mean temperature and 4 cm in global mean sea level change [16]. 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 14 shows three emission pathways for stabilizing concentrations at
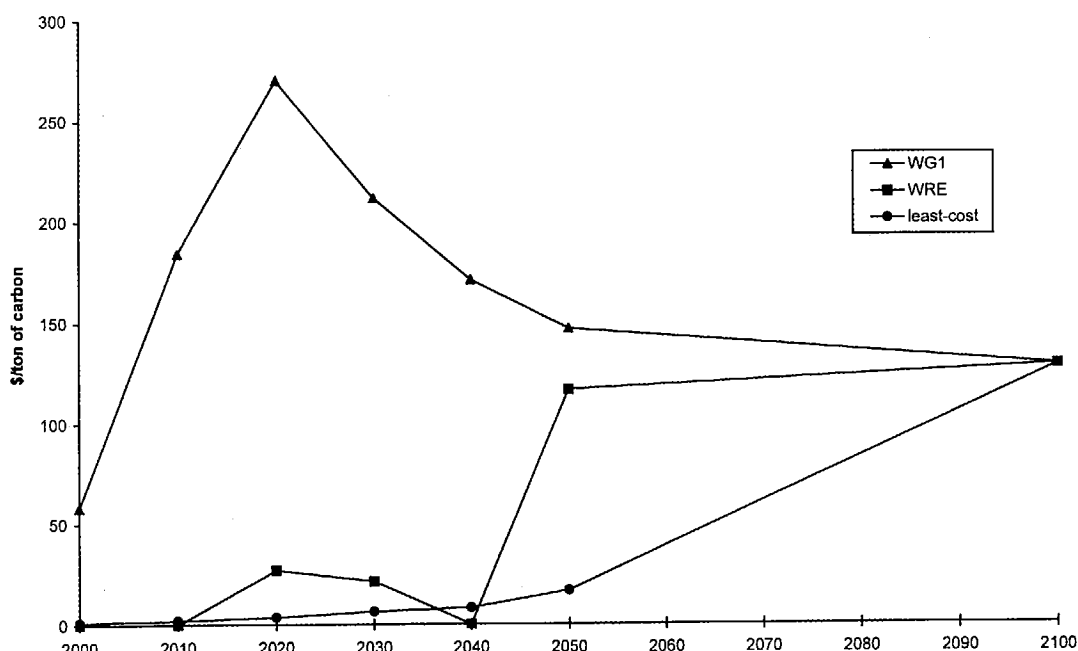
Figure 11. Value of carbon emission rights with alternative pathways for stabilizing concentrations at 550 ppmv.
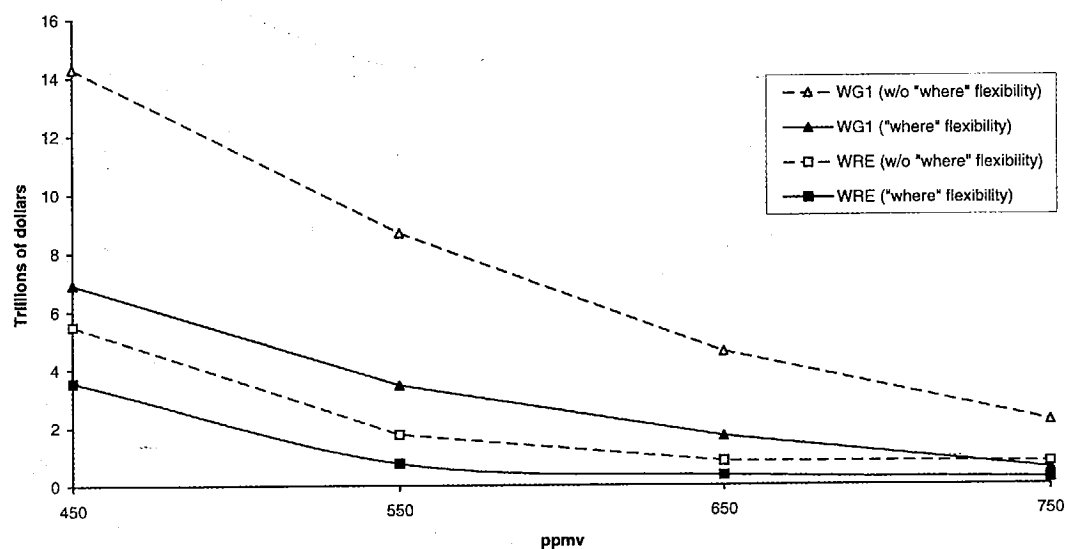

Figure 12. Mitigation cost for stabilizing concentrations at alternative levels – discounted to 1990 at 5%.

550 ppmv 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 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 15 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.
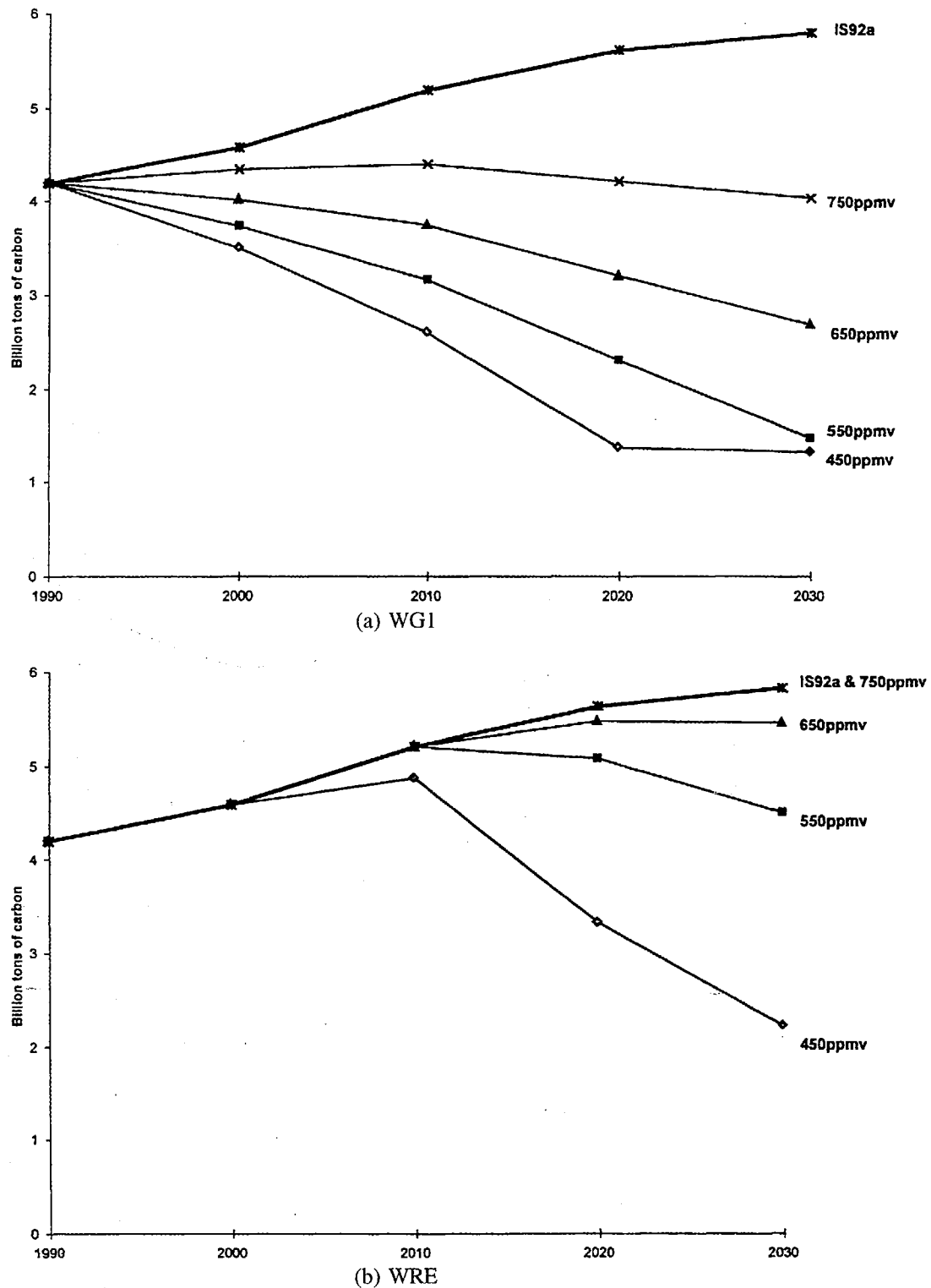
(a) WG1

(b) WRE

Figure 13. Annex 1 emission constraints under alternative concentration targets.

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 Report [6], 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,
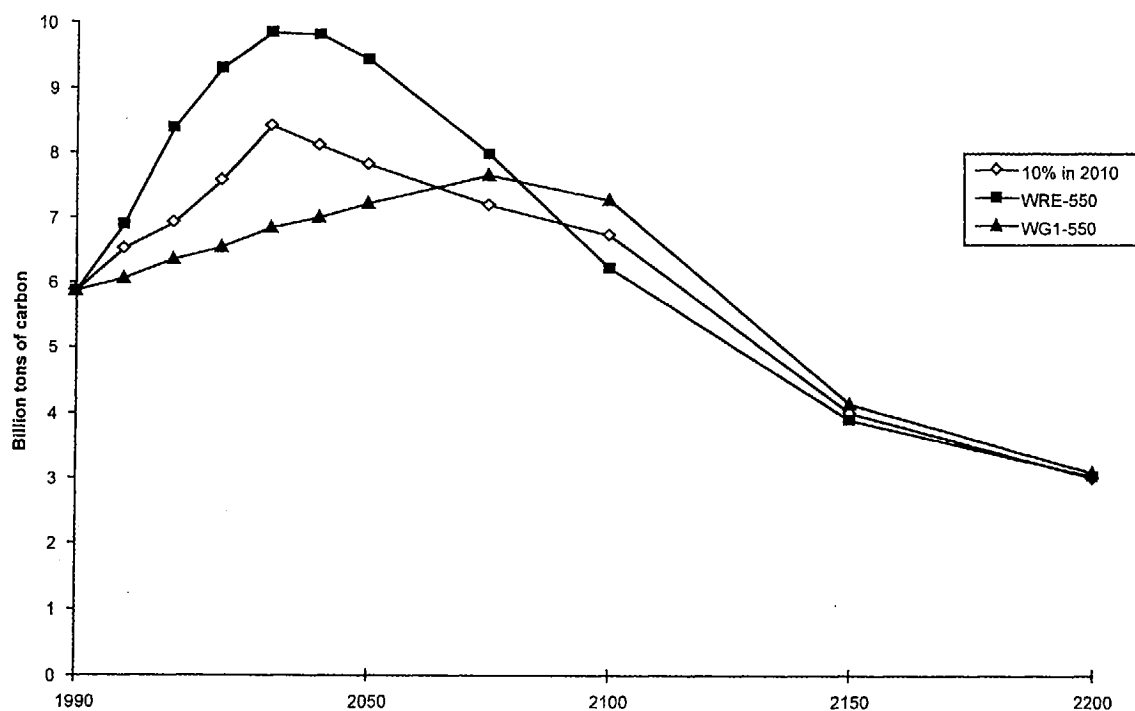
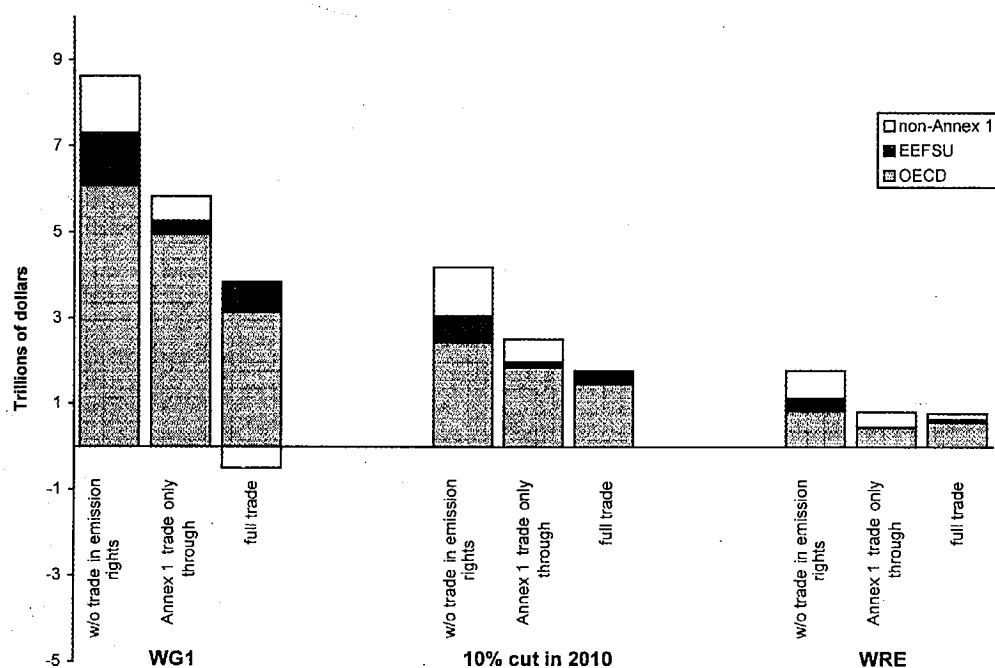Figure 14. Alternative emission pathways for stabilizing concentrations at 550 ppmv.

Figure 15. Regional costs of stabilizing concentrations at 550 ppmv – discounted to 1990 at 5%.

- 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" [6].

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 [2].

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.

Acknowledgements

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