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

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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: CETA[18], EPPA[19], MERGE[20], MiniCAM[21]. 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 disaggragation: 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 loses 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

[1]Electric Power Research Institute

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[7]Electric Power Research Institute

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[9]Pacific Northwest Laboratory

[10]Massachusetts Institute of Technology

[11]For 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

[12] See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapter 1, forthcoming, Cambridge University Press.

[13]The 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."

[14] See Intergovernmental Negotiating Committee for A Framework Convention on Climate Change, Fifth Session, Second Part, New York, 30 April-9 May 1992.

[15]See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapter 9, forthcoming, Cambridge University Press.

[16]See 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.

[17]See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapters 9 & 10, forthcoming, Cambridge University Press.

[18]See Peck, S. and Teisberg, T. "International CO2 Emissions Targets and Timetables: Analysis Using CETA-M", Working Paper, 1995.

[19]See 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.

[20]See 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.

[21]See Edmonds et al

[22]See Hogan, W. and Jorgenson, D. "Productivity Trends and the Costs of Reducing CO2 Emissions"' *Energy Journal* 12 No. 1, 1991.

[23]For a detailed model comparison, see EMF-14.

[24]These 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.

[25]See Intergovernmental Panel on Climate Change (IPCC). *Climate Change 1994*, Cambridge University Press, 1994.

[26]See 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.

[27]The AOSIS proposal calls for Annex 1 countries to reduce emissions by 20% by 2005.

[28]See notes 15 and 16.

[29]There is some trade in emission rights within the OECD, however. This is the consequence of aggregating single countries into larger regions.

[30]With 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.

[31]For a more detailed discussion of the timing issue, see Wigley et al, note 16.

[32]For 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.

[33]EPPA 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

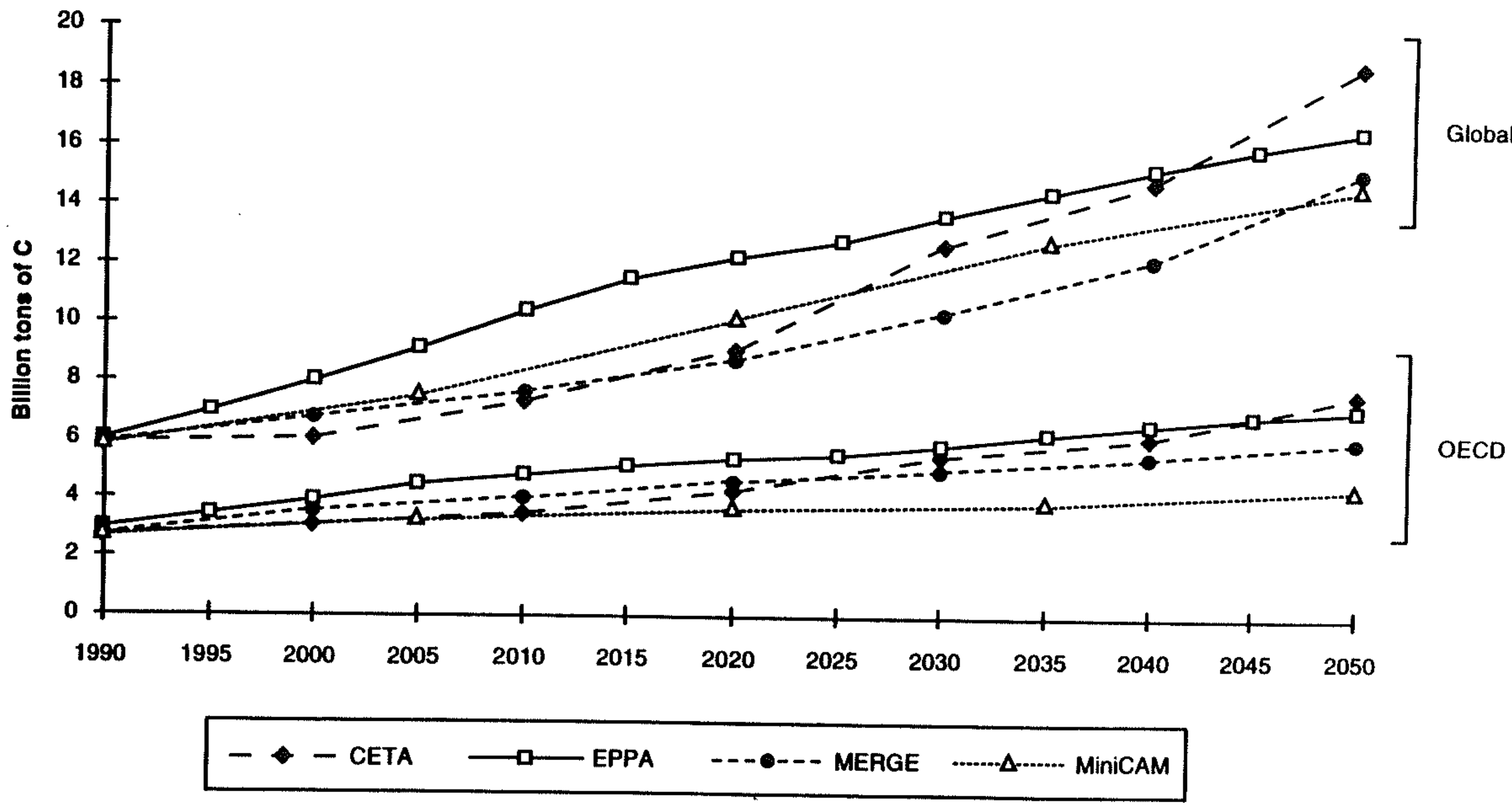


Figure 2. Global Emissions under Business as Usual and with a 20% Cut in OECD Emissions (based on average of model results)

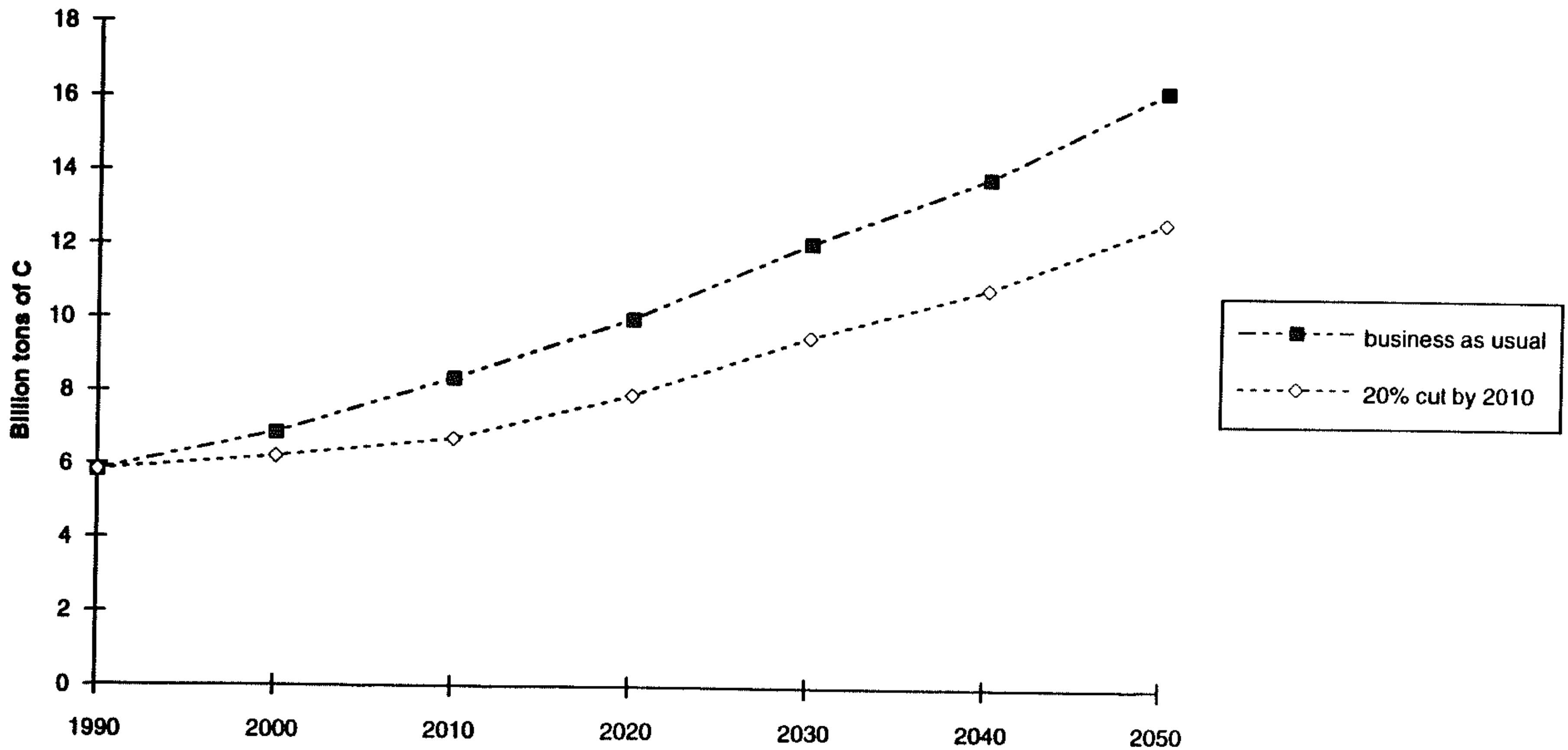


Figure 3. Costs of 20% Cut in OECD Emissions by 2010 -- Case 1
(costs through 2050 discounted to 1990 at 5%)

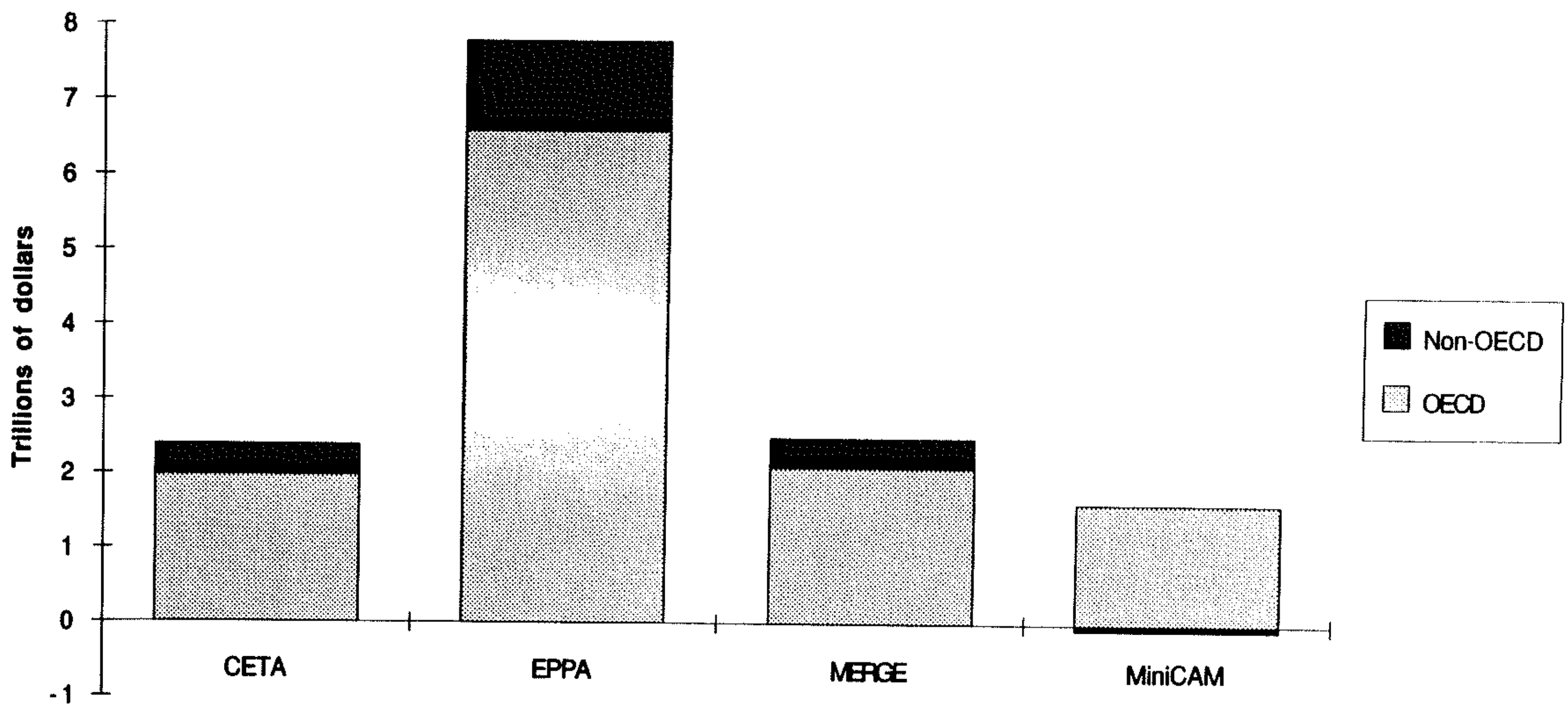


Figure 4. Global Costs under Four Alternative Cases

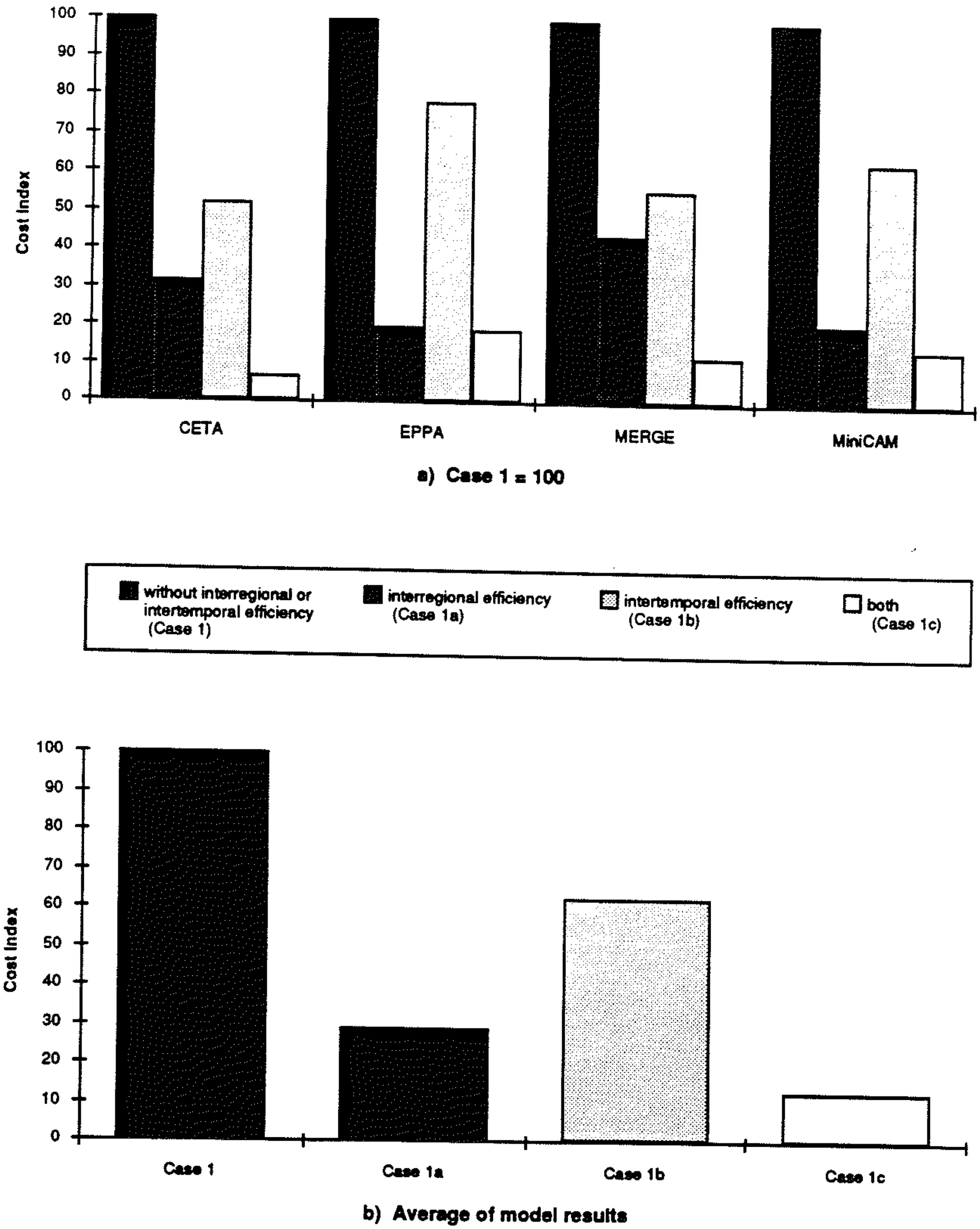


Figure 5. Regional Costs under Four Alternative Cases (costs through 2050 discounted to 1990 at 5%)

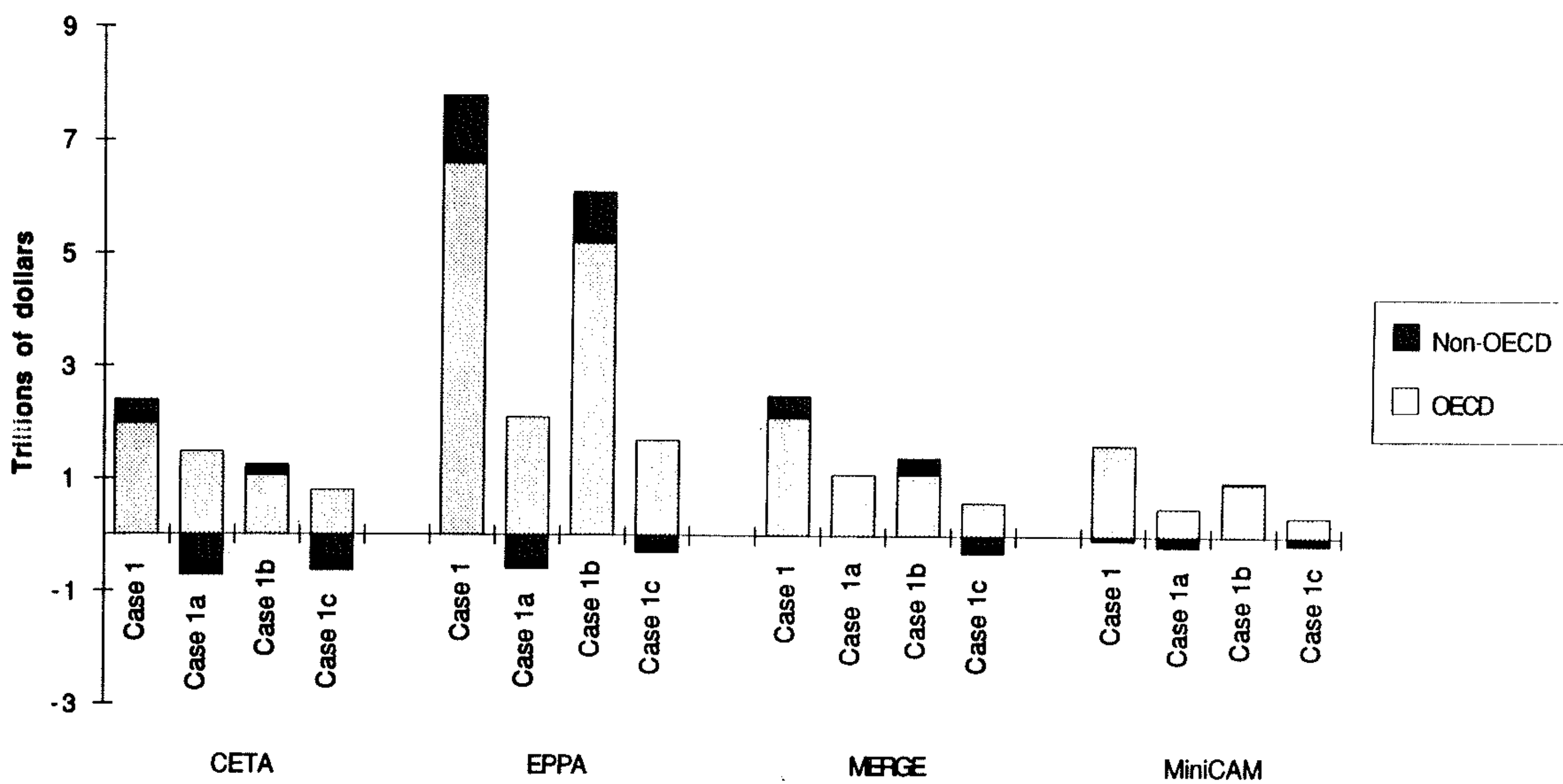
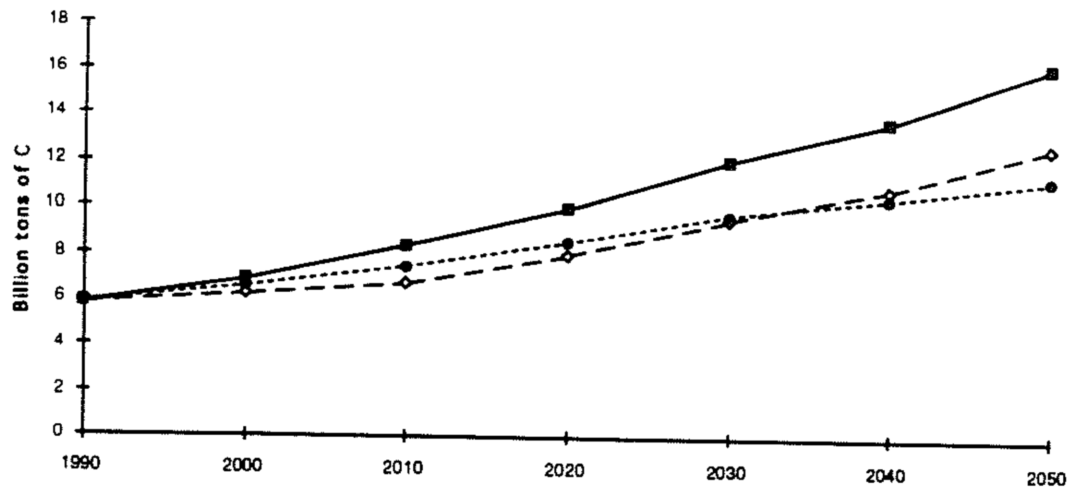
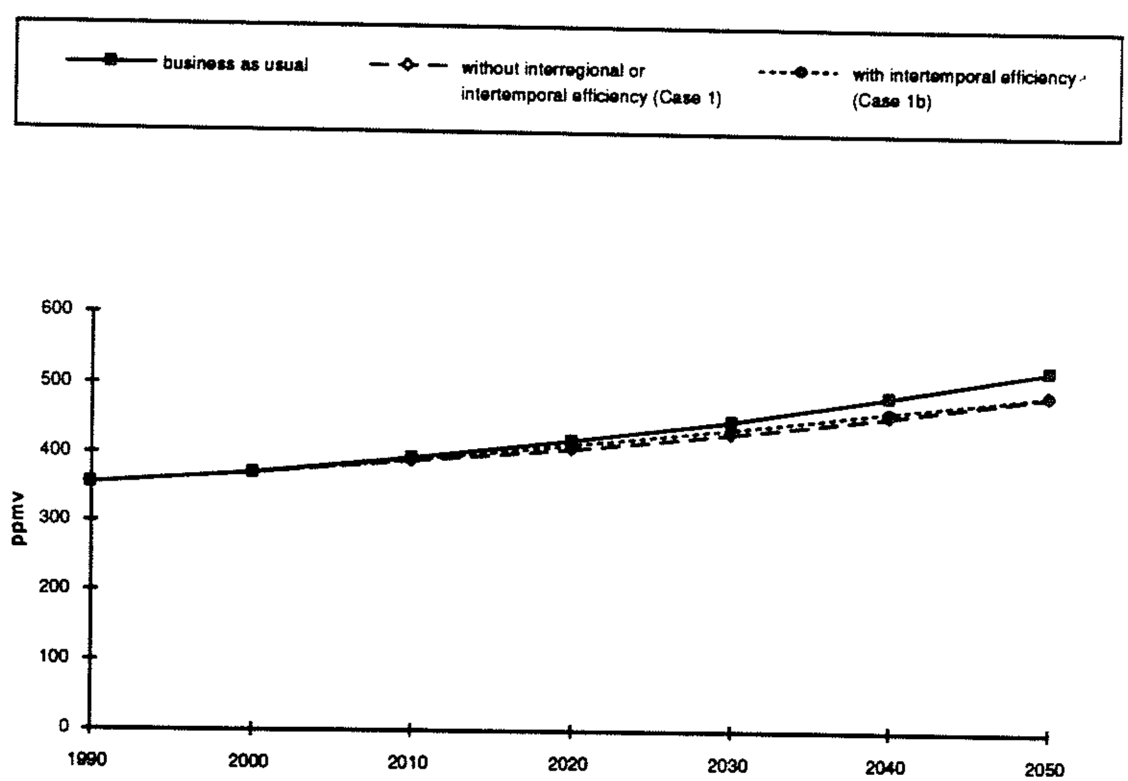


Figure 6. Global Emissions and CO2 Concentrations with and without Intertemporal Efficiency (based on average of model results)



a) Global emissions



b) CO_2 Concentrations

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

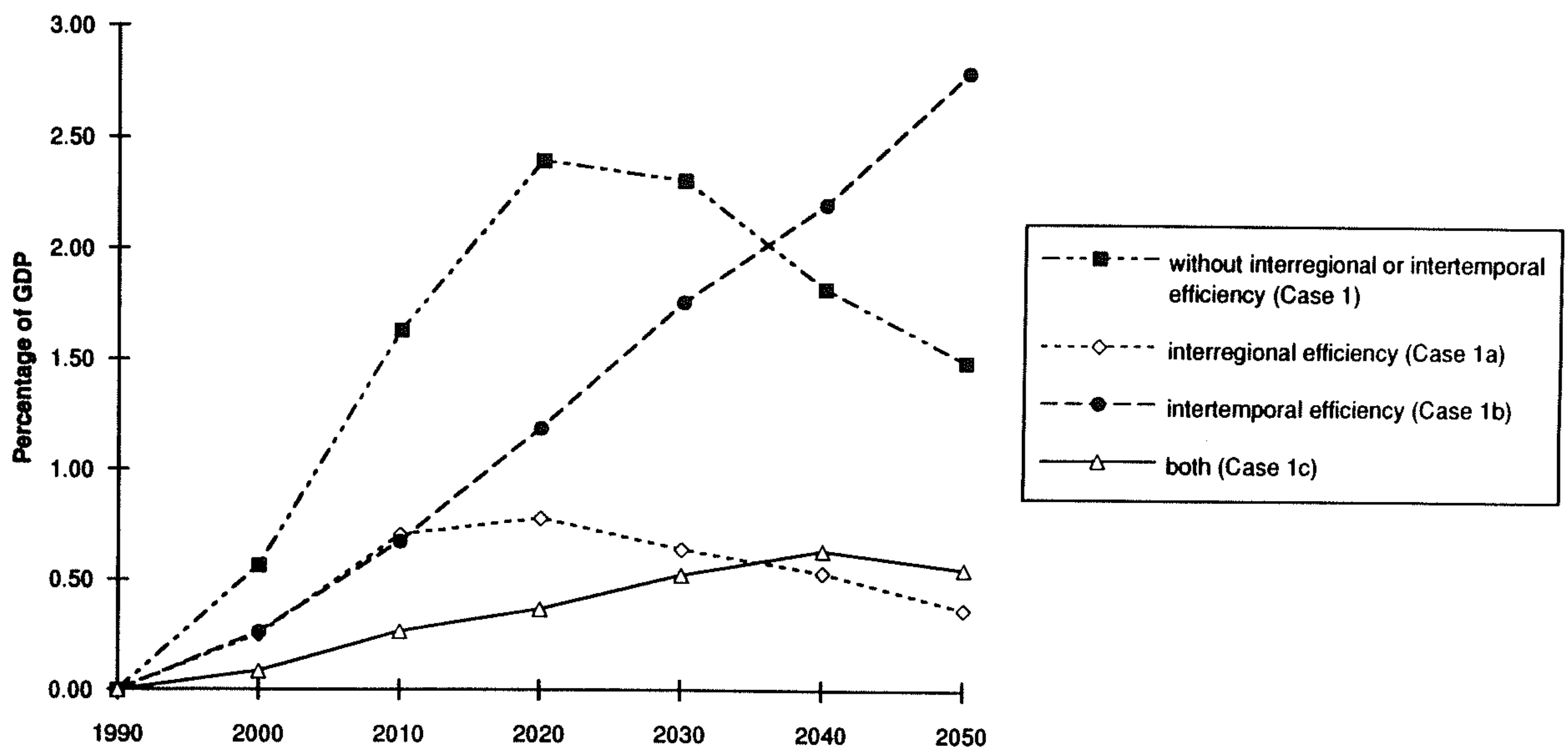


Figure 9. OECD GDP Losses under Alternative Targets and Timetables (based on average of model results)

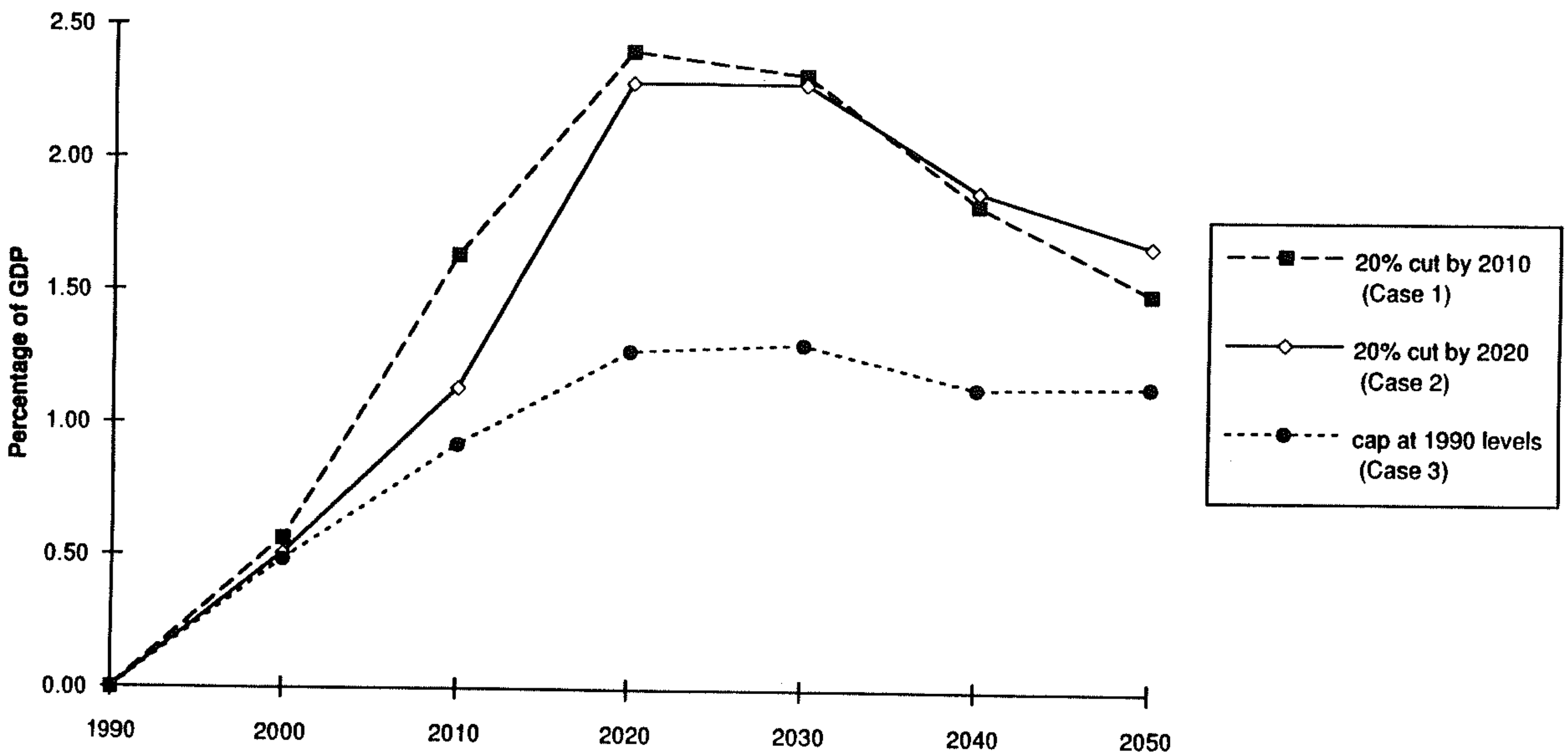
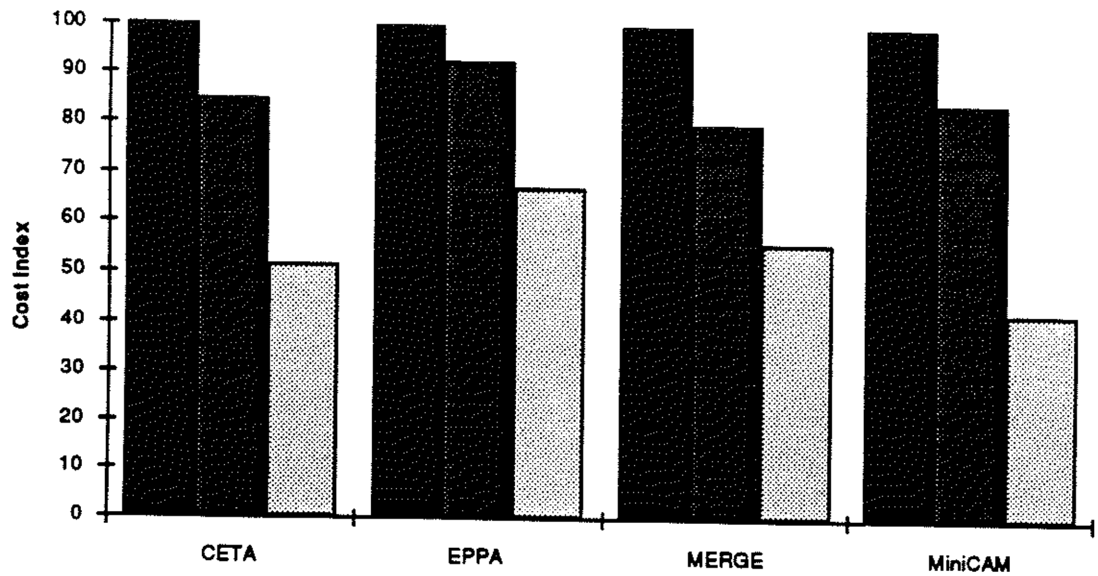
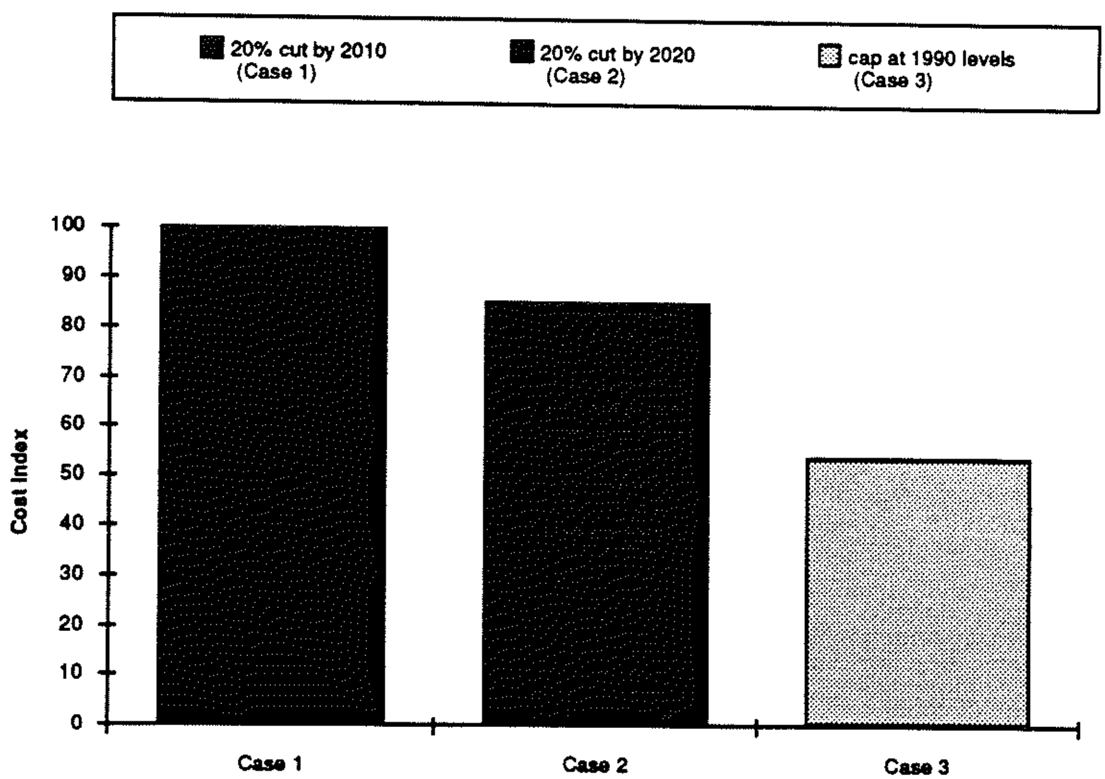


Figure 8. Costs of Alternative Sets of Targets and Timetables



a) Case 1 = 100



b) Average of model results