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[Global Climate Change] Manney Richels Baseline Key Stats & Charts Emissions/Concentrations [2]

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Comparison of Atmospheric CO2 Concentrations Developed by the IPCC (S350-S750) and by Wigley, Richels, and Edmonds (WRE 350-750)
ppmv (parts per million by volume)

YEAR	S350	S450	S550	S650	S750	WRE350	WRE450	WRE550	WRE650	WRE750
1990	354.407	354.407	354.407	354.407	354.407	354.407	354.407	354.407	354.407	354.407
2000	368.754	369.705	369.99	370.51	371.154	372.254	372.255	372.255	372.255	372.255
2005	375.054	377.186	377.879	379.013	380.415	381.935	382.755	382.754	382.755	382.755
2010	380.656	384.486	385.821	387.804	390.249	390.993	393.748	394.192	394.193	394.193
2015	385.482	391.552	393.807	396.868	400.631	398.926	404.213	406.234	406.5	406.5
2020	389.47	398.337	401.823	406.188	411.531	405.249	413.56	418.524	419.487	419.746
2025	392.577	404.797	409.858	415.744	422.913	409.583	421.522	430.83	432.907	433.669
2030	394.778	410.891	417.898	425.511	434.732	411.738	428.074	442.933	446.614	448.008
2050	394.945	431.028	449.77	466.117	485.308	401.991	443.221	485.933	501.321	507.495

Percent Change from 1990 Levels of Atmospheric CO2 Concentrations

2000	4.05%	4.32%	4.40%	4.54%	4.73%	5.04%	5.04%	5.04%	5.04%	5.04%
2005	5.83%	6.43%	6.62%	6.94%	7.34%	7.77%	8.00%	8.00%	8.00%	8.00%
2010	7.41%	8.49%	8.86%	9.42%	10.11%	10.32%	11.10%	11.23%	11.23%	11.23%
2015	8.77%	10.48%	11.12%	11.98%	13.04%	12.56%	14.05%	14.62%	14.70%	14.70%
2020	9.89%	12.40%	13.38%	14.61%	16.12%	14.35%	16.69%	18.09%	18.36%	18.44%
2025	10.77%	14.22%	15.65%	17.31%	19.33%	15.57%	18.94%	21.56%	22.15%	22.36%
2030	11.39%	15.94%	17.91%	20.06%	22.66%	16.18%	20.79%	24.98%	26.02%	26.41%
2050	11.44%	21.62%	26.91%	31.52%	36.94%	13.43%	25.06%	37.11%	41.45%	43.20%

Comparison of Emissions Trajectories Consistent with Various Atmospheric CO2 Concentrations Developed by the IPCC and WRE
PgC (Peta(10^15) grams of Carbon)

YEAR	S350	S450	S550	S650	S750	WRE350	WRE450	WRE550	WRE650	WRE750
1990	6.862	6.862	6.862	6.862	6.862	6.862	6.862	6.862	6.862	6.862
2000	6.793	7.242	7.384	7.623	7.919	8.397	8.399	8.401	8.399	8.399
2010	6.361	7.401	7.798	8.313	8.946	8.373	9.498	9.899	9.901	9.901
2015	6.026	7.404	7.97	8.628	9.429	7.902	9.363	10.378	10.601	10.601
2020	5.626	7.361	8.12	8.932	9.918	7.152	8.974	10.77	11.193	11.4
2025	5.177	7.296	8.284	9.251	10.411	6.179	8.445	11.038	11.715	11.994
2030	4.687	7.201	8.435	9.554	10.884	5.062	7.863	11.18	12.151	12.524
2050	2.635	6.515	8.868	10.544	12.391	1.164	5.886	10.615	12.872	13.85

Percent Change from 1990 Emissions Levels

2000	-1.01%	5.54%	7.61%	11.09%	15.40%	22.37%	22.40%	22.43%	22.40%	22.40%
2010	-7.30%	7.85%	13.64%	21.15%	30.37%	22.02%	38.41%	44.26%	44.29%	44.29%
2015	-12.18%	7.90%	16.15%	25.74%	37.41%	15.16%	36.45%	~~51.24%~~	54.49%	54.49%
2020	-18.01%	7.27%	18.33%	30.17%	44.54%	4.23%	30.78%	56.95%	63.12%	66.13%
2025	-24.56%	6.32%	20.72%	34.81%	51.72%	-9.95%	23.07%	60.86%	70.72%	74.79%
2030	-31.70%	4.94%	22.92%	39.23%	58.61%	-26.23%	14.59%	62.93%	77.08%	82.51%
2050	-61.60%	-5.06%	29.23%	53.66%	80.57%	-83.04%	-14.22%	54.69%	87.58%	101.84%

IPCC vs WRE Projections

Comparison of Emissions Trajectories Consistent with Various Atmospheric CO2 Concentrations
Developed by the IPCC and WRE
PgC (Peta(10^15) grams of Carbon)

YEAR	S350	S450	S550	S650	S750	WRE350	WRE450	WRE550	WRE650	WRE750
1990	6.862	6.862	6.862	6.862	6.862	6.862	6.862	6.862	6.862	6.862
2000	6.793	7.242	7.384	7.623	7.919	8.397	8.399	8.401	8.399	8.399
2010	6.361	7.401	7.798	8.313	8.946	8.373	9.498	9.899	9.901	9.901
2015	6.026	7.404	7.97	8.628	9.429	7.902	9.363	10.378	10.601	10.601
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Percent Change from 1990 Emissions Levels

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2010	-7.30%	7.85%	13.64%	21.15%	30.37%	22.02%	38.41%	44.26%	44.29%	44.29%
2015	-12.18%	7.90%	16.15%	25.74%	37.41%	15.16%	36.45%	51.24%	54.49%	54.49%
2020	-18.01%	7.27%	18.33%	30.17%	44.54%	4.23%	30.78%	56.95%	63.12%	66.13%
2025	-24.56%	6.32%	20.72%	34.81%	51.72%	-9.95%	23.07%	60.86%	70.72%	74.79%
2030	-31.70%	4.94%	22.92%	39.23%	58.61%	-26.23%	14.59%	62.93%	77.08%	82.51%
2050	-61.60%	-5.06%	29.23%	53.66%	80.57%	-83.04%	-14.22%	54.69%	87.58%	101.84%

Global Climate Research
Facsimile Transmission

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Phone: (415) 855-2602
Subject: Revised tax numbers

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Date: August 29, 1997

Destination Information

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Company	CEA
Division	
Phone	
Fax	202 395 6958

I came up with what I believe to be a better way of projecting the necessary carbon taxes.

1. In each instance, the Annex 1 target is maintained 2010- 2030 and then we transition to burden sharing scheme..

2. The taxes are consistent with the least-cost solution subject to the constraint on Annex 1 emissions.

3. The tax is positive in 2000 because I had to assume trading in that year to avoid the earlier problem.

Before 2010 was only year in which not constraint
Now 2010 -

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Phone: (415) 855-2602
Subject: Some Results

Pages (including cover): ~~2~~ 8
Date: August 28, 1997

Destination Information

Name	Jeff Frankel
Company	CEA
Division	
Fax	202 395 6958

Some initial results. More to come.

Richard

A bit rough but sufficient for our next conversation.

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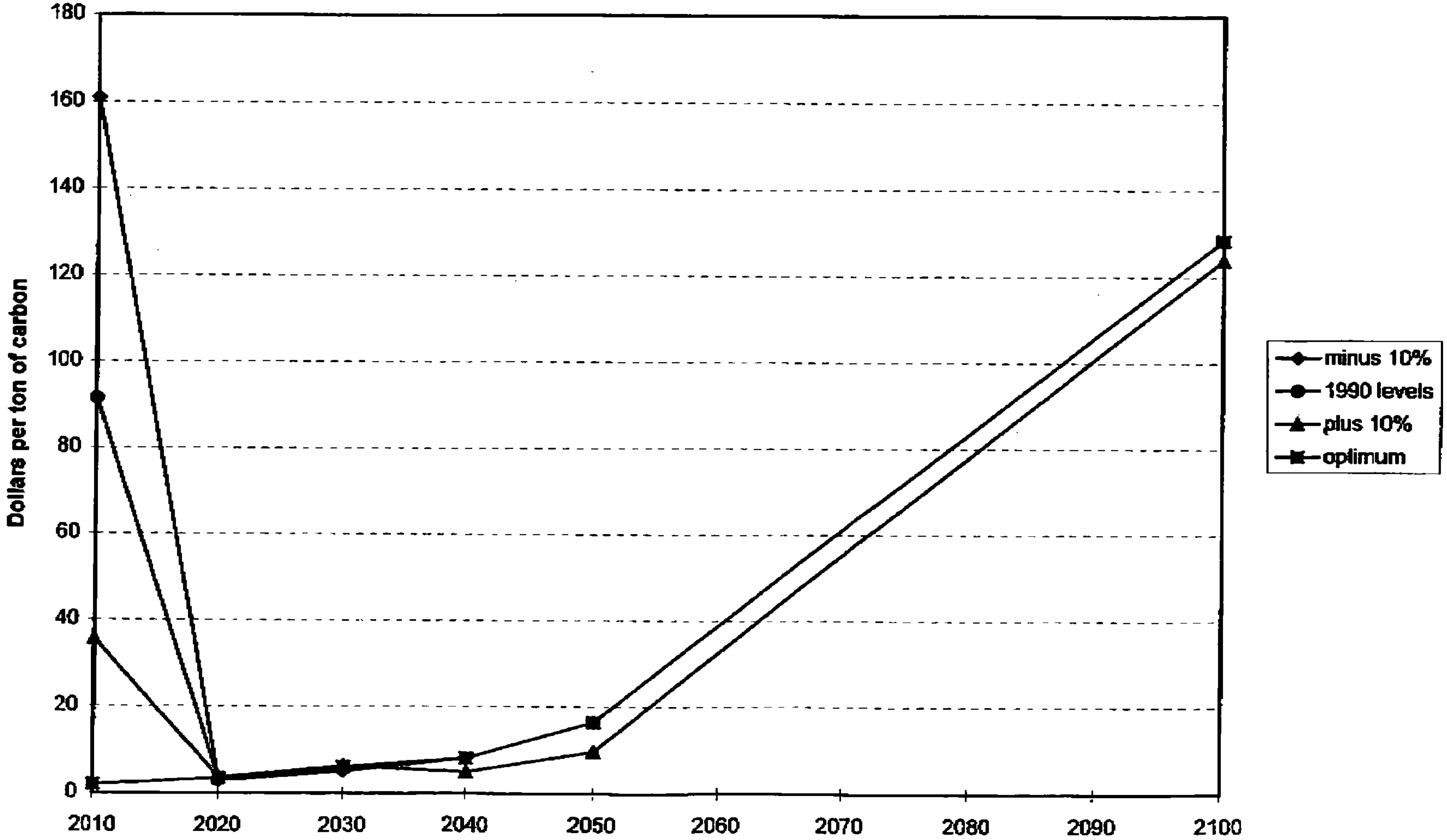
Table 4. Value of Carbon Emission Rights in Dollars/Ton

	minus 10	1990 level	plus 10%	optimum
2010	161.02	91.458	35.522	1.998
2020	2.884	3.122	3.595	3.48
2030	5.108	5.518	6.34	6.126
2040	8.12	8.121	4.946	8.129
2050	16.454	16.447	9.622	16.445
2100	128.389	128.388	123.822	128.394

Figure 3. Value of Carbon Emission Rights



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Global Climate Research
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Subject: Some Results

Pages (including cover): 2

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Name	Jeff Frankel
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Division	
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a little on the low side

Some initial results. More to come.

Richard

reach least cost strategy
by adding constraints

number
other variables

2 maybe constraint of BAU in 2000

straight line from 2010 to 10% below + then straight line

If Annex 1 countries go own way + no trading even within Annex 1 carbon

straight line case max savings in concept ≈ 77 in 2100 575

Lose Assumes LDCs do what they were going to anyway. BAU 776 CO2 excess 737 :74? 26% reduction 22%

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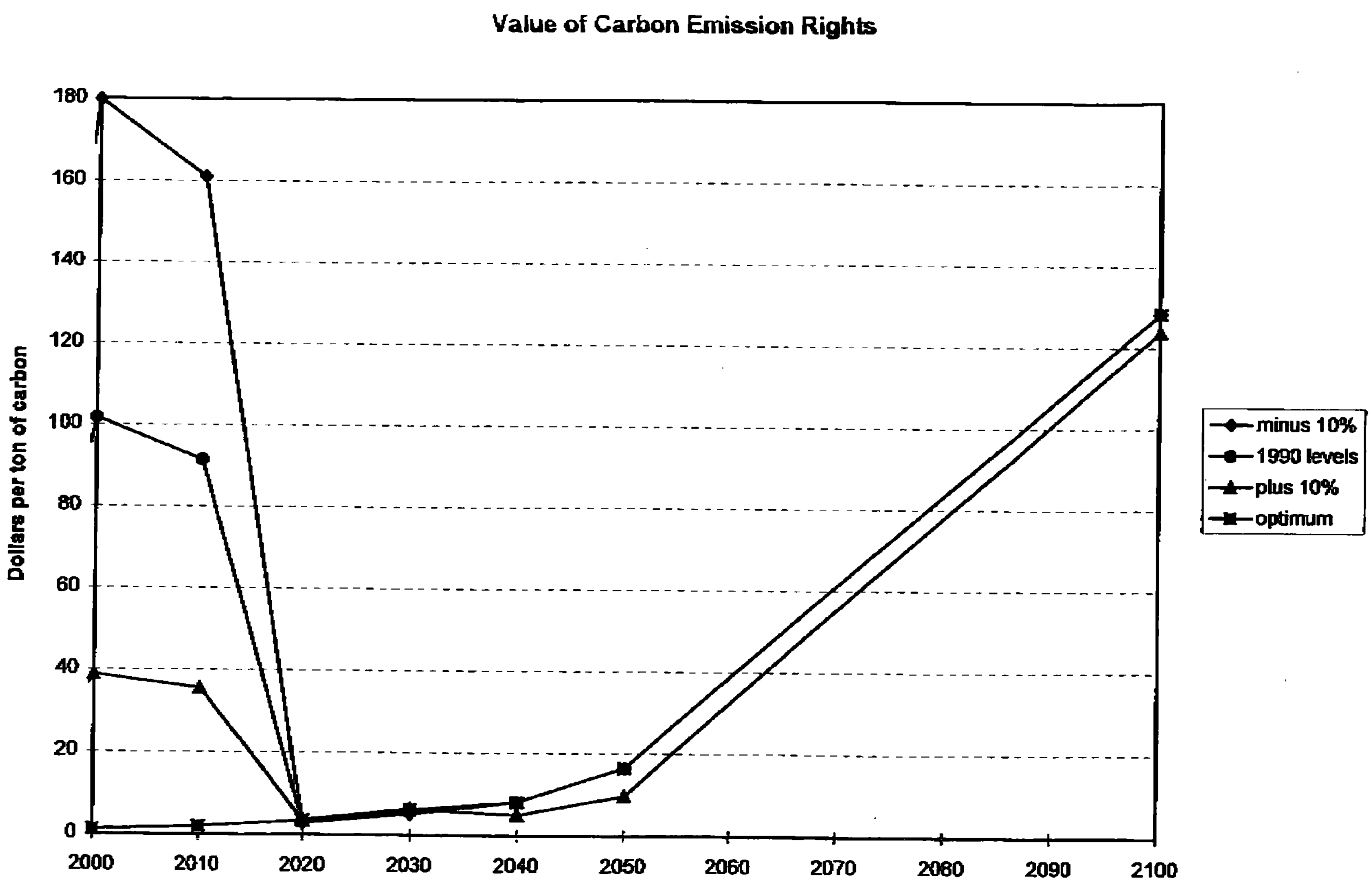
M

Leasy (as?)

	2010	2020	2030
OECD	3.897	4.149	3.811
Eurasia	1.096	1.280	1.466
	4	5.4	5.3

	WGI	WRE	least cost
Annex 1 peak year	1990 ~~or 2020~~	different 2010 (-2020) close	2020-30
non Annex 1	2100 [comes down next cent.]	2050	2050
global	2075	2030 "	2050
Year global em return to 1990 levels	post 2100	post 2100	pre-2100 very roughly 2090 12 2050 4.7 2100

cont


Value of Carbon Emission Rights
Dollars per ton of carbon
180
160
140
120
100
80
60
40
20
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
minus 10%
1990 levels
plus 10%
optimum

DRAFT 1
01/14/97

REGIONAL PATTERNS IN A TECHNOLOGY GREENHOUSE STRATEGY

In ***Toward A Technology Greenhouse Strategy*** we considered some of the global implications for strategies to stabilize the **concentration** of greenhouse gases in the atmosphere at safe levels. We noted that no matter what level turns out to be "safe" this obligation requires that anthropogenic CO_2 emissions must, eventually, decline to zero. We further observed that, since energy use is the most important present and anticipated future source of net CO_2 emissions, eventually declining emissions implies an eventual secession of coal fired power plant construction, and prohibition of coal gasification and liquefaction. Finally, we considered explicit time paths of greenhouse gas emissions and the role of technology in controlling the costs of emissions mitigation.

Global Emissions Patterns

While there are many paths by which the concentration of atmospheric CO_2 the only global emissions path published by the Intergovernmental Panel on Climate Change (IPCC) which could still be put into effect is the WRE path (Wigley, et al., 1996). We have thus chosen this path for examination. The fossil fuel carbon emissions paths for atmospheric stabilization concentrations of 550 ppmv and 650 ppmv are shown in Figure 1 along with two potential business as usual paths. Both business as usual scenarios adopt the same economic and demographic assumptions as the IPCC (Leggett, et al., 1992). They differ only in their technology assumptions. Case IS92a(Tech+) adopts the IS92a technology development assumptions,[1] while IS92a(1990Tech) holds technology fixed at 1990 levels. While WRE550 was constructed to stabilize the concentration of CO_2 at 550 ppmv, Figure 2, neither IS92a(1990Tech) or IS92a(Tech+) achieve that goal.

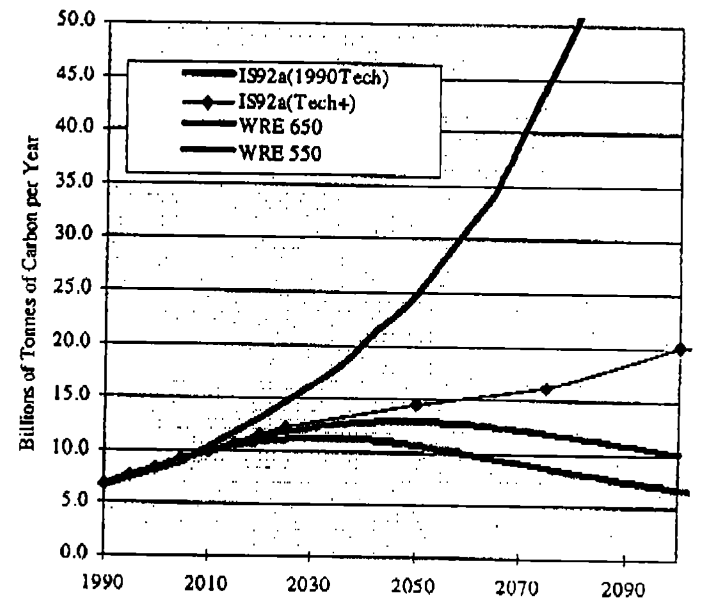


Figure 1: CO_2 Emissions for Alternative Scenarios

Regional Near Term Actions and Atmospheric Stabilization

Global fossil fuel carbon emissions are the sum of all of the national fossil fuel carbon emissions. Controlling global emissions implies controlling regional emissions. No nation is sufficiently important or powerful to be able to control global emissions in either the short term or long term. Even Annex I

---

[1] For example the efficiency of the average fossil fuel powerplant is assumed increase at more than 1.0%/yr between 1990 and 2050, from 0.33 to 0.(?). Exogenous end-use energy intensity proceeds at between 0.5%/yr (OECD nations) and 2.5%/yr (Eastern Europe and the Former Soviet Union). The cost of non-fossil fuel electric power generating technologies, other than nuclear and hydroelectric, declines at an average annual rate of 4.5%/yr between 1990 and 2025, and at 1.25%/yr from 2025 to the year 2100. And the cost of biomass energy production declines at an annual rate of one percent per year between 1990 and 2100 from 1990 values ranging from $2.50/GJ to $4.40/GJ, depending on the location and scale of production

controls insufficient emissions to enable it to force total global emissions to follow the WRE path over the course of the next century. Eventually even complete secession of emissions in all Annex I nations would be insufficient to enforce the path, if non-Annex I nations did not alter their emissions paths.

We can also consider the issue from another perspective. We construct a simple hypothetical Annex I obligation for the purposes of exploring the implications for non-Annex I nations. We assume that Annex I nations return emissions to 1990 levels in the year 2000 and hold them at that level until the year 2005 at which time emissions begin to decline, relative to 1990 levels, 0.75%/yr until the reach 50% of 1990 emissions at which point they are maintained constant for the remainder of the century. This hypothetical Annex I obligation has not been proposed by any government, but is consistent in its general outline with proposals that have been put forward.

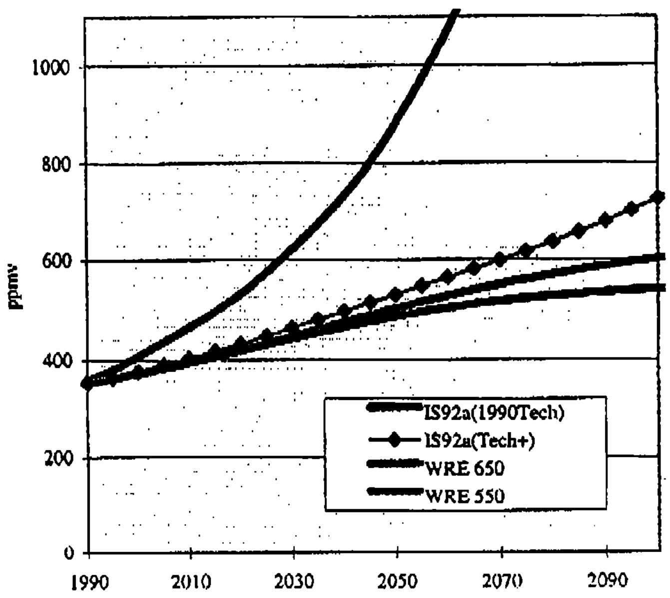


Figure 2: CO_2 Concentrations for Alternative Scenarios

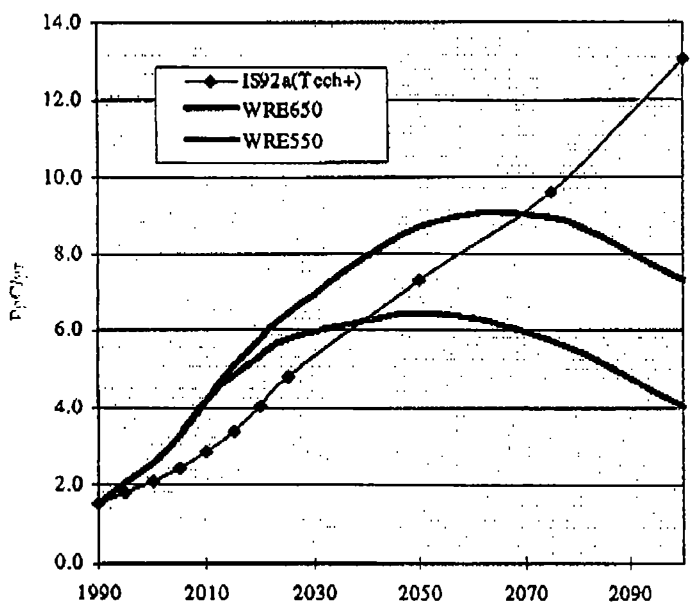


Figure 3: Allowable Non-Annex I Emissions With Aggressive Annex I Policies

We have examined Annex I emissions to satisfy atmospheric stabilization objectives on the assumption that non-Annex I nations do not participate. We can also compute the required non-Annex I emissions required to achieve atmospheric stabilization objectives on the assumption that Annex I takes specific actions such as those outlined above. Required non-Annex I emissions are displayed in Figure 3.

Under both the WRE 650 and WRE 550 cases, non-Annex I nations have allowable emissions greater than anticipated emissions through most of the first half of the next century, if IS92a Technologies become available and penetrate the market. This period of excess emissions is greatly reduced when technologies are assumed to remain as they were in 1990. The excess of allowable emissions over anticipated emissions is potentially useful. The sum could either be used by Annex I nations to reduce the near term burden associated with their actions, or to provide a salable allocation to induce non-Annex I participation in emissions mitigation efforts.

Regional Actions in a 550 ppmv Stabilization With IS92a(Tech+) Technologies

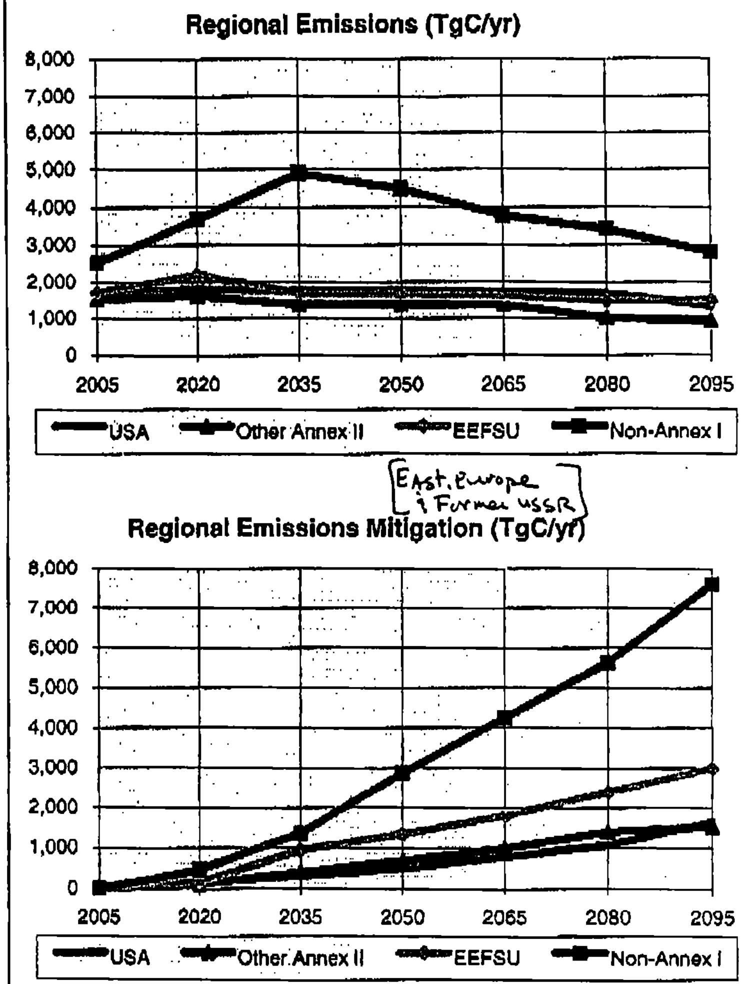


Figure 4: Regional Emissions and Emissions Mitigation in an Atmospheric Stabilization at 550 ppmv

Further USSR Rises in 2020 then falls

The lowest cost to the world of stabilizing the atmosphere is obtained when all nations participate, and when all nations undertake mitigation actions up to the point at which their marginal costs are all equal. That is the point at which the cost of the next tonne of emissions mitigation is the same everywhere.[2] The total cost and the most efficient regional distribution of mitigation efforts depends on both the atmospheric stabilization goal selected, and on the technologies available for producing, transforming, and consuming energy. The regional distribution of costs will also depend on the distribution of emissions rights in the event that such a system is deployed to

To begin to develop some sense of Regional mitigation efforts and costs can vary widely even when participation in mitigation efforts is universal. We examine the case of a ceiling on the concentration of atmospheric CO_2 of 550 ppmv, and assume that the technologies assumed in IS92a(Tech+) are available. We further assume that emissions mitigation is undertaken in a cost effective manner. Cost minimization requires that the price of the marginal tonne of carbon emissions mitigation be equal in all regions. Therefore, regardless of the distribution of emissions allocations, mitigation efforts will be identical in a world in which emissions rights are freely traded! But regional costs will vary radically depending on

[2] If two countries participate and one undertakes mitigation efforts up to the point at which the next tonne cost $100 to withhold from the atmosphere, while the other undertakes mitigation efforts up to the point at which the next tonne costs only $10, then clearly both nations could benefit if the former emitted one more tonne and the latter one less. The former nation could pay the latter up to $99 and still be better off, while the world would have the same level of emissions mitigation.

the distribution of emissions allocations, because the emissions allocation is a valuable financial asset. Regional emissions trajectories and associated emissions mitigation rates for the USA, Other Annex II nations, Eastern Europe and the Former Soviet Union (EEFSU), and Non-Annex I nations, as derived using the MiniCAM 2.0 model, are shown in Figure 4.

Regional Mitigation Costs When Costs are Internalized

If the world levied a uniform carbon tax on all emissions with revenues recycled to the nations from which they were collected, or equivalently if emissions were allocated so that no one ever had an incentive to either buy or sell, then each nation would internalize the cost of emissions mitigation undertaken domestically. The distribution of these costs is shown in Figure 5. While costs are initially low, they rise rapidly with time, and particularly for Non-Annex I nations. However, the largest costs relative to GDP are experienced by Eastern Europe and the Former Soviet Union (EEFSU).

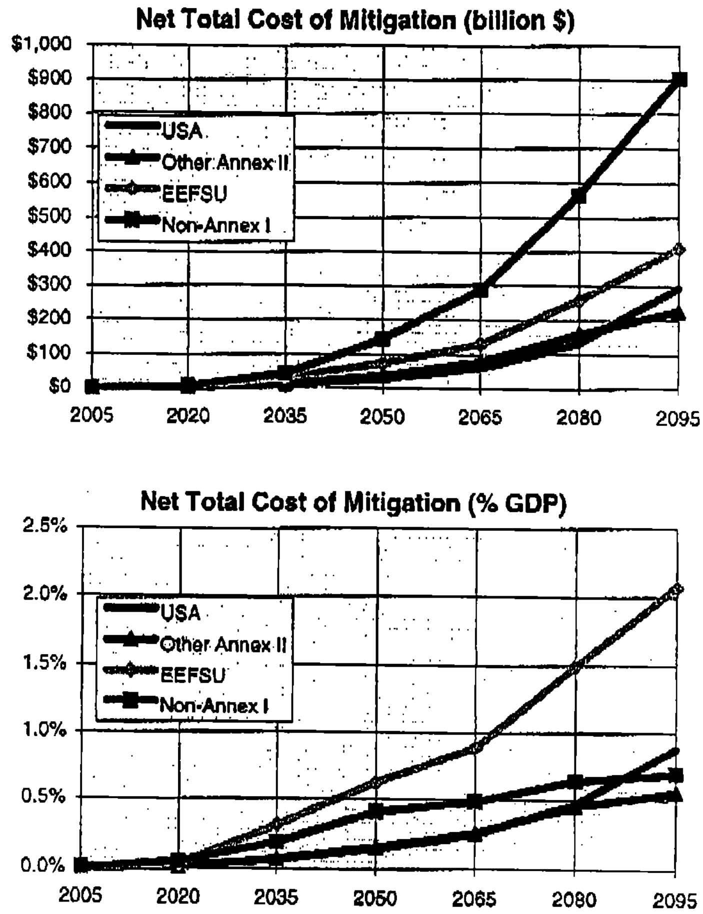


Figure 5: Net Cost of Mitigation, Costs Internalized

Regional costs remain below one percent of GDP for all regions except the EEFSU. Perhaps more importantly, they remain below 0.5% for all regions through the year 2040. Low initial costs reflect the relatively modest near-term emissions mitigation requirements implied by the global WRE 550 trajectory.

Tradable Emissions Rights Allocations

While the introduction of a tradable emissions allocation will not change the distribution of globally efficient emissions mitigation across regions, it can **greatly change** the regional distribution of net costs of mitigation. A tradable emission right will sell in a freely trading, global market at the marginal cost of the emissions reductions. Obviously, the total allocation of emissions rights determines whether or not a nation or region is a net buyer or seller. Large flows of financial resources can either move into or out of a region.

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Financial Flows Under Alternative Emissions Allocation Principles

To see the effect of alternative distributions of emissions rights, we have computed the net purchases and sales of permits under four alternative allocation rules:

1. **Grandfathered Emissions Rights** – Emissions Rights are allocated in proportion to 1990 emissions. Nations with high 1990 emissions receive a larger allocation than those with low emissions. The obvious benefit of this allocation is that it initially reflects relative sacrifice in emissions mitigation. On the other hand, the allocation principle is static in nature and does not accommodate change.
2. **Population Based Emissions Rights** – Emissions Rights are allocated in proportion to current population. Countries with more rapidly growing populations get an increasing proportion over time. The principle distributes the right to emit equally to all individuals, implies large transfers of wealth from those presently emitting at high rates per person top those with low per capita emissions.
3. **GDP Based Emissions Rights** – Emissions Rights are allocated in proportion to current GDP. Thus, countries with more rapidly growing economies get an increasing proportion over time.
4. **Resource Based Emissions Rights** – Emissions Rights are allocated in proportion to the carbon content of 1990 fossil fuel carbon resources in the forms of conventional oil, conventional gas, and coal. The rationale for such an allocation is that the mitigation requires fossil resources to remain unexploited implying a sacrifice roughly in proportion to the unexploited energy.

The transfer of assets for these four allocation rules is displayed in Figure 6. The largest transfers of assets occur under the principle of population based emissions allocations. These eventually reach the level of a trillion dollars per year. Both Grandfathered and Resource based allocation principles lead to net purchases by non-Annex I nations. The GDP based principle initially leads to transfers from developing nations to developed nations, but in later years has exactly the opposite effect in the modeling runs shown here.

Net Costs Under Alternative Emissions Allocation Principles

The costs shown in Figure 5 are directly altered by the financial transfers shown in Figure 6. Net costs in total dollar values are shown in Figure 7, while these same costs are displayed as a fraction of GDP in Figure 8. The effect of these transfers is to directly increase costs to nations and regions which are net purchasers of emissions rights and to decrease costs to regions which are net sellers. In some cases, the transfers are sufficiently large as to transform costs into benefits (negative costs). This is the case for non-Annex I nations when emissions rights are allocated on the basis of population, or for Other Annex II nations when GDP based emissions are applied, or for Eastern Europe and the Former Soviet Union when emissions rights are based on the fossil fuel carbon resource.

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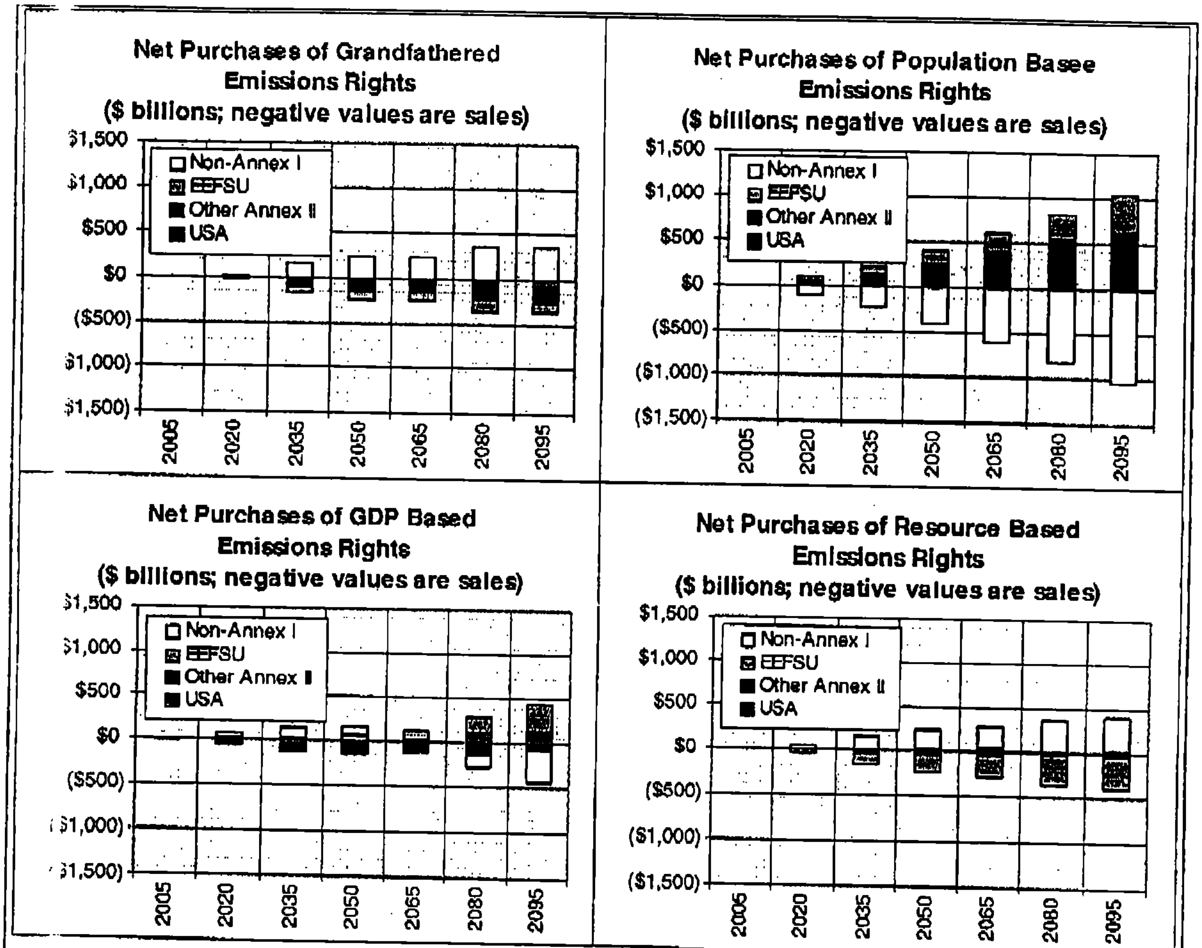

Figure 6: Net Purchase and Sales of Emissions Rights Under Alternative Allocation Principles

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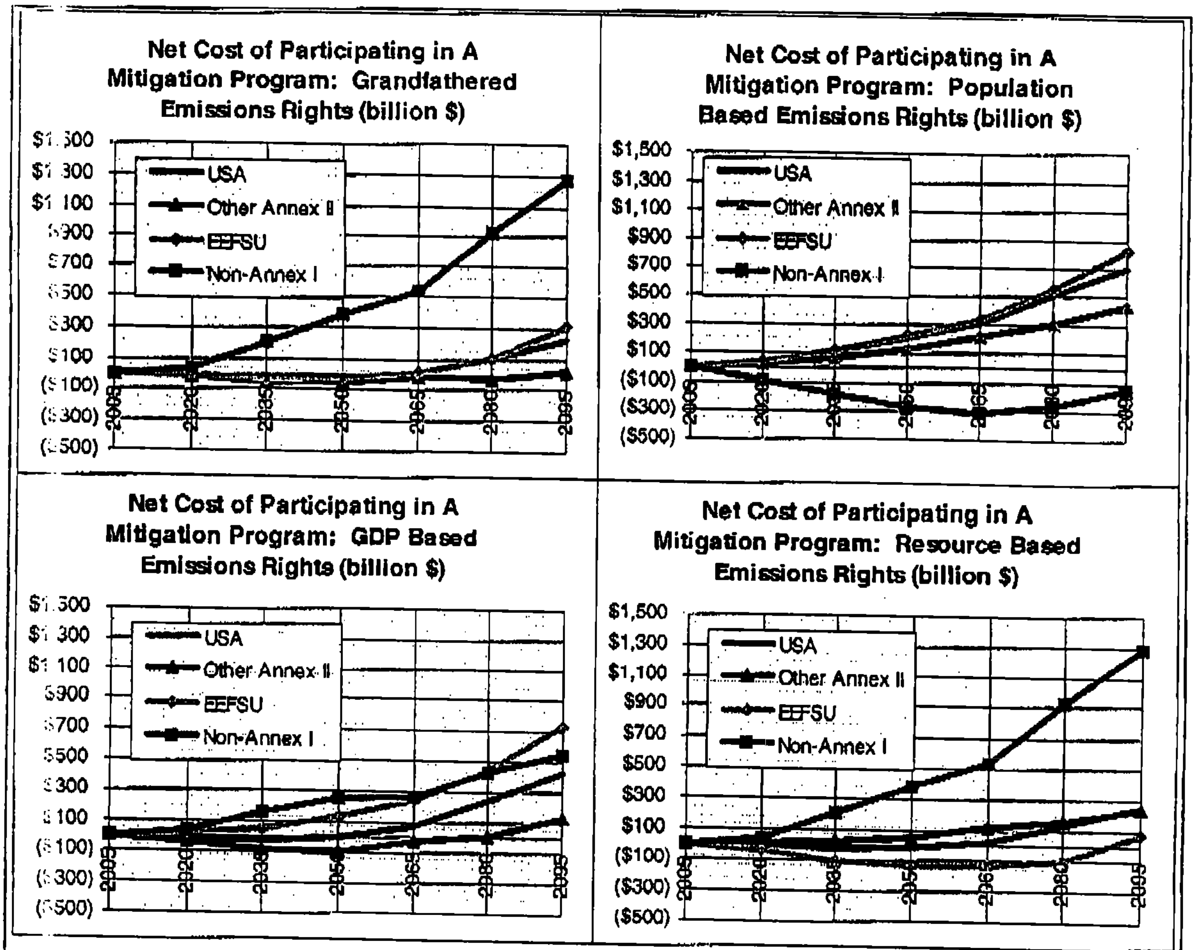

Figure 7: Net Cost of Participating in an Emissions Mitigation Under Alternative Allocation Principles

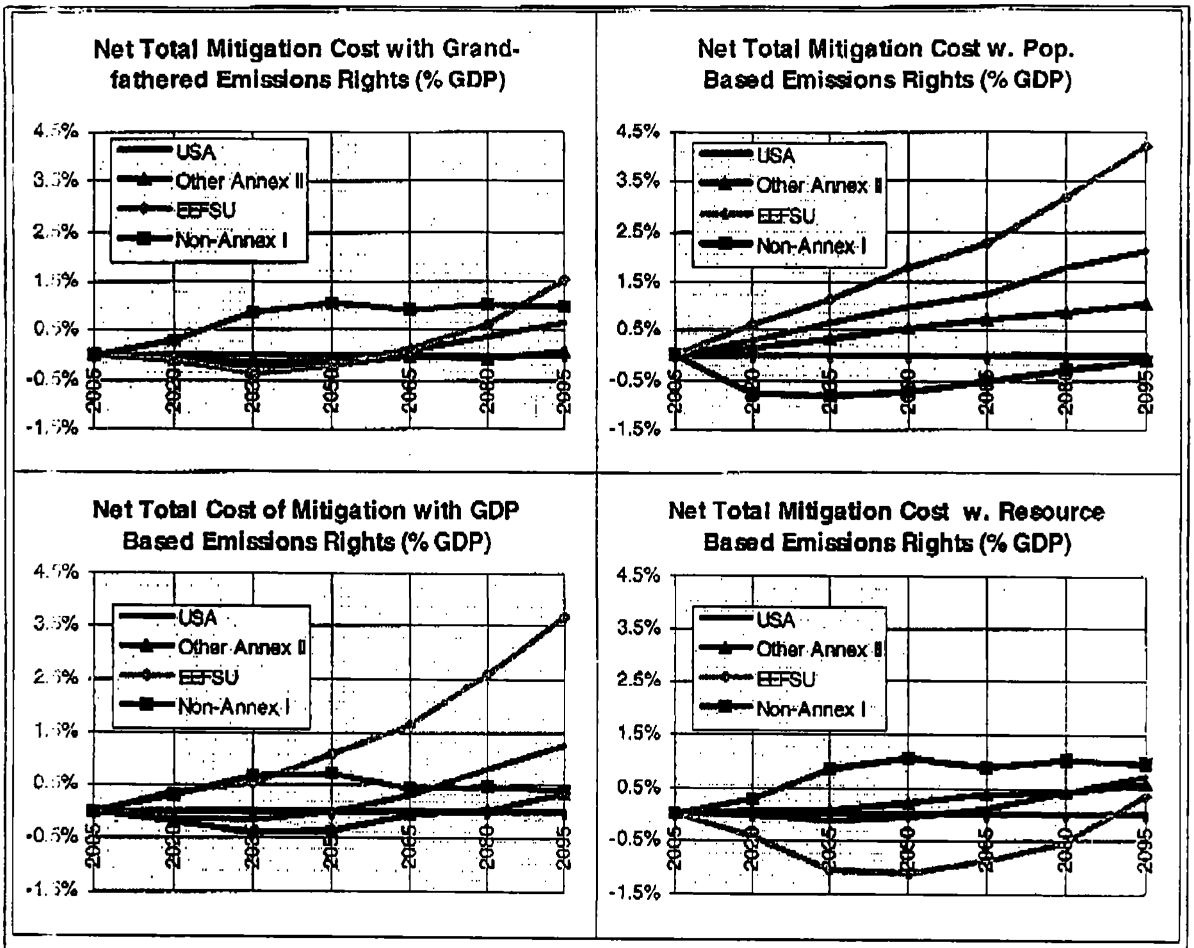

Figure 8: Relative Net Cost as a Percentage of GDP of Participating in an Emissions Mitigation Under Alternative Allocation Principles

Conclusions

Implementing the goal of the FCCC requires that anthropogenic CO_2 emissions must ultimately decline toward zero even though emissions may rise for some years before peaking. This, in turn, requires a global transition from the present suite of carbon-intensive energy technologies and its supporting infrastructure to a new suite of global non-carbon emitting energy technologies. The magnitude of this undertaking should not be underestimated. The global transition must involve rich and poor nations and has implications for the entire fabric of society's infrastructure. The cost of this transition is not entirely outside our control. If new, non-carbon energy technologies can be developed and deployed over the course of the next quarter century, costs can be dramatically reduced from levels that would be required with present technology.

Even if a technology development reflects rates of improvement assumed in the IS92a(Tech+) case, there will still be significant costs of achieving mitigation targets. These costs will be distributed among nations. The distribution of emissions rights will have a profound effect on who pays, how much, and the relative burden.

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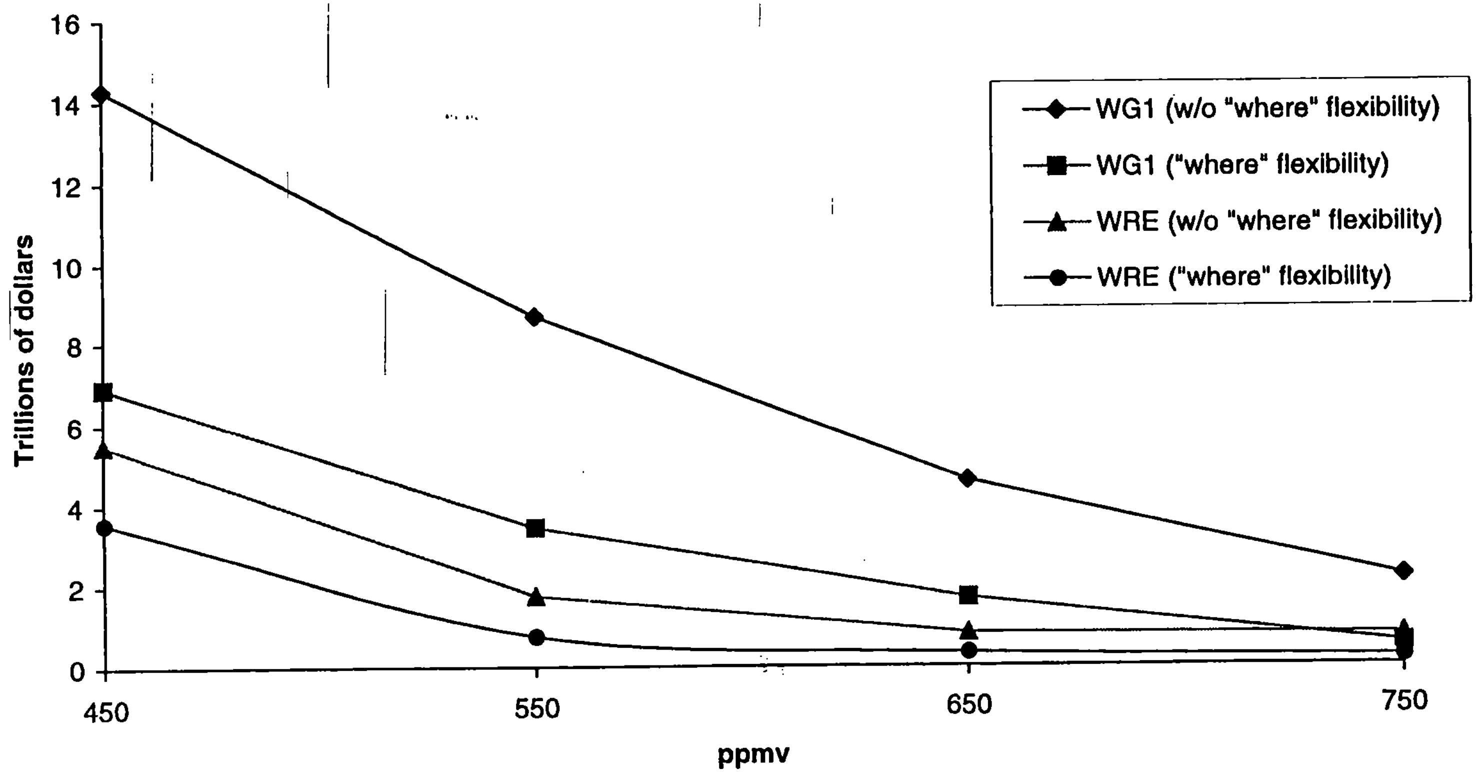
IPCC (Intergovernmental Panel on Climate Change), 1996. ***Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analysis. The Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change***. R.T. Watson, M.C. Zinyowera, R.H. Moss (eds.). Cambridge University Press, Cambridge, UK.

Wigley, T.M.L., R. Richels & J. A. Edmonds. 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," ***Nature***. 379(6562):240-243.

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



Climate and Economic Variables under Alternative Emissions Paths *

August 15, 1997

		Concentration Level (ppmv)		Year at Which Concentration Reaches 2x Pre-Industrial Level **	Change in Temperature from 1990 Level (Celsius)		Carbon Permit Price ($ per ton) ***	Oil Price *** ($ per barrel)	Gasoline Price *** ($ per gallon)	Coal Price *** ($ per ton)
	Year	2050	2100		2050	2100	2010	2010	2010	2010
	Business As Usual (BAU)	522.1	729.8	2058	1.15	2.45	0.00	21.24	1.31	13.76
Deviation from BAU:										
Annex I Participation Only	1990 -10% beginning in 2010	-30.3	-95.0	+15	-0.13	-0.36	+200	+23	+0.54	+108
	1990 beginning in 2010	-24.8	-83.4	+12	-0.10	-0.31	+95	+11	+0.26	+51
	peak in 2015, 1990 in 2040	-17.6	-77.6	+9	-0.06	-0.28	+12	+1	+0.03	+7
Worldwide Participation	1990 -10% beginning in 2010	-82.2	-248.6	over 40	-0.43	-1.10				
	1990 beginning in 2010	-74.6	-233.8	over 40	-0.40	-1.02				
	peak in 2015, 1990 in 2040	-56.4	-220.2	over 40	-0.28	-0.93				

A plan to return carbon emissions to their 1990 levels by 2010 postpones by 12 years the date at which CO2 concentrations reach twice pre-industrial levels. Global warming would be reduced by 0.31 degrees by the year 2100 versus an estimated 2.45 degrees under BAU.

The estimated increase in the price of carbon that would be necessary under this plan would raise gasoline prices by 26 cents a gallon and coal prices by 273 % in 2010.

A less ambitious path – "eliminate emissions growth by 2010-2020" – would postpone the doubling date by 3 years less, and would lead to another 0.03 degrees of warming. But, the economics would become much easier: The price of gasoline in 2010 need go up only 3 cents and coal prices by only 53 %.

* Preliminary CEA projections. Revisions due by early next week. The origin of these preliminary numbers is described on the accompanying page.
** Pre-industrial concentrations of CO2 were approximately 275 ppmv.
*** Domestic Trading Only. Annex I or International Trading may substantially reduce these costs.

Draft - Close Hold

August 15, 1997

Sources and Explanations

Sources

Business As Usual (BAU) emissions projections are based on published IPCC IS92a emissions profiles. BAU concentration and temperature projections are from the MiniCAM model provided to CEA by Jae Edmonds, Marshall Wise, and Chris MacCracken at Battelle, Washington, DC.

Participation Cases

Annex I Participation Only: Assumes full compliance of stated targets and timetables by countries in Annex I; rest of the world behaves as in BAU.

Worldwide Participation: All nations including developing countries are assumed to comply fully with the same targets and timetables.

Targets and Timetables

1990 (-10%) in 2010: Emissions follow BAU through 2000, reduce to 1990 (-10%) levels by 2010, and remain at 1990 levels thereafter.

Peak in 2015, 1990 in 2040: Emissions follow BAU through 2005, peak at 2010 BAU levels in 2015, and stabilize at 1990 levels in 2040 and into the future. Because of linear interpolation in emissions profile between 2015 and 2040, this scenario may slightly overestimate the deviation of concentration from BAU.

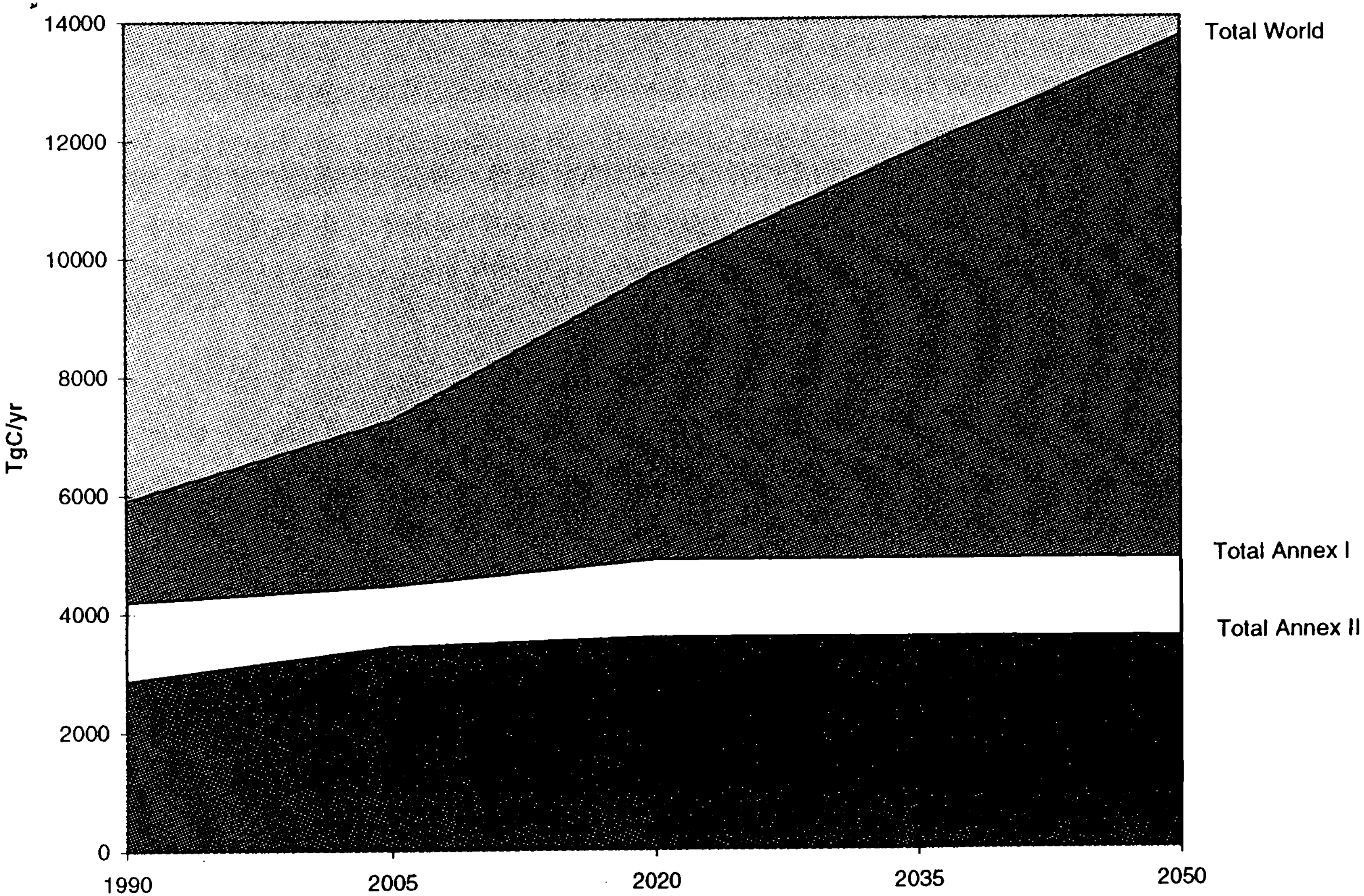
Price Assumptions

Carbon: U.S. permit prices for the policy options to attain 1990 emissions level in 2010 and 10% below 1990 emissions level in 2010 are from the DRI model used by EPA, which assumes that all revenues are used to improve the federal budget. The estimated permit price necessary under the policy option that peaks in 2015 is a linear interpolations based on these models.

Oil, Gasoline, and Coal: U.S. price increases of fuels were calculated based on the permit price and the fuels' carbon content.

Comparison of Atmospheric CO2 Concentrations Developed by the IPCC (S350-S750) and by Wigley, Richels, and Edmonds (WRE 350-750)																
(ppmv: parts per million by volume)																
YEAR	S350	S450	S550	S650	S750	WRE350	WRE450	WRE550	WRE650	WRE750						
2010	380.656	384.486	385.821	387.804	390.249	390.993	393.748	394.192	394.193	394.193						
2020	389.47	398.337	401.823	406.188	411.531	405.249	413.56	418.524	419.487	419.746						
2050	394.945	431.028	449.77	466.117	485.308	401.991	443.221	485.933	501.321	507.495						
Comparison of Emissions Trajectories Consistent with Various Atmospheric CO2 Concentrations Developed by the IPCC and WRE																
(PgC: Peta(10^15) grams of Carbon)																
YEAR	S350	S450	S550	S650	S750	WRE350	WRE450	WRE550	WRE650	WRE750						
2010	6.361	7.401	7.798	8.313	8.946	8.373	9.498	9.899	9.901	9.901						
2020	5.626	7.361	8.12	8.932	9.918	7.152	8.974	10.77	11.193	11.4						
2050	2.635	6.515	8.868	10.544	12.391	1.164	5.886	10.615	12.872	13.85						
Differences in Atmospheric CO2 Concentrations Between Those Developed by the IPCC and by WRE																
(ppmv)																
YEAR	Delt350	Delt450	Delt550	Delt650	Delt750	S350	S450	S550	S650	S750	S350a	S450a	S550a	S650a	S750a	
2010	10.337	9.262	8.371	6.389	3.944	380.656	384.486	385.821	387.804	390.249	390.993	393.748	394.192	394.193	394.193	
2020	15.779	15.223	16.701	13.299	8.215	389.47	398.337	401.823	406.188	411.531	405.249	413.56	418.524	419.487	419.746	
2050	7.046	12.193	36.163	35.204	22.187	394.945	431.028	449.77	466.117	485.308	401.991	443.221	485.933	501.321	507.495	
Differences in Anthropogenic Carbon Emissions Between Those Developed by the IPCC and by WRE																
(PgC)																
YEAR	Delt350	Delt450	Delt550	Delt650	Delt750	S350	S450	S550	S650	S750	S350a	S450a	S550a	S650a	S750a	
2010	2.012	2.097	2.101	1.588	0.955	6.361	7.401	7.798	8.313	8.946	8.373	9.498	9.899	9.901	9.901	9.9
2020	1.526	1.613	2.65	2.261	1.482	5.626	7.361	8.12	8.932	9.918	7.152	8.974	10.77	11.193	11.4	11.4
2050	-1.471	-0.629	1.747	2.328	1.459	2.635	6.515	8.868	10.544	12.391	1.164	5.886	10.615	12.872	13.85	14.5
Decadal Delta PPMV																
(ppmv)																
YEAR	S350	S450	S550	S650	S750	S350a	S450a	S550a	S650a	S750a						
2010	11.902	14.781	15.831	17.294	19.095	18.739	21.493	21.937	21.938	21.938						
2020	8.814	13.851	16.002	18.384	21.282	14.256	19.812	24.332	25.294	25.553						
2050	-1.555	9.175	15.843	20.546	25.83	-7.867	5.732	20.153	27.042	29.958						
Note: Sxxxa is the same as WRExxx.																

Projected Carbon Emissions from Fossil Fuel Energy Consumption
Business As Usual



Source: PNNL MiniCAM Model, 1996

M

E X E C U T I V E   O F F I C E   O F   T H E   P R E S I D E N T

27-Dec-1996 10:03am

TO: Raymond Prince

FROM: Jeffrey A. Frankel
Council of Economic Advisers

SUBJECT: RE: CO_2 emissions estimates

Ray,

We really want emission numbers for 2020, and if possible 2010. When I eyeball the grpah in the WRE paper, I notice:

(1) the IPCC paths for different terminal concentration levels don't start to diverge until 2020, which would make it difficult to answer the question. But the WRE paper says that the IPCC paths were not chosen as the outcome of any sort of optimization. It seems that we should be far more interested in the paths that WRE themselves offer.

(2) Eyeballing the WRE paths, it seems to me that, roughly, terminal concentration levels and corresponding paths identified by 2010 emission levels go as follows:

```
350 ppm -- 6.4 ggt C = - 9% from 1990
450     -- 7.5       = + 7%
550     -- 8.4       = +20%
baseline             = +40% .
```

Can't you please contact somebody (Wigley, Riches or Edmonds?) to get the exact numbers from their estimates/simulations?

JF

E X E C U T I V E   O F F I C E   O F   T H E   P R E S I D E N T

23-Dec-1996 07:47pm

TO: Jeffrey A. Frankel

FROM: Raymond Prince
Council of Economic Advisers

SUBJECT: <u>CO2 emissions estimates</u>

I haven't been able to get decade by decade figures for the Edmonds and IPCC scenarios yet, but the final draft of the IPCC technical paper on stabilization does have cumulative emissions from 1990 to 2100 for different target concentration levels. For 550 ppm (doubling of preindustrial levels), the IPCC report estimates total emissions of 870 gigatons of CO2 for its scenario; for the Edmonds scenario (business as usual up to 2000, an emissions trajectory that minimizes the present value of costs at 5% afterward) the total is 990 gigatons.

The IPCC report, which divides fossil fuels into conventional oil and gas, coal, and unconventional oil and gas (e.g., tar sand, oil shale, and coalbed methane) makes the following observation.

"The degree to which conventional oil and gas resources are depleted changes significantly when the stablisation target is raised to 500 ppm....This quantity would allow society to exhaust its conventional supplies of oil and gas and nearly exhaust its conventional supplies of coal. A stablisation target of 550 ppm allows cumulative emissions to exceed current central estimates of total conventional plus unconventional oil and gas and total conventional oil and gas plus coal resources." p. 24

baseline up 40%
9.8
8.4 550 ppm up 20%
7.5 450 ppm up 7%
7
6.4
350 ppm down 9%
-0
4% 2015

MEMORANDUM

COUNCIL OF ECONOMIC ADVISERS

Oct 16, 1996

COPY

TO: JOE STIGLITZ, ALICIA MUNNELL, JEFF FRANKEL

FROM: RAY PRINCE

SUBJECT: WHEN AND WHERE FLEXIBILITY

Attached are two graphs from a series of seminal papers by Tom Wigley (National Center for Atmospheric Research), Richard Richels (Electric Power Research Institute) and Jae Edmonds (Pacific NW labs) on the benefits of adopting policies with "When" and "Where" flexibility.

The first graph shows the estimated optimal time path of emissions for four different target levels of concentrations (target date: 2300; concentration levels: 350-750). All but the 350 path show the optimal level of emissions rising for several years after 1990 and then falling. As a benchmark, a concentration level of 650 ppm is expected to raise global temperatures 3 degrees centigrade above pre-industrial levels (2+ above current temperatures).

The second graph indicates the estimated cost of not setting the price or emissions levels at the optimal level nor having an adjustment mechanism that would get you back to the optimal path.

The "without when and where flexibility" scenario is based on each country having a set emissions target for each year based on their 1990 levels which are met at least cost.

The "When only" scenario assumes each country has an emissions budget which they spend optimally over time.

The "Where only" scenario assumes international emissions trading but a set world target for each year so that all potential intra-temporal efficiencies are captured (no banking or borrowing).

The "When and Where" scenario assumes a world emissions budget which is spent optimally over space and time so that all potential intra and inter-temporal efficiencies are captured.

IPCC EMISSIONS

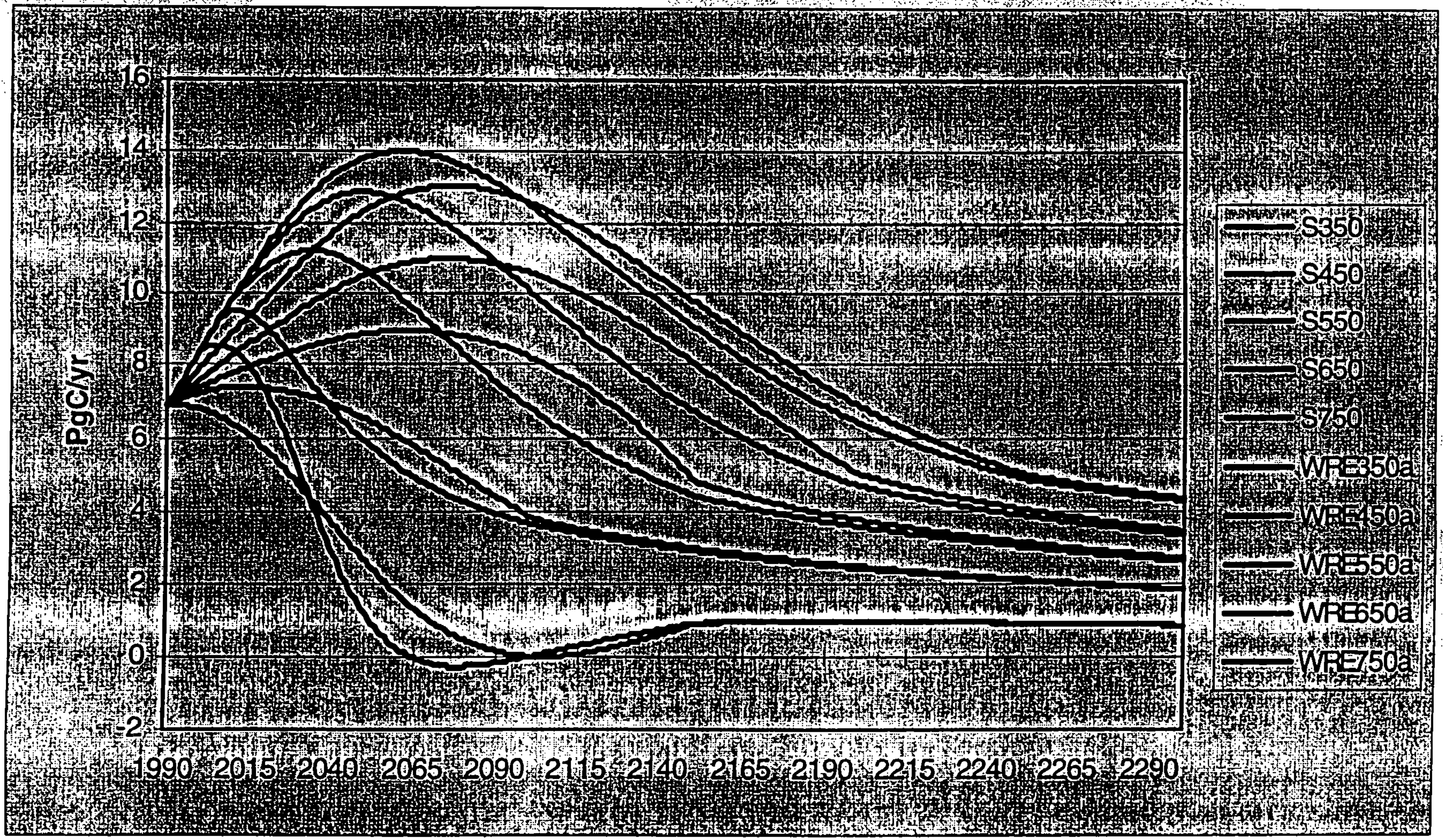
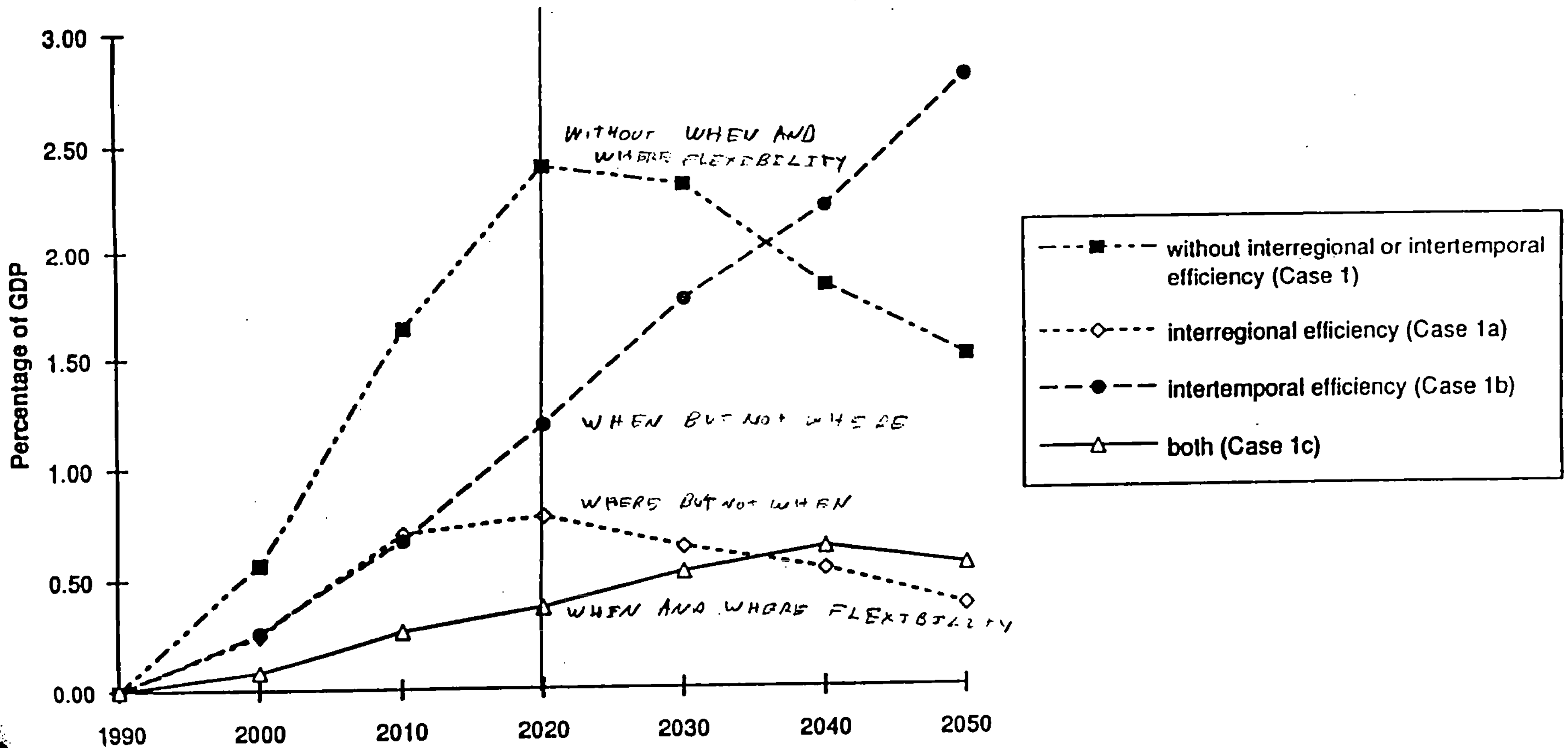


Figure 7. OECD GDP Losses under Alternative Assumptions about Economic Efficiency (based on average of model results)

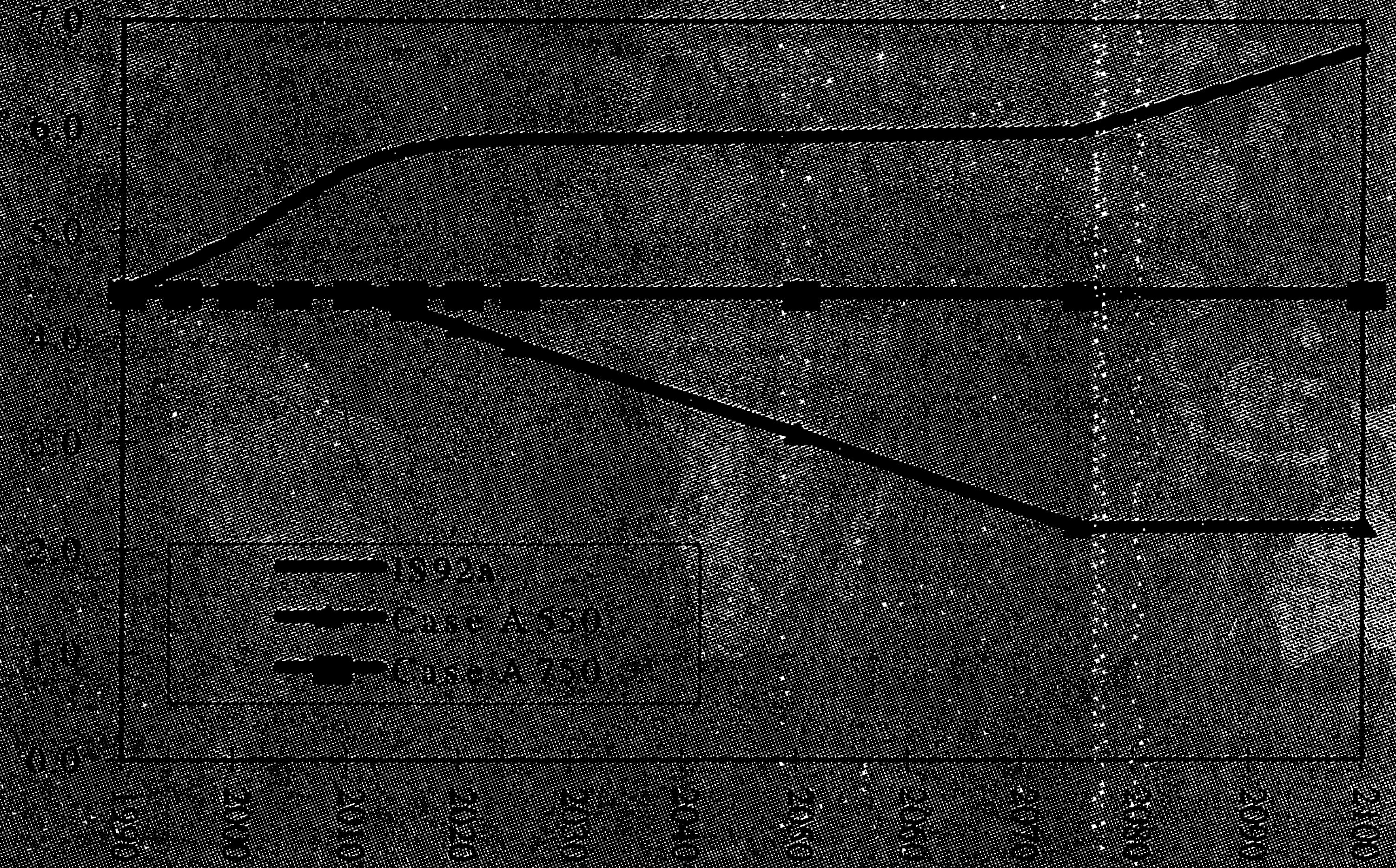


CASE A750 HYPOTHETICAL ANNEX I EMISSIONS

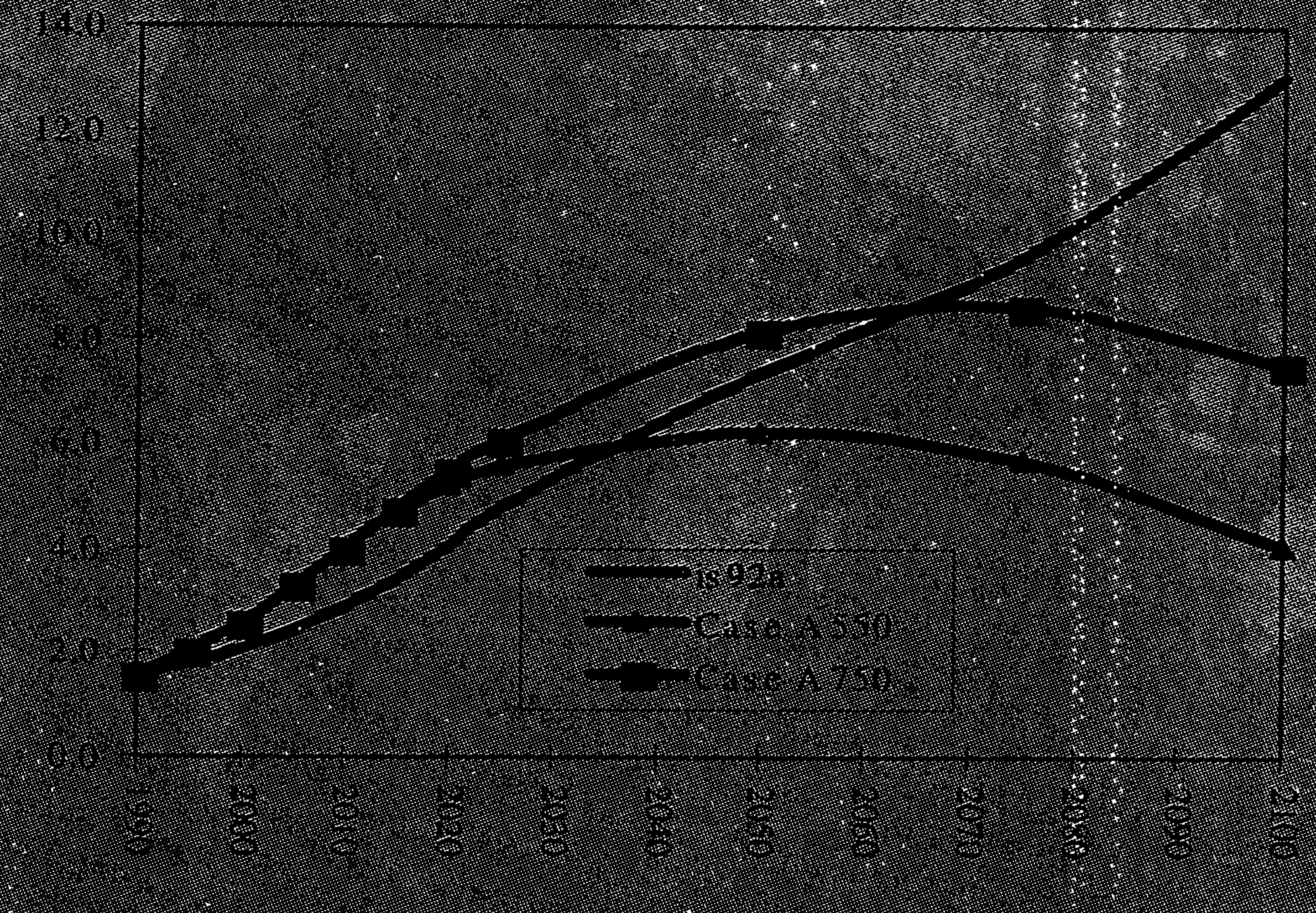
ANNEX I ASSUMPTIONS

- Stabilization of Emissions at 1990 levels to 2020.
- Emissions Stable @ 1990 levels thereafter.

ANNEX I ENERGY EMISSIONS

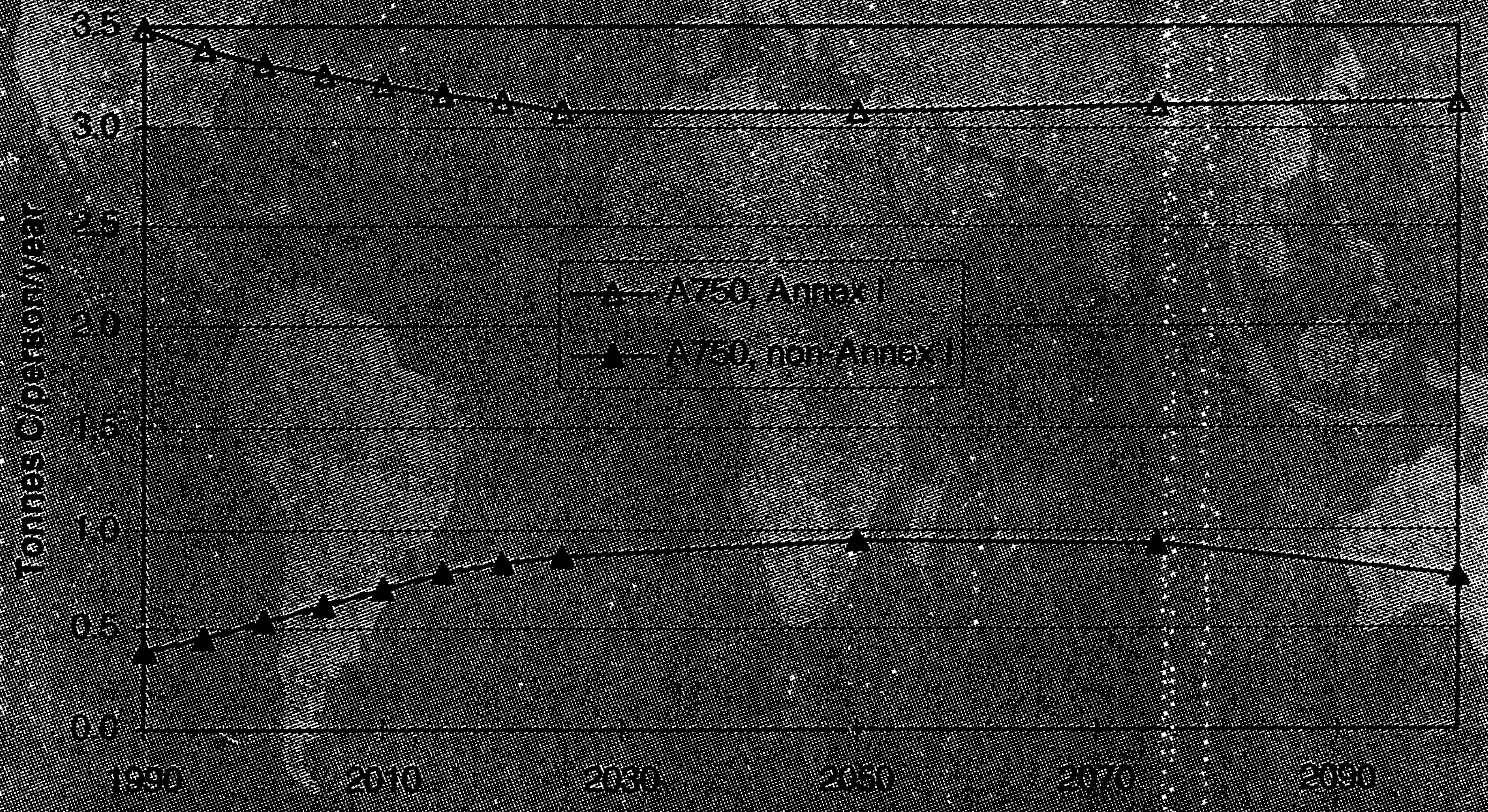


NON-ANNEX I ENERGY EMISSIONS ALLOWANCES



PER CAPITA EMISSIONS

Annex I and non-Annex I, Case A750



M

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

by Richard Richels[1], Jae Edmonds[2], Howard Gruenspecht[3] and Tom Wigley[4]

with contributions from Henry Jacoby[5], Alan Manne[6], Stephen Peck[7], Tom Teisberg[8], Marshal Wise[9] and Zili Yang[10]

Energy Modeling Forum Working Paper
Stanford University

February 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: 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
[2]Pacific Northwest Laboratory
[3]US Department of Energy
[4]University Corporation for Atmospheric Research
[5]Massachusetts Institute of Technology
[6]Stanford University
[7]Electric Power Research Institute
[8]Teisberg and Associates
[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

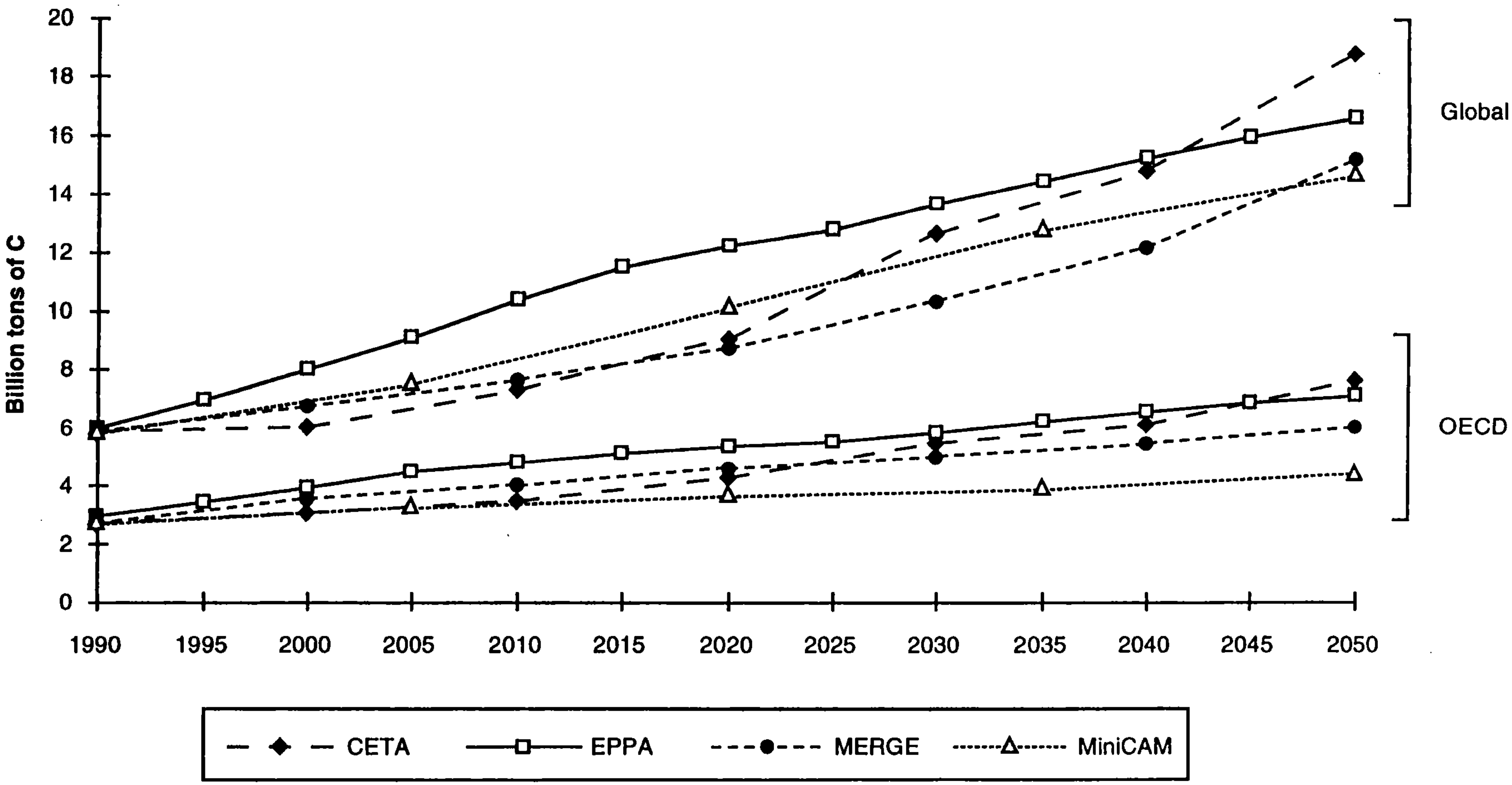


Figure 2. Global Emissions under Business as Usual and with a 20% Cut in OECD Emissions (based on average of model results)

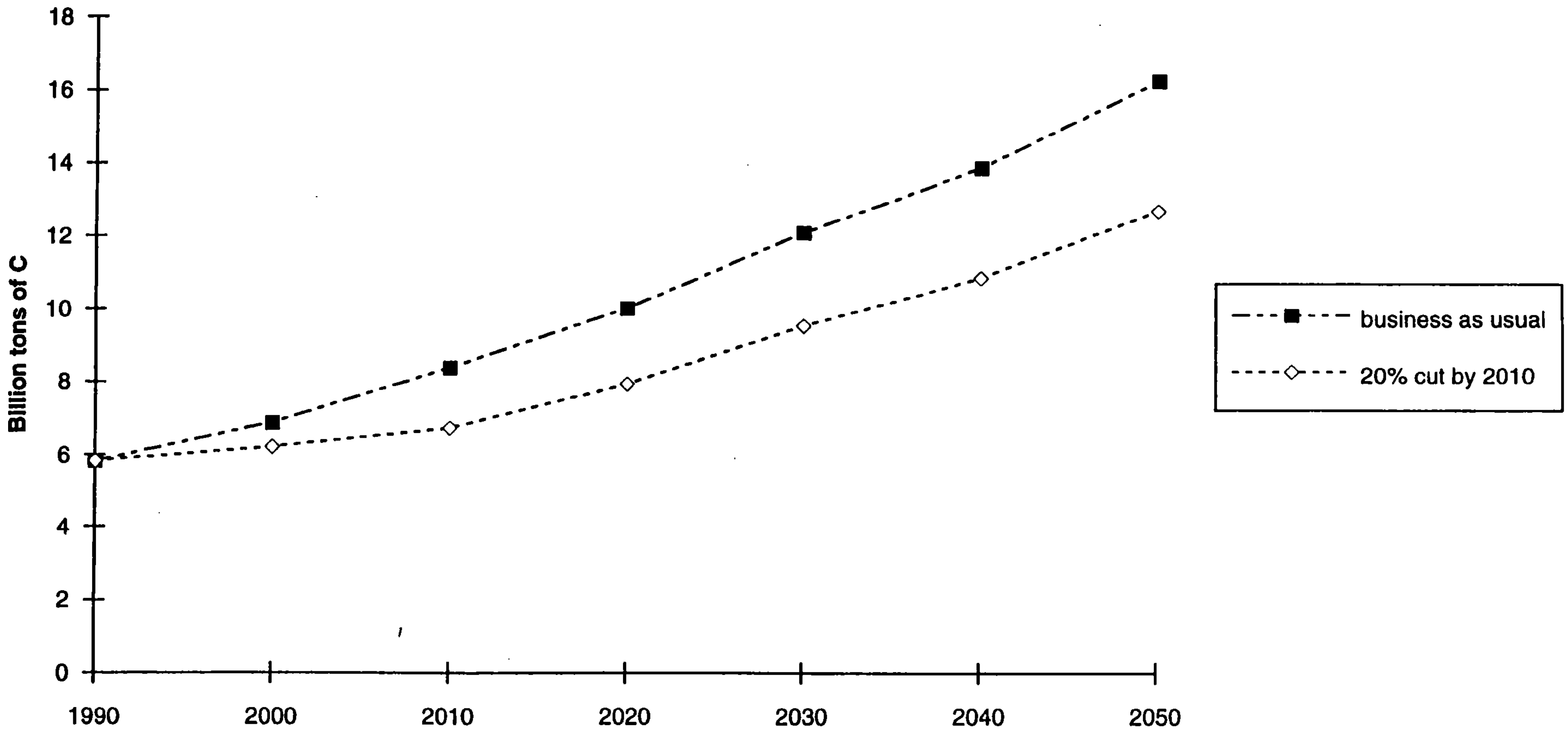


Figure 3. Costs of 20% Cut in OECD Emissions by 2010 -- Case 1 (costs through 2050 discounted to 1990 at 5%)

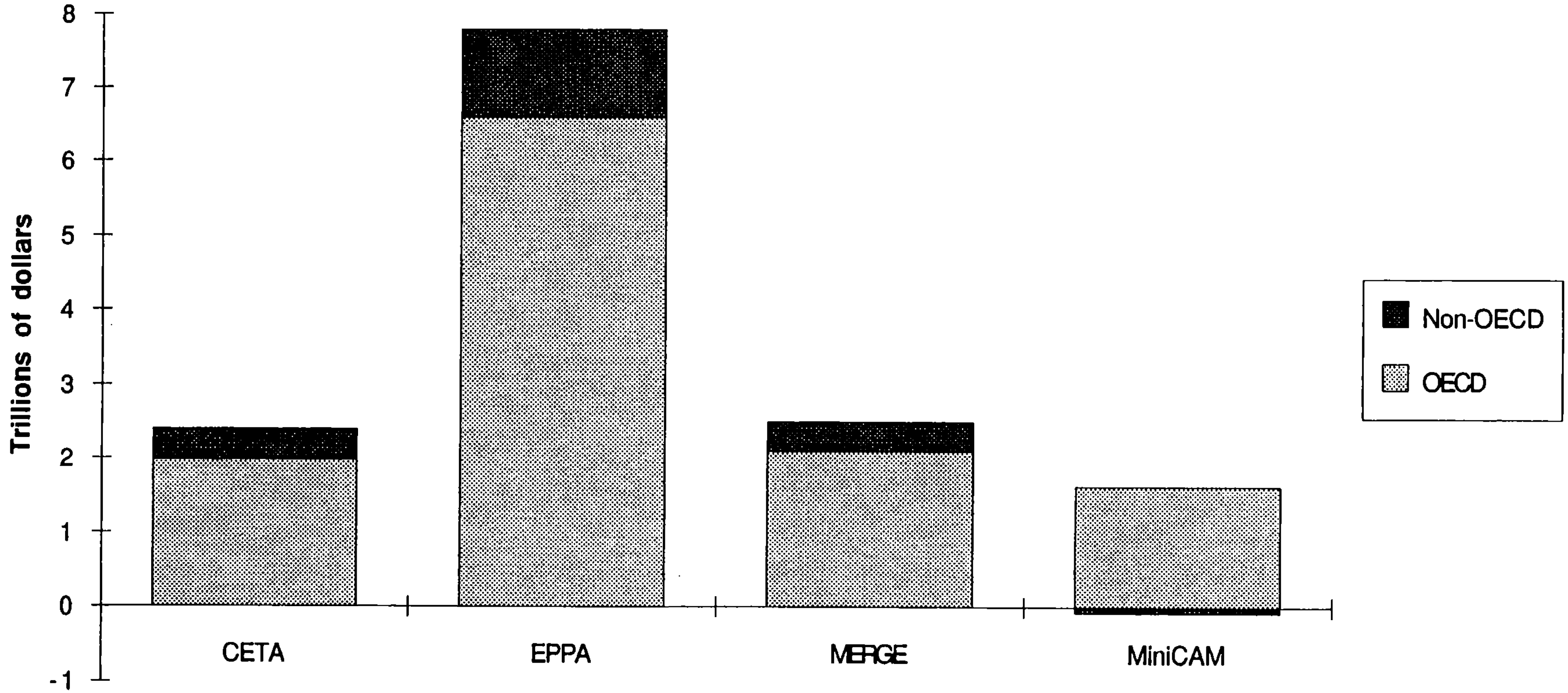


Figure 4. Global Costs under Four Alternative Cases

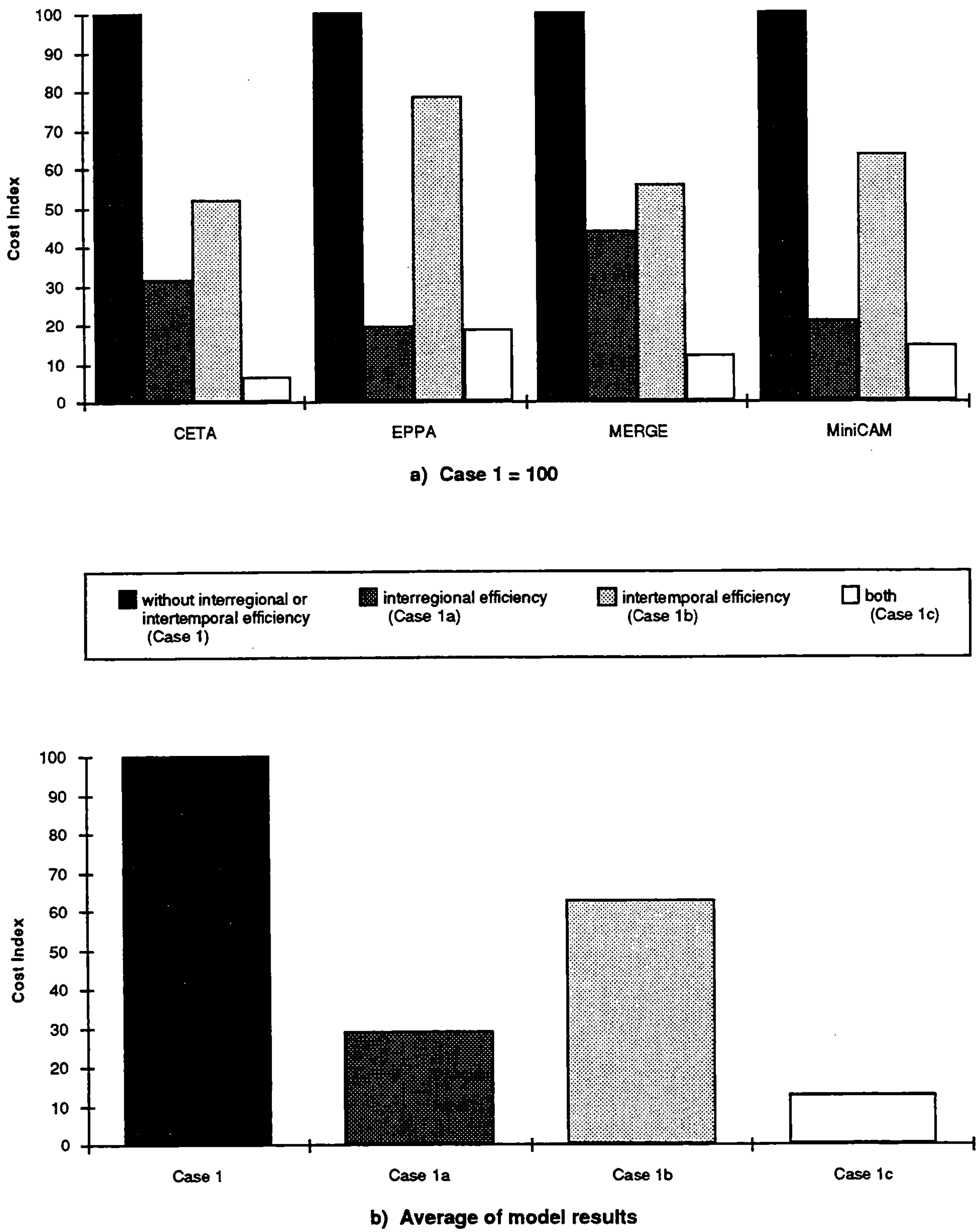


Figure 5. Regional Costs under Four Alternative Cases
(costs through 2050 discounted to 1990 at 5%)

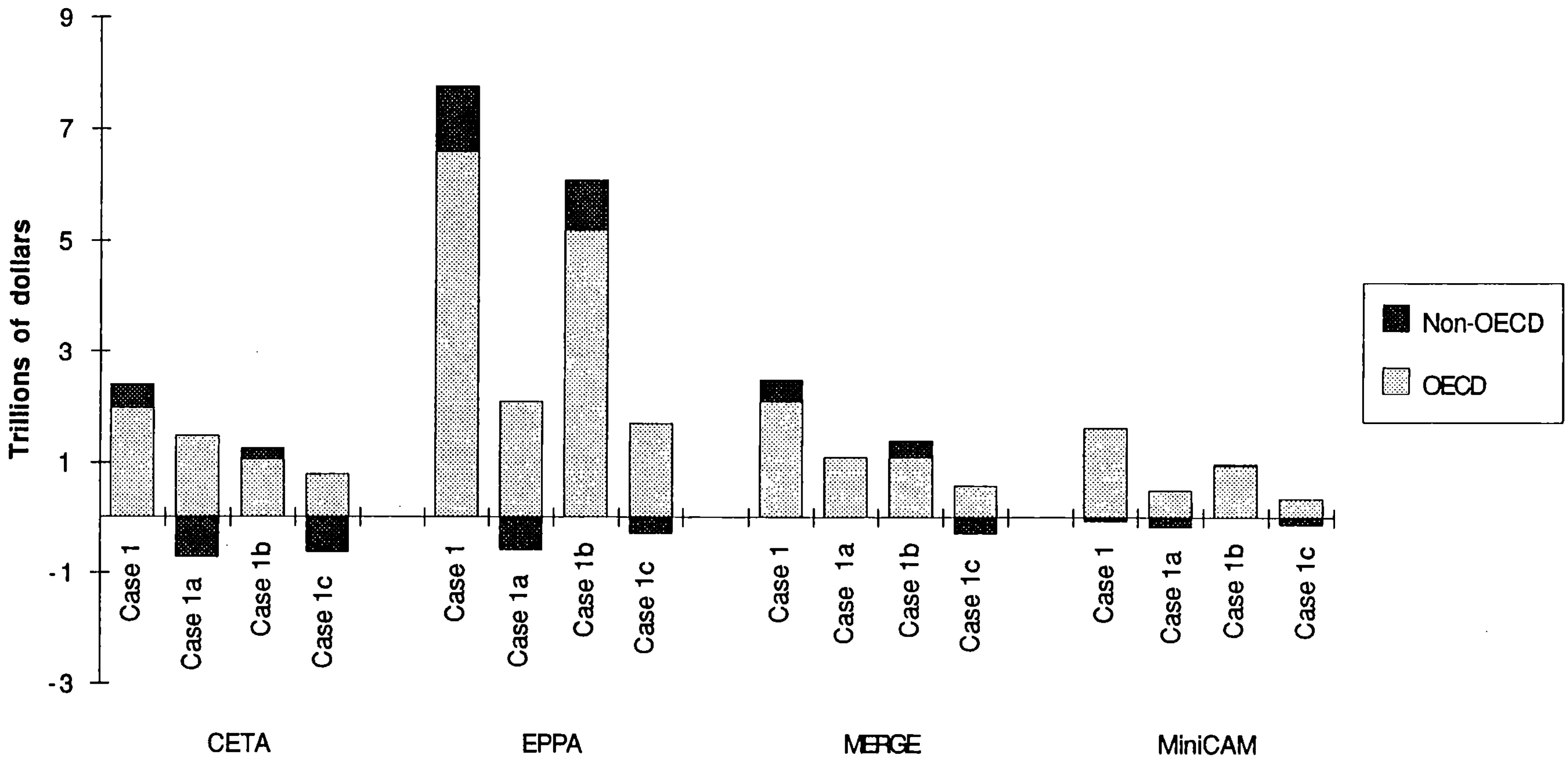
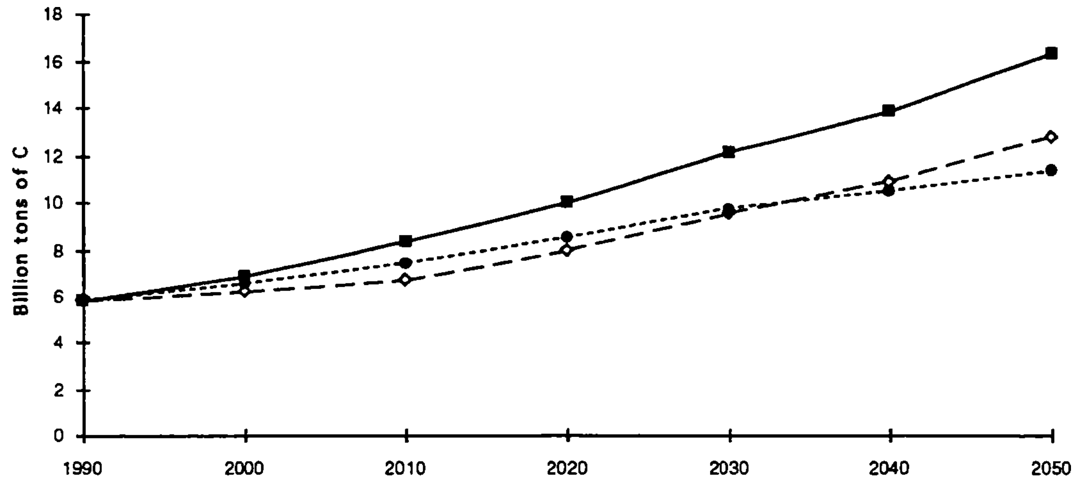
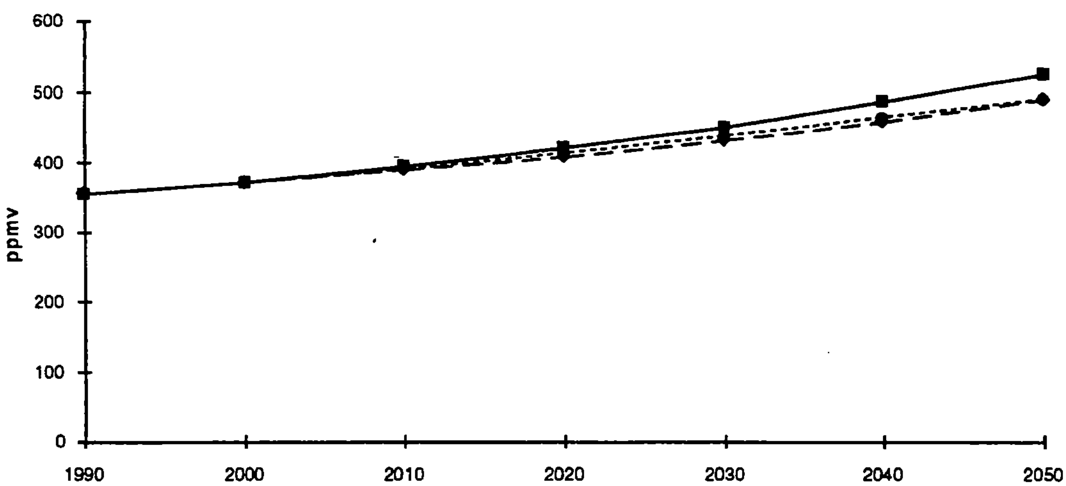


Figure 6. Global Emissions and CO2 Concentrations with and without Intertemporal Efficiency (based on average of model results)



a) Global emissions



b) CO_2 Concentrations

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

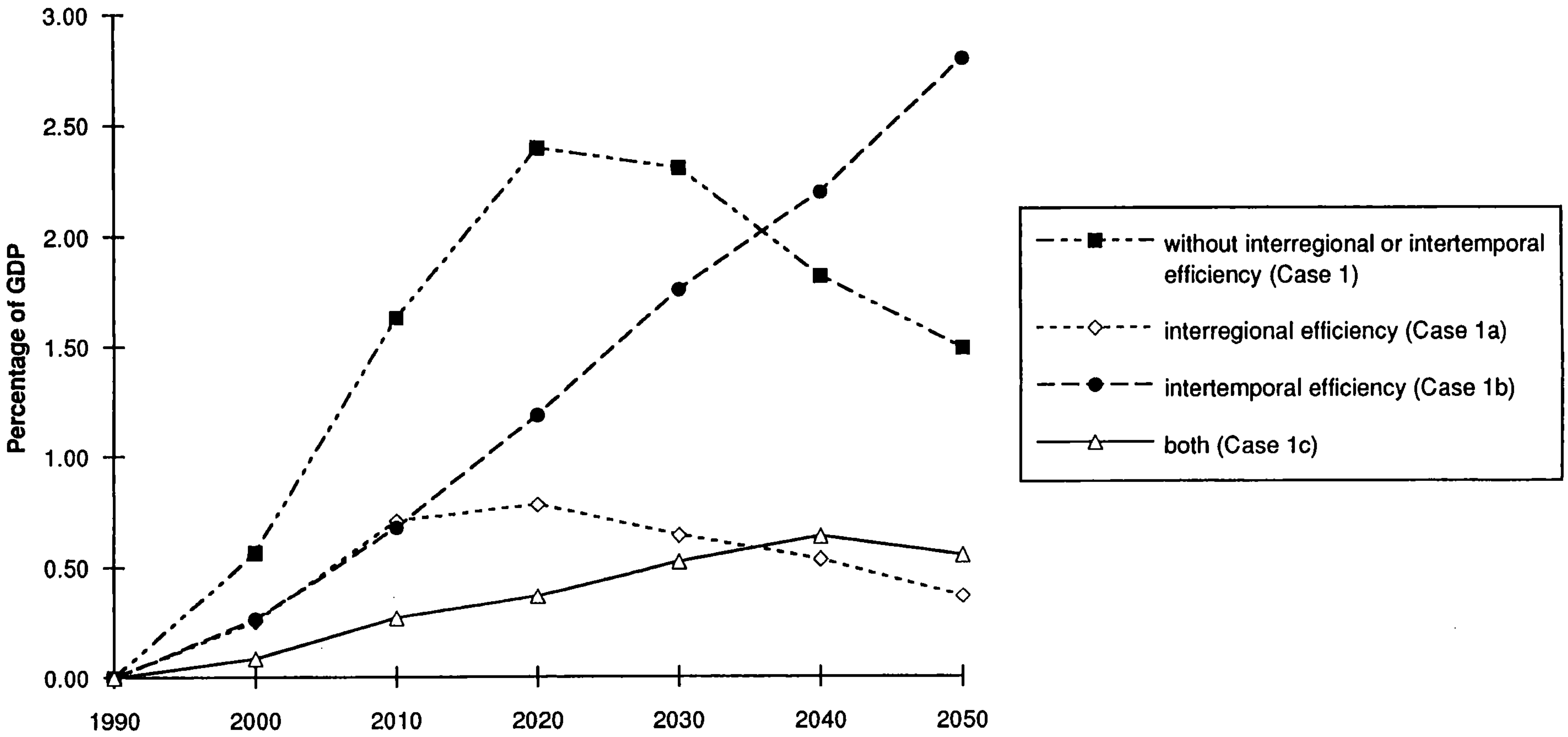
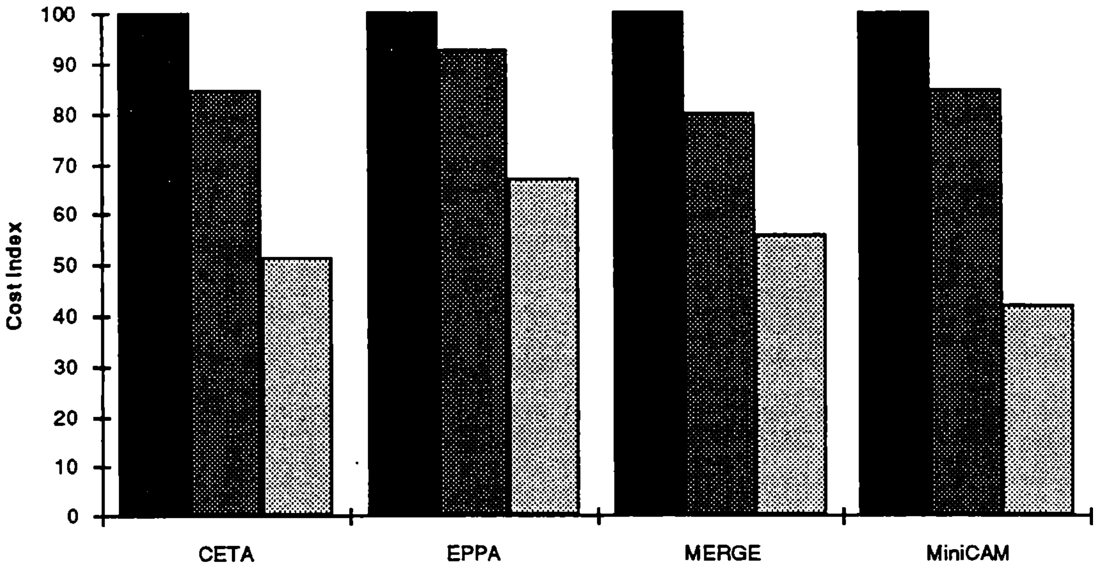
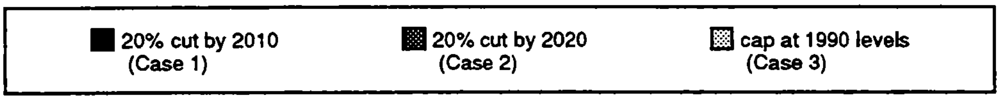
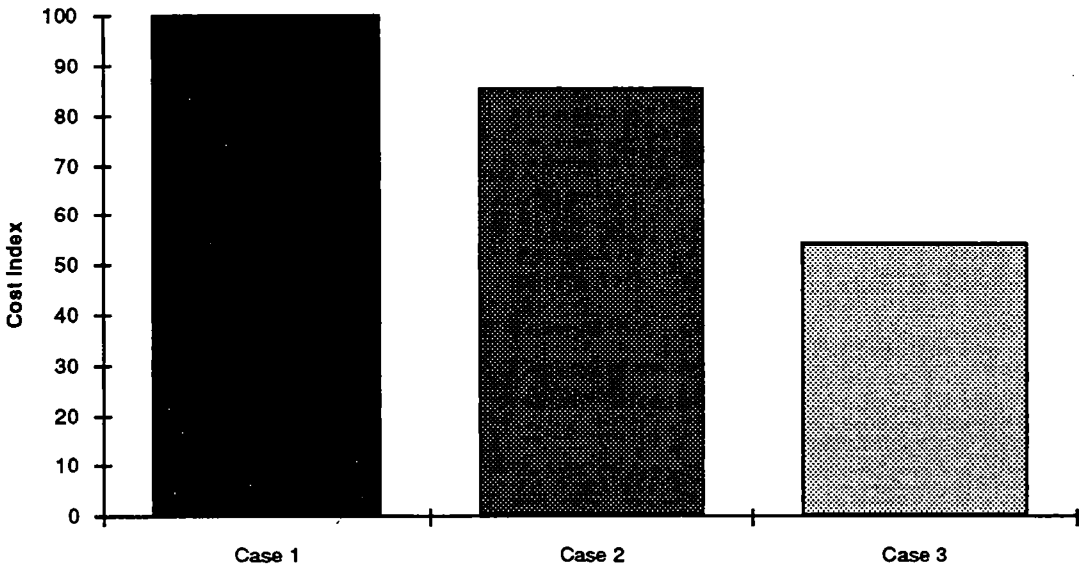


Figure 8. Costs of Alternative Sets of Targets and Timetables



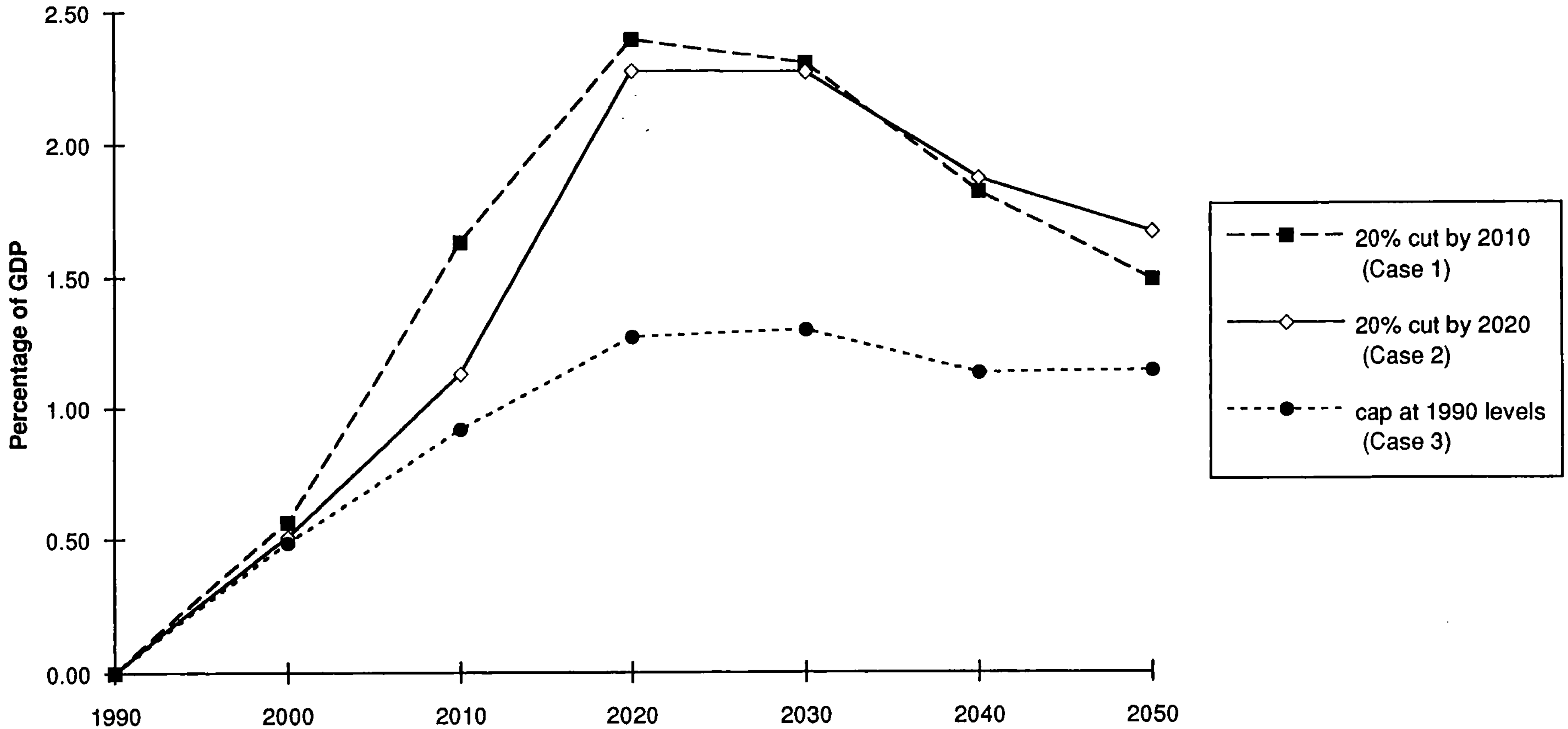
a) Case 1 = 100





b) Average of model results

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



Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations

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THE ultimate goal of the UN Framework Convention on Climate Change is to achieve "stabilization of greenhouse-gas concentrations...at a level that would prevent dangerous anthropogenic interference with the climate system". With the concentration targets yet to be determined, Working Group I of the Intergovernmental Panel on Climate Change developed a set of illustrative pathways for stabilizing the atmospheric CO_2 concentration at 350, 450, 550, 650 and 750 p.p.m.v. over the next few hundred years[1,2]. But no attempt was made to determine whether the implied emissions might constitute a realistic transition away from the current heavy dependence on fossil fuels. Here we devise new stabilization profiles that explicitly (albeit qualitatively) incorporate considerations of the global economic system, estimate the corresponding anthropogenic emissions requirements, and assess the significance of the profiles in terms of global-mean temperature and sea level changes. Our findings raise a number of important issues for those engaged in climate-change policy making, particularly with regard to the optimal timing of mitigation measures.

The IPCC Working Group I (WGI) concentration profiles (S350–S750; Fig. 1) were constructed under the following constraints: (1) prescribed initial (1990) concentration and rate of change of concentration; (2) a range of prescribed stabilization levels and attainment dates; and (3) the requirement that the implied emissions should not change too abruptly. Inverse calculations

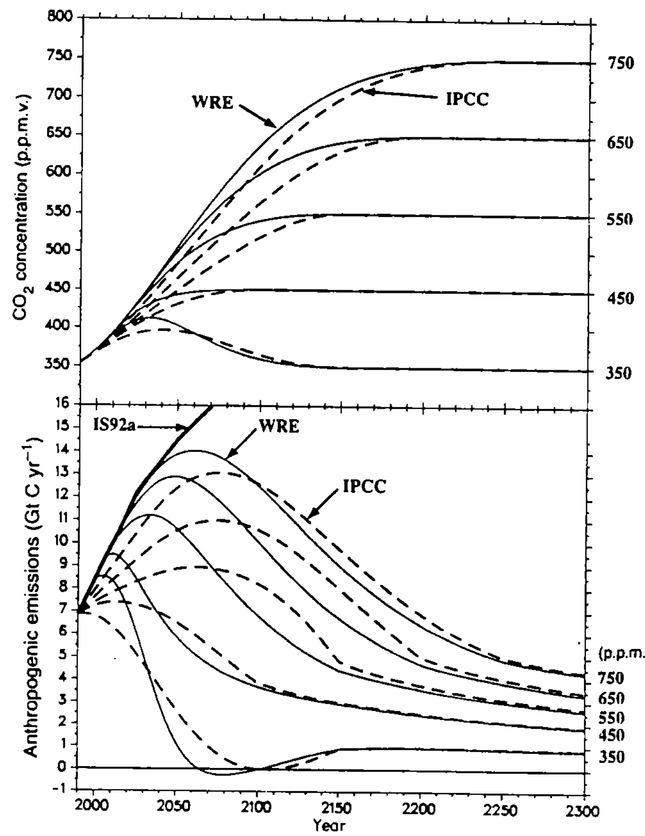

FIG. 1 Top, IPCC WGI[1,2] (dashed lines) and revised concentration profiles (WRE (this paper), solid lines) for stabilization of CO_2 at 350–750 p.p.m.v. Bottom, implied anthropogenic emissions using the model of Wigley[5]. IS92a is shown (thicker line) for comparison. Emissions were calculated following the procedure in ref. 1 in which the terrestrial biosphere sink is characterized solely by CO_2 fertilization of net primary productivity. The implications of using CO_2 fertilization as the sole terrestrial sink are discussed in ref. 4. The post-1990 inverse calculations were initialized by specifying a value for the 1980s-mean net deforestation (D_n80s). This determines the magnitude of the CO_2 fertilization factor. In the calculations in refs 1 and 2, D_n80s was taken as 1.6 Gt C yr^{-1}. This value has subsequently been revised downwards to 1.1 Gt C yr^{-1} (ref. 2), the value used here. Other minor budget changes have been made to accord with most recent data.

were then used to determine the emission rates required to achieve stabilization via the specified pathways. These show that stabilization requires an eventual and sustained reduction of emissions to substantially below current levels. Furthermore, some have interpreted the results for the IPCC pathways to imply that an immediate reduction in emissions (relative to the central IPCC "existing policies" or "business as usual" emissions scenario, IS92a[3]) is required to achieve any of the stabilization targets.

The WGI analysis was not intended as a recommendation for policy, but it will be carefully scrutinized for its policy implications. Consequently, it is important to understand what the analysis does and does not tell us. The first conclusion of the IPCC analysis, that meeting any of the prescribed targets will require emissions to decline eventually to levels well below today's, is robust. One cannot conclude from the WGI results, however, that an immediate reduction in emissions is required if we are to stabilize concentrations at 750 p.p.m.v. or below. The WGI emissions results correspond to just one of a range of possible pathways toward a particular concentration target. Stabilization at the same level, via different concentration routes, would produce different emissions.

What therefore are appropriate criteria for selecting a concentration (and hence emissions) time-path? Some guidance is found in the Framework Convention itself. Article 3 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". Thus, if two paths were indistinguishable in terms of their environmental implications, then the path with the lower mitigation (that is, emissions reduction) costs would be preferred. If two paths differed in terms of their environmental impacts, the issue becomes one of balancing benefits and costs. Here we examine alternative pathways for meeting the prescribed concentration targets. We then consider both the economic (costs) and environmental (benefits) implications of choosing one concentration trajectory over another.

In revising the IPCC WGI profiles, we add an additional constraint to the three noted above: that the resulting emissions trajectories initially track a 'business as usual' (BAU) path. This is an idealization of the assumption that the initial departure from BAU would be slow. We also assume that the higher the concentration target, the longer the adherence to BAU. This produces quite different concentration pathways, complementing the ones defined by IPCC WGI.

If we constrain emissions to follow BAU initially, the required concentration paths must depend on what we assume for this baseline scenario. We concentrate here on results for the central IPCC scenario (IS92a[3]). A higher baseline (such as IS92e or f) will lead to higher initial emissions. For a lower baseline such as IS92c, the task of stabilization of CO_2 concentrations at a level around 500 p.p.m.v. would require little action[4]. To derive the new profiles, we followed IS92a concentrations for 10–30 years and then fitted a smooth curve to the stabilization levels and dates used in ref. 1, using the same Padé approximant method. Figure 1 compares the new profiles with the WGI profiles. Further details are given in ref. 4.

The emissions implied by these new pathways (Fig. 1, lower panel) were obtained using the model of Wigley[5]. Although the precise values are model-specific, as shown by the inter-model comparison of Enting *et al.*[1], the qualitative character of the results and the relative differences in emissions due to concentration pathway differences are not.

The WGI analysis suggests that an immediate departure from the BAU path is required to meet all CO_2 concentration targets. Figure 1 shows that this is not so for concentration targets of 450 p.p.m.v. and above. Furthermore, for targets of 550 p.p.m.v. and above, the maximum rates of emissions decline are similar in both the new and WGI cases (but more prolonged in the former).

Figure 2 compares the old (WGI) and new results in more detail for the 550 p.p.m.v. stabilization case, and assesses the sensitivity of the results to the length of the interval over which BAU emissions are followed. The upper panel shows the WGI pathway and revised pathways following BAU for 10, 20 and 30 years (the 20-year case is that considered earlier). The emissions differences (middle panel) are striking in terms of the implied carbon intensity of the global energy system in the early decades of the next century. The different cumulative emissions pathways diverge initially and then become nearly parallel as one approaches and moves beyond the stabilization point (AD 2150 in this case). Cumulative emissions are noticeably higher in the cases that follow IS92a initially (a result that applies to all stabilization levels). This is because the products of early emissions have a longer time to be removed from the atmosphere, and because the associated higher concentrations give stronger oceanic and terrestrial sinks. Thus, later emissions reductions allow greater total CO_2 production, particularly for higher stabilization levels. These cumulative emissions differences, not considered by IPCC[2], may have important economic implications.

We now turn to how mitigation costs might vary with the choice of concentration profile. The rising emissions baseline that we use corresponds to an assumption that, in the absence of policy intervention, CO_2 emissions will continue to grow. This is consistent with the overwhelming majority of studies recently reviewed by the IPCC[6]. The implication is that stabilizing concentrations will entail some positive mitigation costs. A growing baseline, however, does not imply the absence of "no regrets" emissions reduction options (that is, with zero or negative mitigation costs). Such options are typically included in sizeable

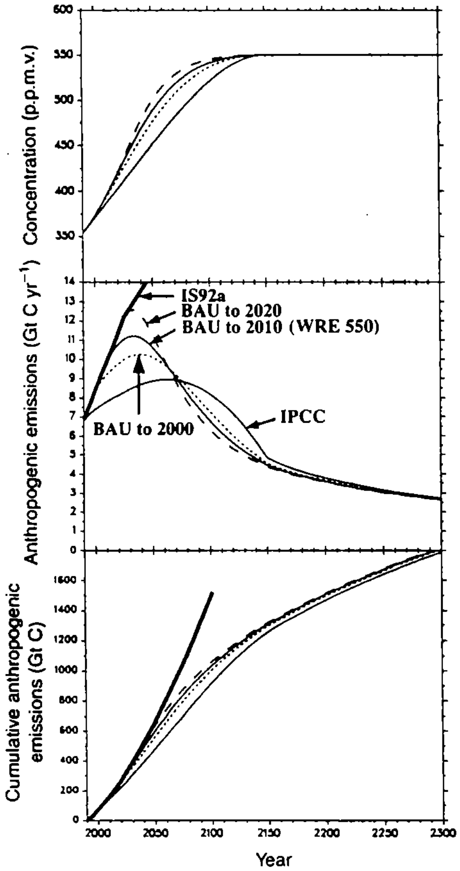

FIG. 2 Comparison of different concentration pathways (top panel) and implied emissions (middle) for stabilization of CO_2 levels at 550 p.p.m.v. in AD 2150. The pathways are: the original IPCC WGI S550 case[1]; the revised profile shown in Fig. 1 based on following BAU background emissions for 20 years, from 1990 to 2010 (WRE 550); and alternative revised profiles in which BAU is followed by 10 (BAU to 2000) or 30 years (BAU to 2020). The bottom panel shows the corresponding cumulative emissions. IS92a values are shown for comparison (thicker dashed lines).

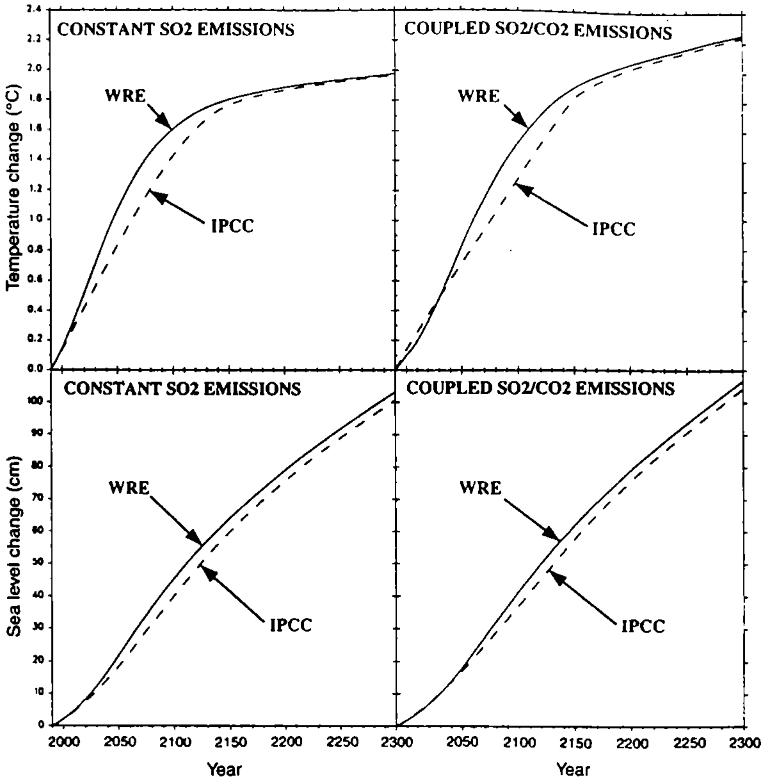

FIG. 3 Global-mean temperature (upper panels) and sea level changes (lower panels) for the S550 and WRE550 concentration stabilization pathways shown in Fig. 1. Results are from the models used in ref. 17, using the latest IPCC WGI estimate of the radiative forcing to 1990 and best-guess values of the climate sensitivity and ice-melt model parameters. Sea level changes include the contributions from oceanic thermal expansion, and ice melt from the world's glaciers and small ice caps, Greenland, and Antarctica. For the left panels, SO_2 emissions are held constant at their 1990 level. For the right panels, the effects of changes in anthropogenic SO_2 emissions (S) are added, with these changes directly coupled to those of fossil CO_2 emissions (F; values from Fig. 1) using $S = [S(1990)/F(1990)]F$. In both cases, the effects of non-CO_2 greenhouse-gases are accounted for by scaling CO_2 forcing by 1.33, the mean scaling for the IS92 emissions scenarios (compare ref. 21).

quantities in most economic analyses[7,8]. A growing baseline only means that economically competitive low-carbon alternatives are in insufficient supply to arrest future growth in carbon emissions. Conversely, if one were to assume that there are ample no-cost options to produce a falling emissions baseline, stabilization would entail little if any mitigation costs[9].

Several analysts have studied how mitigation costs might vary with the timing of the emissions reductions. For example, Nordhaus[10] and Manne and Richels[11] have identified cost-effective mitigation strategies for meeting a range of concentration targets. These studies show that to maintain cost-effectiveness, emissions tend to adhere longer to BAU the higher the concentration target (as assumed *a priori* here). Richels and Edmonds[12], in examining alternative emissions reduction pathways for stabilization at 500 p.p.m.v., found that the pathway can be just as important as the concentration stabilization level in determining the ultimate cost. Pathways involving modest reductions below a BAU scenario in the early years followed by sharper reductions later on were found to be less expensive than those involving substantial reductions in the short term. A similar conclusion can be found in Kosobud *et al.*[13].

Viewing the stabilization issue as a carbon budget allocation problem helps explain why concentration pathways with higher near-term emissions have lower overall mitigation costs. Because cumulative emissions are approximately independent of the concentration pathway, for each stabilization level there is, roughly, a fixed allowable amount of CO_2 to be released. The basic choice is, therefore, how this budget is to be allocated over time. From this perspective, the reasons for drawing more heavily on the budget in the early years are: (1) *Positive marginal productivity of capital.* With the economy yielding a positive return on capital[14], the further in the future an economic burden (here, emissions reduction) lies, the smaller is the set of resources that must be set aside today to finance the burden. (2) *Capital stock.* Stock for energy production and use is typically long-lived (for example, power plant, housing and transport). The current system is configured based upon a set of expectations about the future. Unanticipated changes will be costly. Time is therefore needed to reoptimize the capital stock. (3) *Technical progress.* There is ample evidence for past and potential future improvements in the efficiency of energy supply, transformation and end-use technologies. Thus, the availability of low-carbon substitutes will probably improve and their costs reduce over time. In addition, as the emissions budget will be somewhat larger (that is, greater cumulative emissions) for pathways with higher emissions earlier, dependence on higher-cost, carbon-free alternatives is reduced.

We must stress that, even from the narrow perspective of a cost-effectiveness analysis, our results should not be interpreted as suggesting a "do nothing" or "wait and see" policy. First, all stabilization pathways still require future capital stock to be less carbon intensive than under a BAU scenario. As most energy production and use technologies are long-lived, this has implications for current investment decisions. Second, new supply options typically take many years to enter the market place. To ensure sufficient quantities of low-cost, low-carbon substitutes in the future requires a sustained commitment to research, development and demonstration today. Third, any available "no regrets" measures for reducing emissions should be adopted immediately. Last, it is clear from Fig. 1 that one cannot go on deferring emissions reductions indefinitely, and that the need for substantial reductions of emissions is sooner the lower the concentration target.

It is, of course, also important to examine the environmental consequences of selecting one concentration or emissions trajectory over another. This is because different concentration pathways imply, not only different emissions reduction costs, but also different benefits in terms of averted environmental impacts. In benefit-cost analyses of climate change policy options, it is common to use global-mean temperature and sea level rise as coarse indicators of the extent of climate impacts[14,15]. We therefore calculate how these indicators are affected by differences in the pathways to stabilization at an atmospheric CO_2 concentration of 550 p.p.m.v., based on the model of Wigley and Raper[16,17]. We first consider the direct effects of greenhouse-gas concentration changes, and then how these results may be modified by SO_2 emissions. All results use the central IPCC-recommended estimate of climate sensitivity[18] (2.5 °C equilibrium global-mean warming for a doubling of atmospheric CO_2 levels) and best-guess ice-melt model parameters[17].

Figure 3 (left panels) shows that, if greenhouse gases alone are considered, both temperature change and sea level rise would be noticeably affected by the choice of pathway towards stabilization at 550 p.p.m.v. These results, however, depend critically on how SO_2 emissions are assumed to change in the future. For the greenhouse-gas-alone case, we have assumed these emissions to remain constant at their 1990 level. As an alternative, we also consider a case where SO_2 emissions are closely coupled to fossil-fuel-derived CO_2 emissions. This case is consistent with the IPCC (IS92) emissions scenarios, except for IS92d, out to at least 2050 (ref. 3). It could occur if developing countries were less successful than developed countries in decoupling SO_2 and CO_2 emissions. In global-mean terms, SO_2/CO_2 emissions coupling leads to compensation between the reduced warming from reduced CO_2 emissions and an increased warming due to reduced SO_2 emissions[19,20].

To demonstrate the significance of this link, we give a specific example. This example is not meant to provide quantitative information on environmental impacts (which, for climate change, cannot be achieved through global-mean temperature alone), but to draw attention to aerosol influences as a critical factor in assessing the benefit–cost balance. Figure 3 compares global-mean temperature and sea level results for constant SO_2 emissions (left panels) with those for directly coupled CO_2 and SO_2 emissions (right panels). With SO_2 coupling, the lower-emissions case (S550) actually has warmer temperatures out to around 2040. This is because the much shorter lifetime of aerosols leads to a more rapid radiative forcing response to SO_2 emissions changes than to CO_2 emissions changes, allowing the former to dominate initially (compare refs 19,20). For sea level, coupling has a similar but less marked effect.

The market (for example, agriculture, timber and fisheries) and non-market (for example, biodiversity, environmental quality and human health) implications of these results are unclear: do pathway-related differentials up to ~0.2 °C in global-mean temperature and 4 cm in global-mean sea level change translate into significantly higher damages and, if so, are these large enough to offset the reduced cost of a more economical transition away from fossil fuels? The answer depends on the regional details associated with these changes, and the sensitivities of impact categories to changes in important climate variables. Both aspects are highly uncertain. Nevertheless, it is clear that the choice of emissions path requires the consideration of both costs and benefits. □

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DRAFT **09/21/97**

Additional Analysis of the Costs of Stabilizing CO2 Concentrations[a]

by Alan Manne[b] and Richard Richels[c]

1. Introduction

The Berlin Mandate calls for further commitments on the part of Annex 1 to reduce greenhouse gas emissions. These commitments are to be negotiated and prepared for approval at COP-3 in December of 1997. As the deadline approaches, the signatories to the Climate Convention are struggling to determine what might constitute sensible next steps in terms of emission paths. Proposals range from slowing the rate of growth to deep and immediate cuts. These deliberations are being supported, in part, by an "analysis and assessment" phase designed to assist policy makers in understanding the environmental and economic implications of alternative proposals.

As part of this process, we recently examined the costs of complying with alternative constraints on CO2 emissions.[1] Our effort differed from most previous economic analyses in that we explored the emission constraints in the context of possible long-term concentration targets. The ultimate goal of the Climate Convention is the stabilization of atmospheric concentrations -- at a level yet to be determined. Rather than focus on arbitrary emission limits, it seemed to make more sense to examine future targets and timetables in the context of possible concentration goals. In this way, we can explore the sensitivity of near-term mitigation decisions, to the long-term objective.

This note extends our earlier work in several ways. We begin by modifying our previous emission profiles to encompass several proposals which have recently come under consideration. In each instance, we calculate costs under alternative assumptions about the timing and the magnitude of the emission reductions, and examine the implications for future atmospheric concentrations. We also explore what would happen if non-Annex 1 countries fail to participate. How would welfare losses be affected? What would be the implications for atmospheric concentrations?

The primary focus of our analysis is on mitigation costs. This, of course, is only part of the story. Sensible climate policy not only requires consideration of mitigation costs, it also requires consideration of what might be gained in terms of reducing the undesirable consequences of global climate change. In this paper, we make no attempt to estimate the potential benefits of slowing climate change, nor do we try to determine what might constitute a societally desirable concentration level. We do, however, in

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[a]The analysis from which the present research is derived (ref. 1) was undertaken as part of the authors' participation in Stanford University's Energy Modeling Forum-14 Study. Support was provided by the Electric Power Research Institute. The views expressed here, however, are solely those of its authors.
[b] Stanford University
[c] Electric Power Research Institute

addition to calculating costs, attempt to assess the impact of alternative policies on future atmospheric concentrations.

2. The model

The analysis is based on the MERGE model (a model for evaluating the regional and global effects of greenhouse gas reduction policies).[2,3] MERGE is an intertemporal optimization model. It combines a bottom-up representation of the energy supply sector together with a top-down perspective on the remainder of the economy.

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). Note that the OECD (regions 1 through 4) together with EEFSU constitute Annex 1.

Each of the model's regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region's wealth includes not only capital, labor and exhaustible resources, but also its negotiated international share in carbon emission rights.

Particularly relevant for the present analyses, MERGE provides a general equilibrium formulation of the global economy. We model international trade in carbon emission rights, allowing regions with high marginal abatement costs to purchase emission rights from regions with low marginal abatement costs.

When mitigation is limited to a subset of regions, so-called carbon "leakage" effects may become an issue. Here, we refer to the impacts of the emission policies of abating regions upon the emission levels of non-abating regions. In MERGE, we model international trade in oil and natural gas, but not in energy intensive basic materials. Hence, carbon leakage is detected only as it occurs through fuel markets.

In calibrating MERGE for the present analysis, several supply- and demand-side parameters for the energy-economy submodel were adjusted so that the global emissions baseline approximates the Intergovernmental Panel on Climate Change (IPCC) central case "no policy" scenario (IS92a) through the year 2100. See ref. 1 for our original estimates of Annex 1 and non-Annex 1 baseline emissions and total primary energy use by fuel type.

For constrained scenarios, it was also necessary to make assumptions about the allocation of emission rights across regions. Few issues are likely to be as contentious for international negotiators. For the present analysis, we have tried to be consistent with the Berlin Mandate. We assume that the burden will fall on Annex 1 countries during the early decades of the next century.

Specifically, we assume that: 1) non-Annex 1 countries will be permitted to emit up to their baseline through 2030 (that is, no constraints will be placed on their emissions until that date), 2) there will be a gradual transition to equal per capita emission rights (based on 1990 population) between 2030 and 2050, and 3) the equal per capita burden sharing rule will be maintained thereafter.

3. Three emission paths for stabilizing concentrations at 550 ppmv

A "prudent" concentration level has yet to be determined. Hence, in ref. 1 we examined a range of possible targets (i.e., 450-750 ppmv). For the present analysis, we concentrate on 550 ppmv. Most of the general insights gained from the analysis, however, should apply to other targets as well.

Figure 1 shows three pathways for stabilizing concentrations at 550 ppmv by the middle of the 22nd century. The first, developed by IPCC Working Group 1 (WG1)[4] involves a rapid departure from the baseline. The second, developed by Wigley, Richels and Edmonds (WRE)[5] entails a more gradual transition to a less carbon intensive economy. The third identifies the least-cost mitigation path for stabilizing atmospheric concentrations at the prescribed level.

The least-cost pathway incorporates both "where" and "when" flexibility. Economic efficiency requires that emission reductions be made both where and when it is cheapest to do so. The first requires international cooperation (for example, through trade in emission rights across all regions). The second requires flexible timing (reallocation of emission rights across generations).

Figure 2 shows the regional distribution of emissions for the least-cost mitigation path. Under this scenario, Annex 1 (OECD and EEFSU) emissions peak in 2030. The rate of growth, however, is relatively slow by historical standards. This is because anticipated improvements on both the supply- and demand-sides of the energy system are expected to lead to less carbon intensive economies. Hence, the fact that Annex 1 emissions tend to follow the baseline during the early decades should not be confused with a "business-as-usual" future in which carbon emissions grow at historical rates.

Table 1 presents an economic comparison of our three pathways for stabilizing concentrations at 550 ppmv. In the least-cost scenario, the value of emission rights begins at a relatively low level and increases gradually over time. This is consistent with a gradual transition away from the baseline. Such a transition provides valuable time: 1) to adapt the energy-using and energy-producing capital stock, 2) to develop low-cost substitutes to carbon intensive technologies, and 3) to draw the CO2 out of 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. 5.

The WRE and WG1 pathways place progressively increasing pressure on global emissions. The implications for welfare losses are shown in the rightmost columns of Table 1. The WRE path follows the least-cost path fairly closely in the early years. The associated welfare losses are therefore much closer to the least-cost scenario than to WG1. Nevertheless, from a global perspective, they are still 38% higher than the least-cost path. The increase in welfare losses is even greater when we focus on Annex 1 countries. Here, losses rise by more than 100% when we shift from the least-cost to the WRE path.

Welfare losses are highest under WG1. The tight near-term constraint drives up the value of emission rights. Global losses rise accordingly. Note, however, that non-Annex 1 comes out ahead under WG1 if there is trade in carbon emission rights. The sale of permits during the early decades of the 21^{st} century would result in a large wealth transfer from Annex 1 to non-Annex 1. This should not obscure the fact that from a global perspective, losses are far higher under WG1.

4. Alternative emission constraints

We next modify the WRE emissions pathway to explore several additional scenarios currently under consideration. Specifically, we examine scenarios in which Annex 1 emissions: 1) are allowed to increase by 10% above 1990 levels in 2010, 2) are returned to 1990 levels in 2010, and 3) are reduced by 10% below 1990 levels in 2010. For each of these scenarios, the 2010 target is maintained through 2030. At that point, Annex 1 emissions are determined by our burden sharing formula.

Figure 3 compares the global emission paths for the various scenarios. The WRE emission path was calibrated so that it would achieve the prescribed target of 550 ppmv. The modifications to the WRE path results in lower concentration levels. However, at most, the modified scenarios differ from the initial WRE concentration path by approximately 1% in 2100.

In calculating the welfare losses associated with the modified WRE scenarios, we assume global trading. That is, we assume that emission reductions will take place wherever it is cheapest to do so -- regardless of their geographical location. Hence, Annex 1 can purchase emission rights from non-Annex 1 and exceed its year-by-year emission constraint as defined above. We do not allow for intertemporal trading, however. There is no provision for shifting emission reductions into the future. Hence, we provide for where, but not when flexibility.

Table 2 summarizes the results. As we saw earlier, the value of carbon emission rights rises gradually under the least-cost scenario. This is in contrast to the modified WRE scenarios where the constraint on emissions is tightened during the early decades of the next century. This raises the value of emission rights in the early years..

Similarly, the modified WRE scenarios result in higher welfare losses. From a global perspective, the increases relative to the least-cost scenario range from 39% to 129% depending upon which of the three scenarios we adopt. The losses are even more pronounced in the case of Annex 1. Here the increases relative to the least-cost scenario range from 100% to 275%. The larger increases (in percentage terms) reflect the fact that the increased reductions fall on Annex 1.

5. The value of "where" flexibility

Thus far, the calculations for the modified WRE scenarios have been made under the assumptions that there will be global trading in carbon emission rights. Some have questioned whether such a market will actually materialize. They argue that the potential wealth transfers, together with troublesome implementation issues, pose formidable, if not insurmountable obstacles.

A discussion of the feasibility of global trading is beyond the scope of this analysis. However, we will explore the implications of restricting international trading to Annex 1 only or of eliminating it altogether. We will focus on the case where Annex 1 emissions are returned to 1990 levels in 2010.

Table 3 summarizes our results. Not surprisingly, welfare losses increase substantially in the absenee of global trading. The explanation lies in the value of carbon emission rights. Prior to 2030, non-Annex 1 can emit below their baseline and sell their excess emission rights to Annex 1. This allows Annex 1 countries to substitute high marginal cost options internally with low marginal cost options elsewhere in the world.

If this option is foreclosed and Annex 1 countries can only trade among themselves, they will have to forego cost-effective options in non-Annex 1. This is reflected in the higher value of emission rights. The problem is further exacerbated when international trading is eliminated altogether. In this case, each country must move up or down its own marginal cost curve to achieve the desired target.

6. Delaying the Target

In the above, we assumed that the modified WRE scenarios would take effect in 2010. What would be the implications of shifting the date by 10 years? That is, suppose we first constrain emissions relative to 1990 levels in 2020. For this set of experiments, we maintain our previous assumptions about non-Annex 1 involvement. We also assume full global trading.

Figure 4 shows what happens to emissions in 2010 when the constraint is postponed 10 years. Notice that the increase in emissions is relatively small. This is because MERGE is an intertemporal optimization model. In 2010, producers and consumers are able to foresee the impending constraint in 2020 and beyond. As a result, they begin moving towards a less carbon intensive economy prior to the imposition of the constraint. Otherwise, the energy-using and energy producing capital stock will be inappropriate for the future slate of fuel prices.

From Table 4, notice that when the constraint is postponed until 2020, the value of carbon emission rights in 2010 falls to zero. This is because the constraint in 2010 is no longer binding. Rather than having to reduce emissions relative to1990 levels, Annex 1 can now emit up to their baseline. This is an option it does not choose to exercise.

The increases in concentrations that result from the 10 year delay are small. For example, even in the case where emissions are reduced by 10% below 1990 levels, the increase in concentrations in 2100 due to a 10 year delay is less than 1%. So in effect we have delayed taxes (either explicit or implicit) to 2020, decreased mitigation costs somewhat (depending upon the case), and incurred only a small increase in future concentrations relative to implementing the constraint in 2010.

Postponing the constraint until 2020 compares unfavorably, however, to the least-cost mitigation scenario. Global welfare losses are still 39% to 92% higher depending upon which of the three scenarios we adopt. Losses to Annex 1 are 96% to 242% higher.

7. The effect of non-Annex 1 participation on welfare losses

Finally, we examine the case where non-Annex 1 does not choose to participate. Suppose, for example, that Annex 1 adopts the WRE path, but non-Annex 1 continues to follow its baseline. What are the implications for Annex 1 welfare losses?

From Table 5, we see that the welfare losses will depend upon whether there is trade in carbon emission rights among Annex 1 countries. If this is the case, Annex 1 losses rise from $.62 trillion to $.91 trillion or 47%. If emission trading among Annex 1 countries is prohibited, then losses rise to $1.10 trillion or 77%. Turning to the US, assuming Annex 1 trading, welfare losses rise from $.28 to $.36 trillion or 29%. In the absence of Annex 1 trading, losses rise to $.41 trillion or 46%.

Figure 5 shows the implications for CO2 concentrations. We consider two cases. In the first, non-Annex 1 countries are unaffected by actions taken in Annex 1. They continue to follow their initial baseline. In the second, there are ~~so-called~~ "leakage" effects. Here, actions on the part of Annex 1 lead to increases in non-Annex 1 emissions. For example, a carbon constraint on the part of Annex 1 will depress its demand for oil and hence lower its price. This will lead to increased demand for oil in oil importing developing countries. The result will be increased emissions on their part. It is important to note, however, that although MERGE tracks leakages via fuel markets, it does not account for the migration of carbon intensive industries. It therefore leads to an underestimation of the overall leakage effect.

From Figure 5, we see that if mitigation is limited to Annex 1 only, this can slow the growth in atmospheric concentrations, but not lead to stabilization. According to our calculations concentrations drop by between 7% and 9% in the year 2100. Clearly, Annex 1 cannot accomplish a 550 ppmv target by itself. The projected growth in non-Annex 1 emissions is too large.

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Table 1. Comparison of Least-Cost, WRE and WGI Emission Reduction Scenarios

Scenario	Value of carbon emission rights ($/ton of carbon)			Welfare losses (trillion dollars of consumption discounted between 1990 and 2100 at 5%)		
	2010	2020	2100	Global	Annex 1	USA
Least-cost (includes "where" and "when" flexibility)	2	3	156	.56	.28	.12
WRE (includes "where" flexibility)	0	27	129	.77	.62	.28
WGI (includes "where" flexibility)	184	270	129	3.32	3.83	1.42

Table 2. Comparison of Least-Cost and Modified-WRE Emission Reduction Scenarios

Scenario	Value of carbon emission rights ($/ton of carbon)			Welfare losses (trillion dollars of consumption discounted between 1990 and 2100 at 5%)		
	2010	2020	2100	Global	Annex 1	USA
Least-cost mitigation path (includes "where" and "when" flexibility)	2	3	156	.56	.28	.12
Constrain Annex 1 emissions to 10% above 1990 levels by 2010 (includes "where" flexibility)	4	65	129	.78	.56	.29
Constrain Annex 1 emissions to 1990 levels by 2010 (includes "where" flexibility)	67	88	129	.94	.62	.30
Constrain Annex 1 emissions to 10% below 1990 levels by 2010 (includes "where" flexibility)	120	112	129	1.28	1.05	.43

Table 3. Sensitivity of Welfare Losses to "Where" Flexibility
(Annex 1 emissions returned to 1990 levels in 2010)

"Where" flexibility	Value of carbon emission rights ($/ton of carbon)		Welfare losses (trillion dollars of consumption discounted between 1990 and 2100 at 5%)		
	2010	2020	Global	Annex 1	USA
Global	67	88	.94	.62	.30
Annex 1 only	131	134	1.76	1.04	.42
None	204	120	2.40	1.59	.43

Table 4. Sensitivity of Welfare Losses to Ten-Year Change in Implementation Date

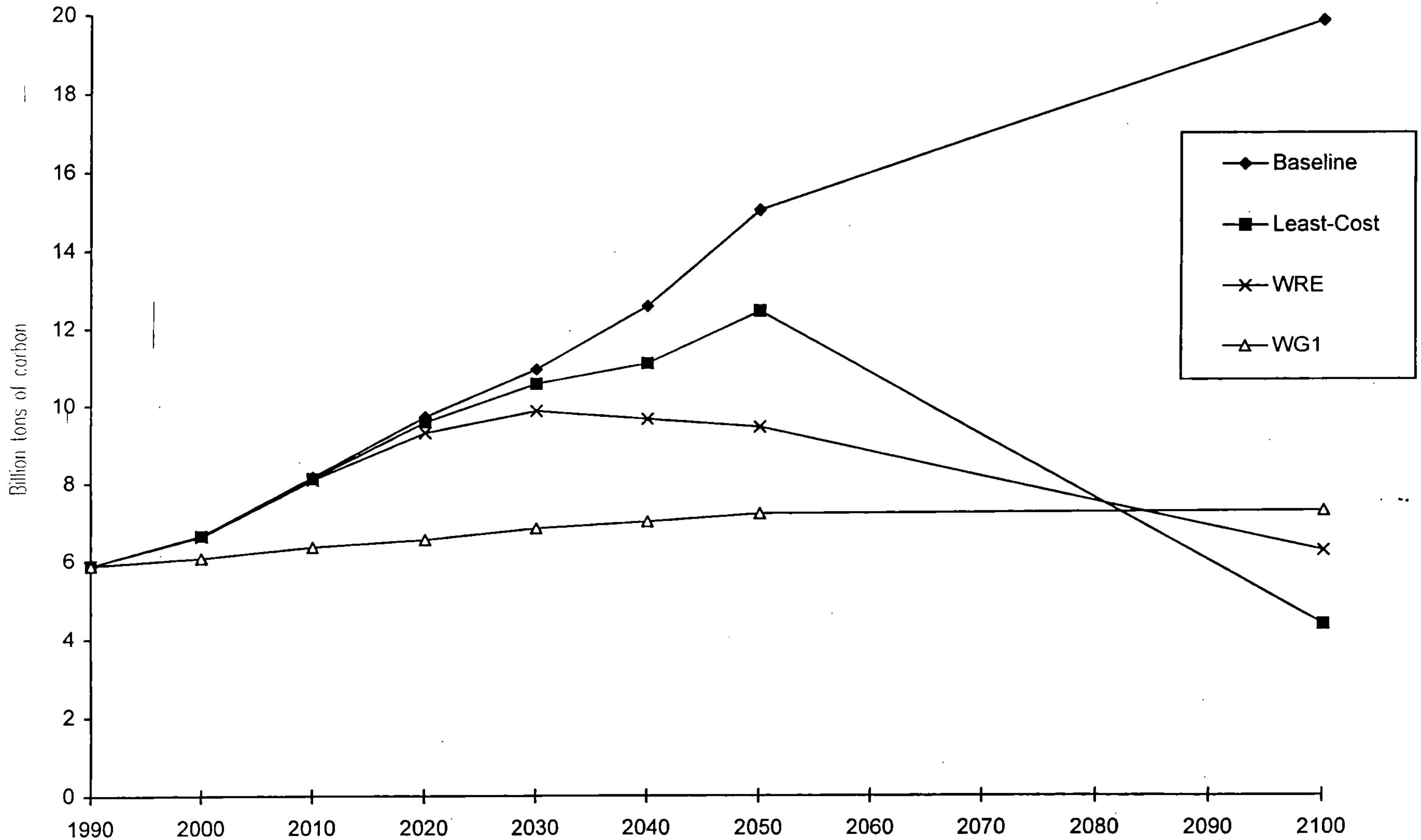
Scenario	Value of carbon emission rights ($/ton of carbon)			Welfare losses (trillion dollars of consumption discounted between 1990 and 2100 at 5%)		
	2010	2020	2100	Global	Annex 1	USA
Least-cost mitigation path (includes "where" and "when" flexibility)	2	3	156	.56	.28	.12
Constrain Annex 1 emissions to 10% above 1990 levels by 2020 (includes "where" flexibility)	0	68	129	.78	.55	.28
Constrain Annex 1 emissions to 1990 levels by 2020 (includes "where" flexibility)	0	111	129	.88	.64	.29

Constrain Annex 1 emissions to 10% below 1990 levels by 2020 **(includes "where" flexibility)**	0	151	129	1.08	.96	.40

Table 5. Effect of Non-Annex 1 Non-Participation on Welfare Losses
(Annex 1 follows WRE Scenario)

Non-Annex 1 participation	Trading	Welfare losses (trillion dollars of consumption discounted between 1990 and 2100 at 5%)		
		Global	Annex 1	USA
Yes	Global	.77	.62	.28
No	Annex 1 only	.79	.91	.36
No	None	.97	1.10	.41

Figure 1. Alternative Emission Pathways for Stabilizing Concentrations at 550 ppmv



Manne & Richels (1997b)

Concentrations capped at 550 ppmv
(twice pre-industrial levels)

Figure 2. Least-Cost (L-C) Mitigation Path

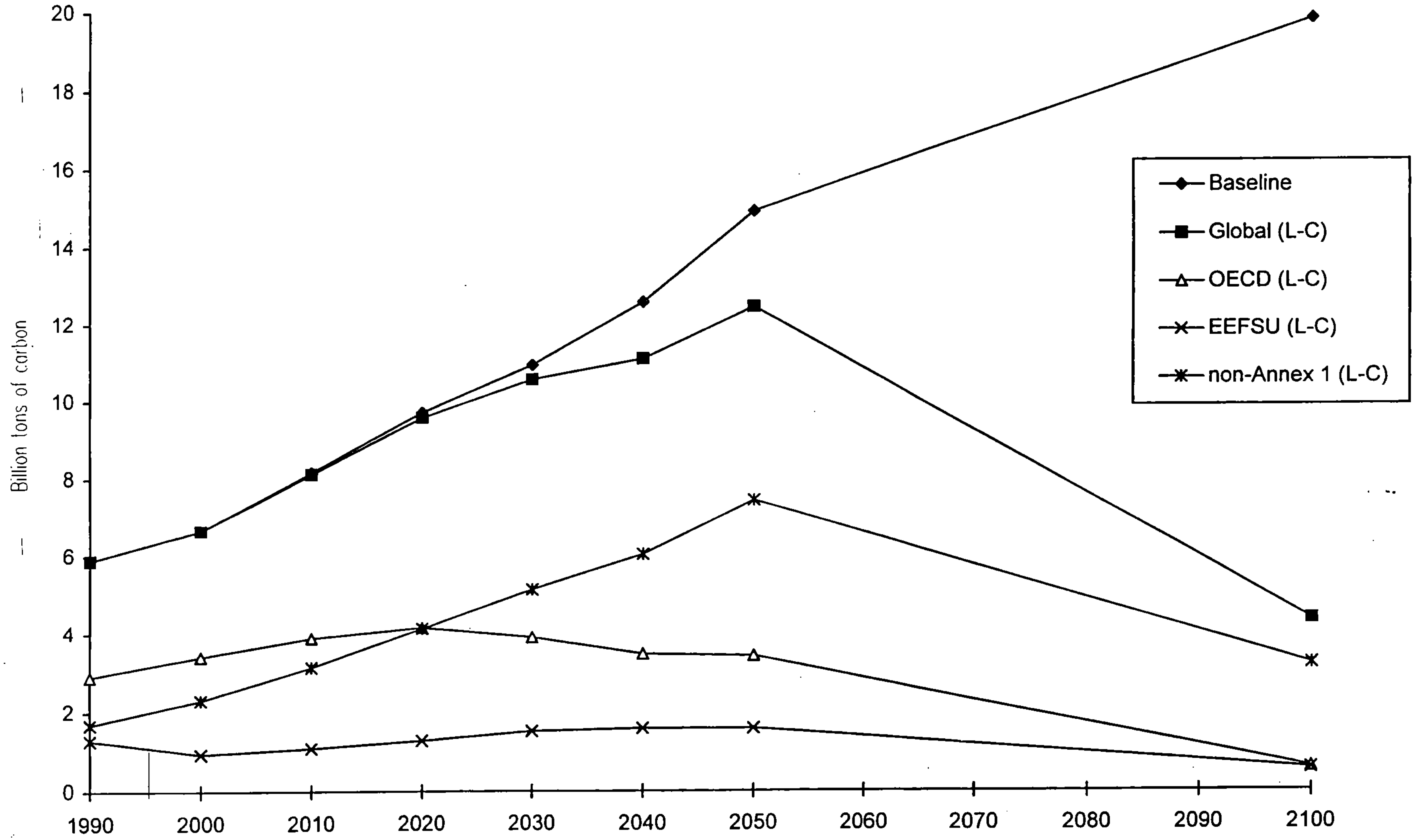


Figure 3. Alternative Emission Constraints

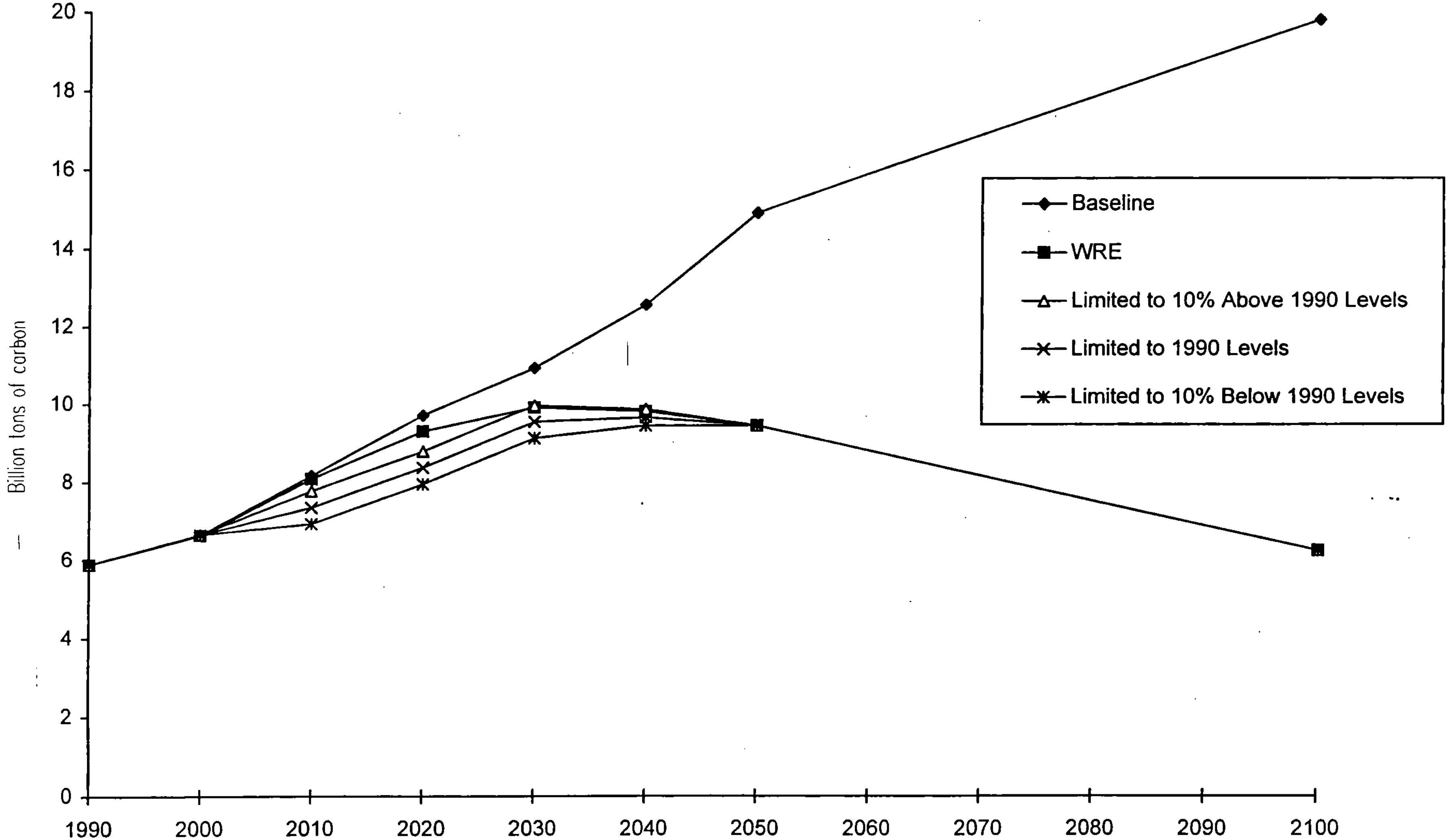


Figure 4. Emissions in 2010

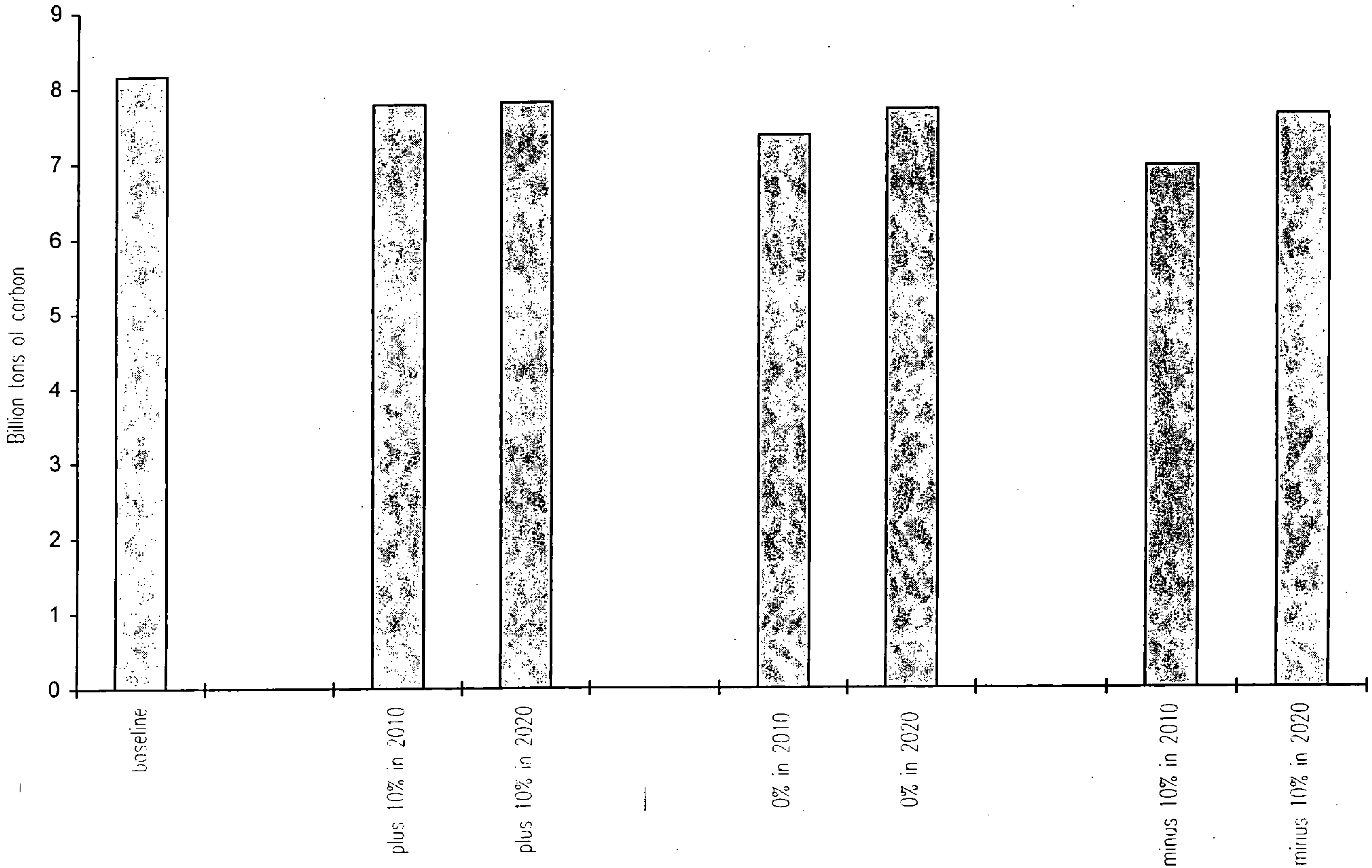
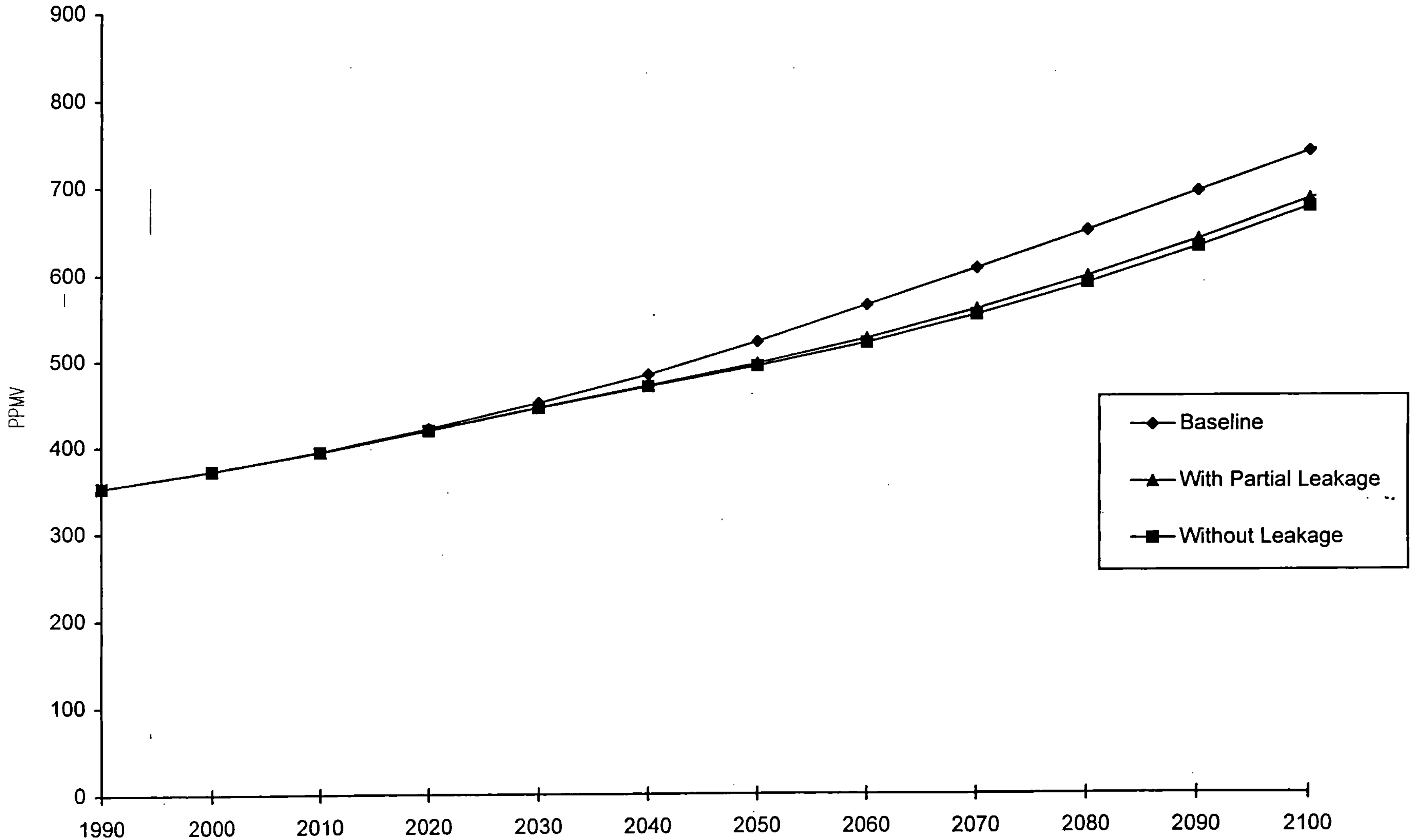


Figure 5. Atmospheric CO2 Concentrations



DRAFT

Fig. 6.1 WGE peaks in 2030
least-cost peaks in 2050
(for 2100 conc. = 550)

On Stabilizing CO2 Concentrations - Cost-Effective Emission Reduction Strategies

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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) 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. 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 IS92a[9] 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 not optimized

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.

"Go slow"

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.

Must not include fact that FSU emissions now < 90, & so could sell paper tons.

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 Report[20], 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

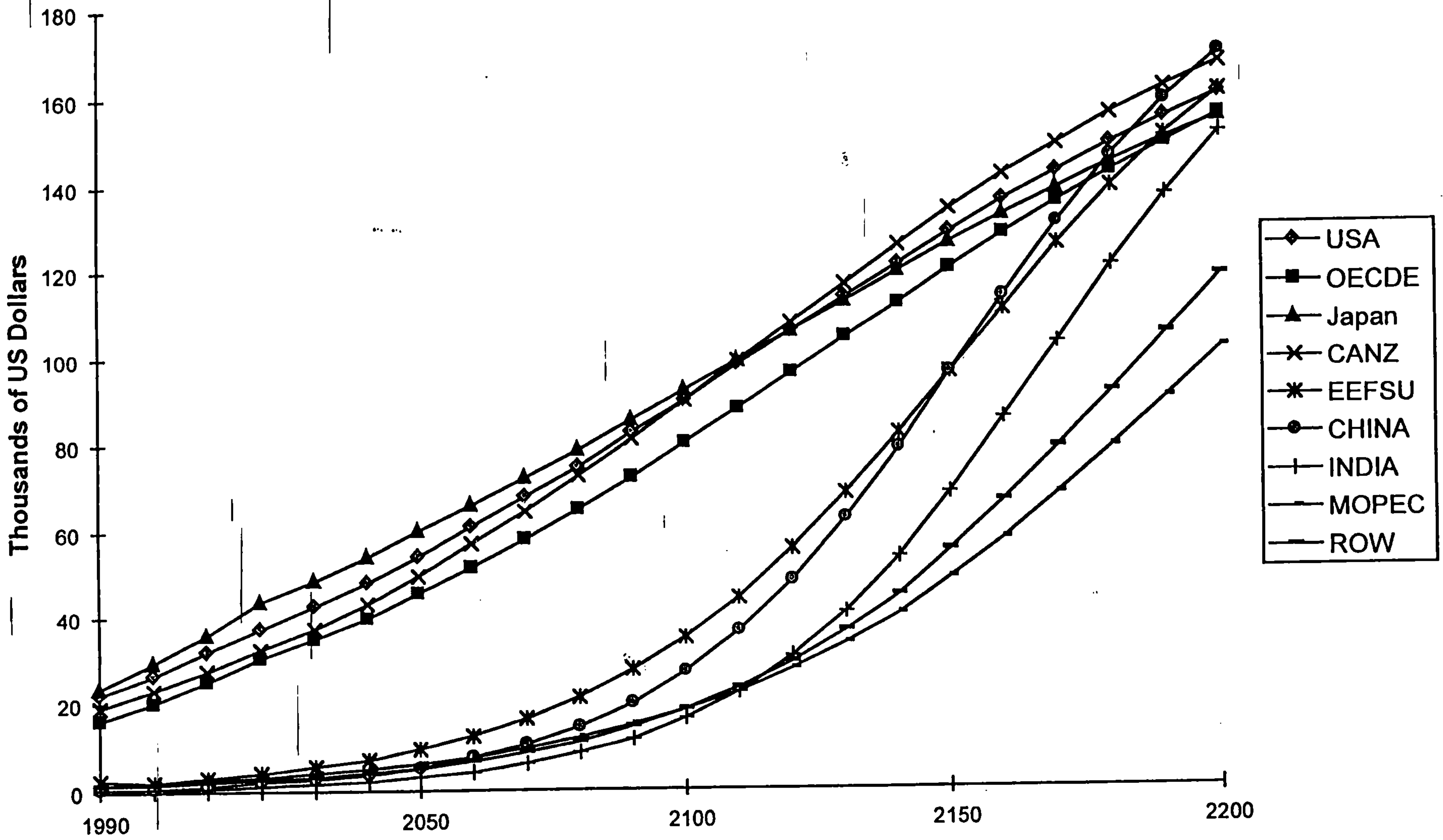


Figure 2.2 Regional Carbon Emissions

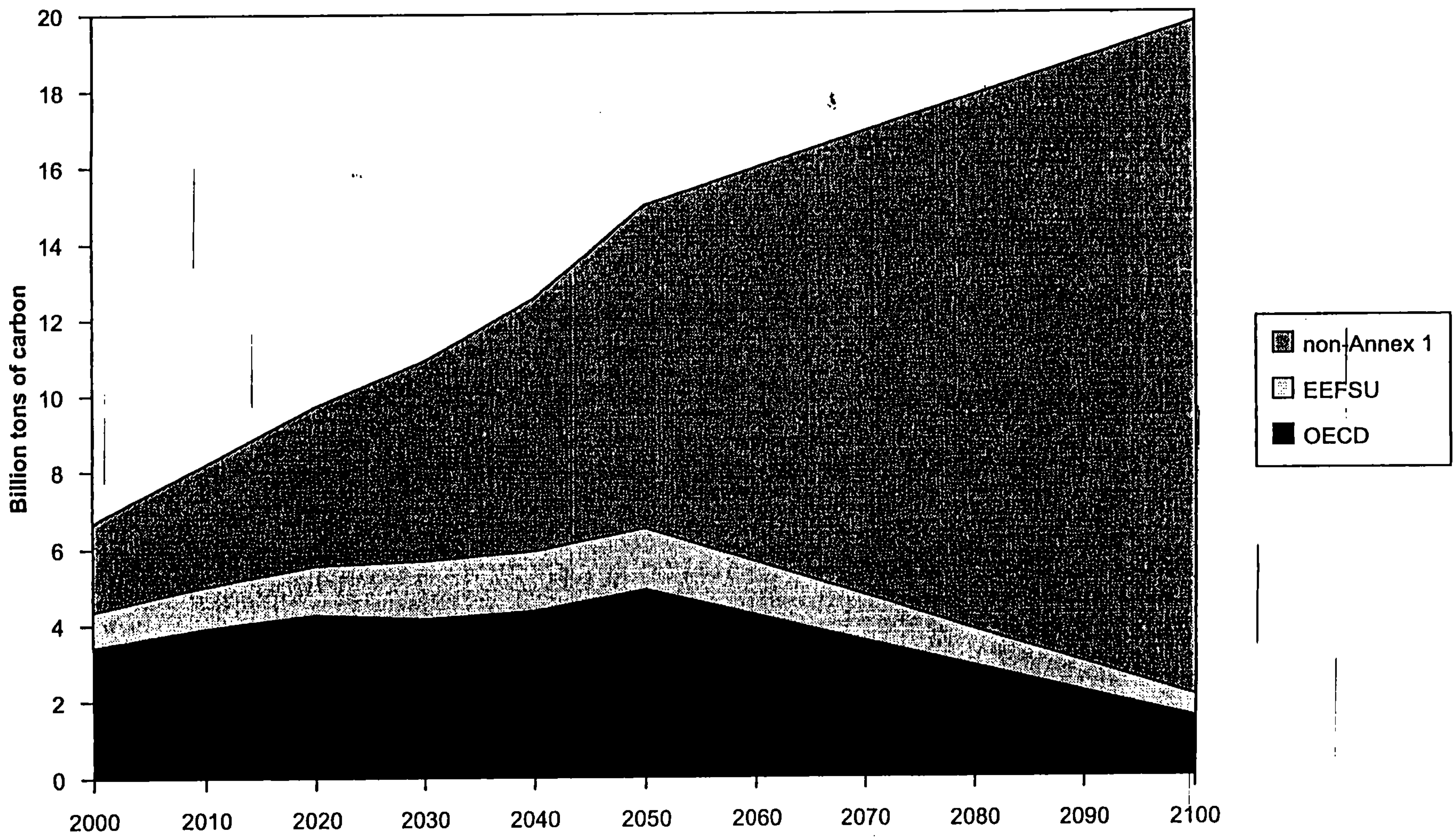


Figure 2.3 Total Primary Energy Use - Basecase

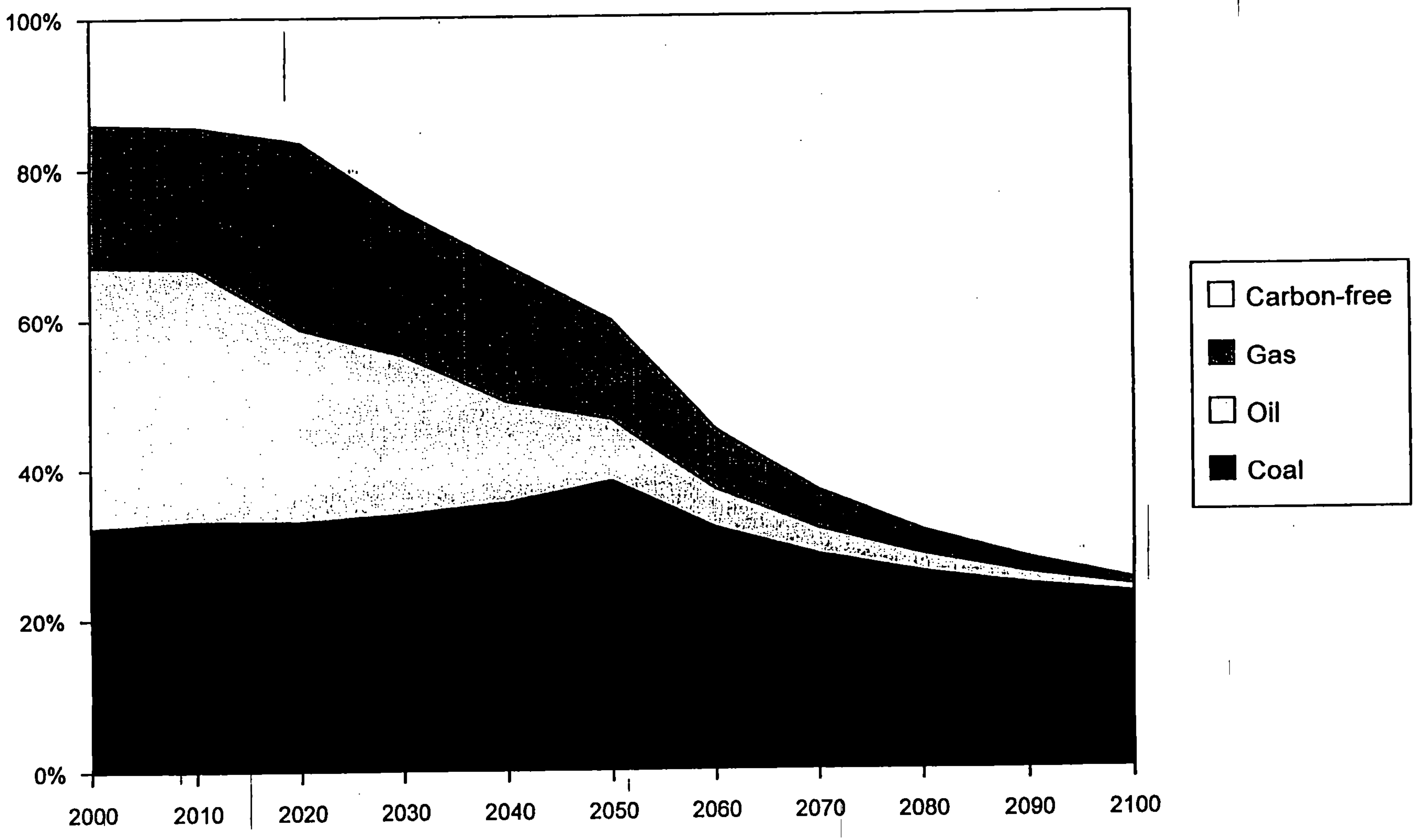
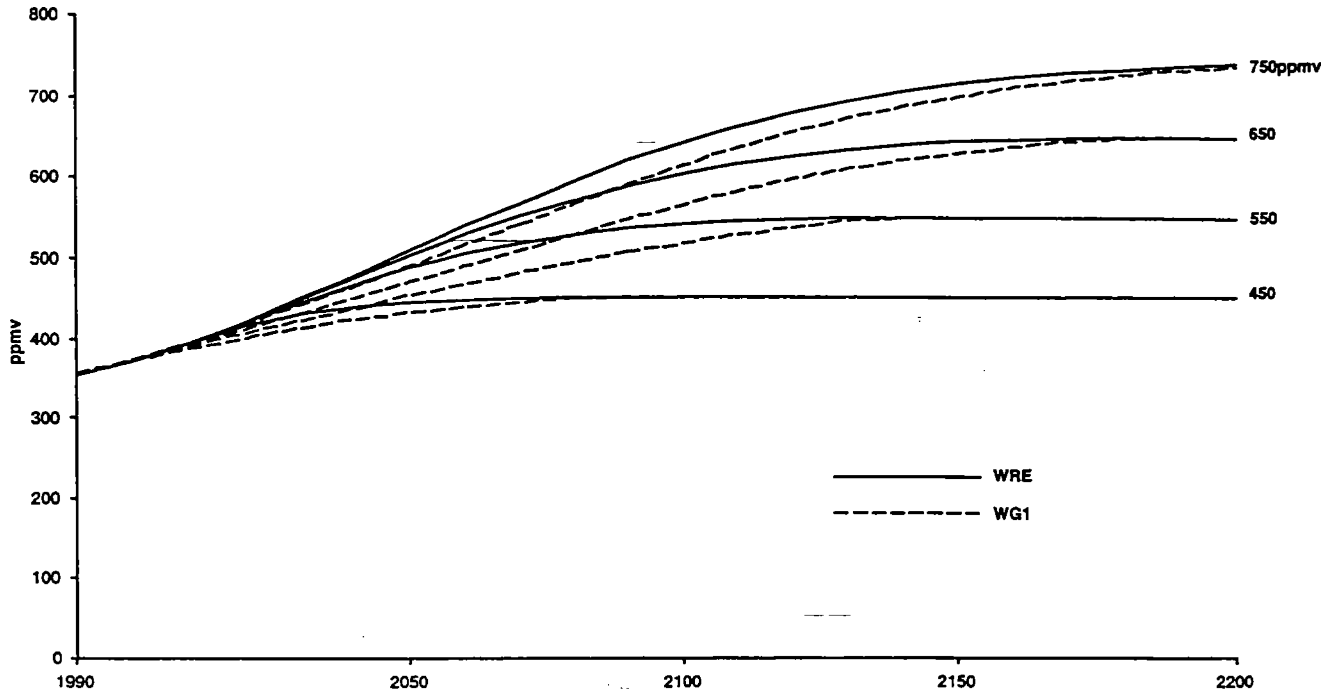
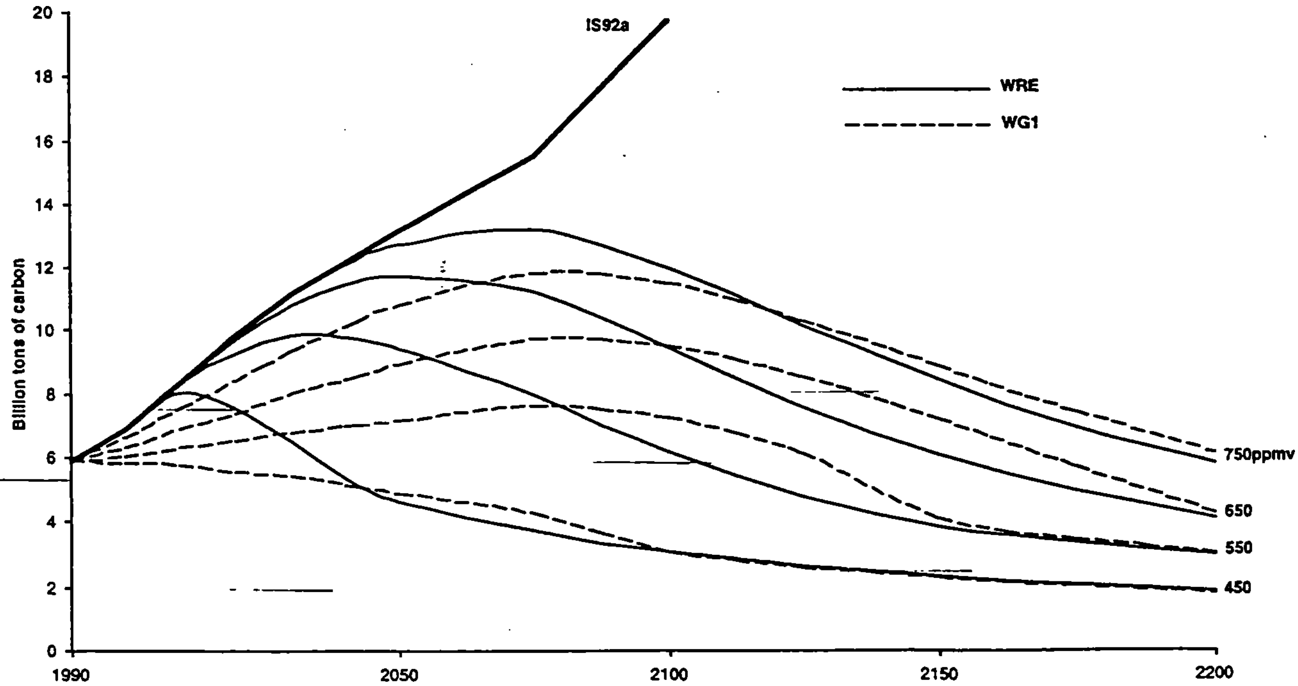


Figure 3.1 Alternative Routes to CO_2 Stabilization

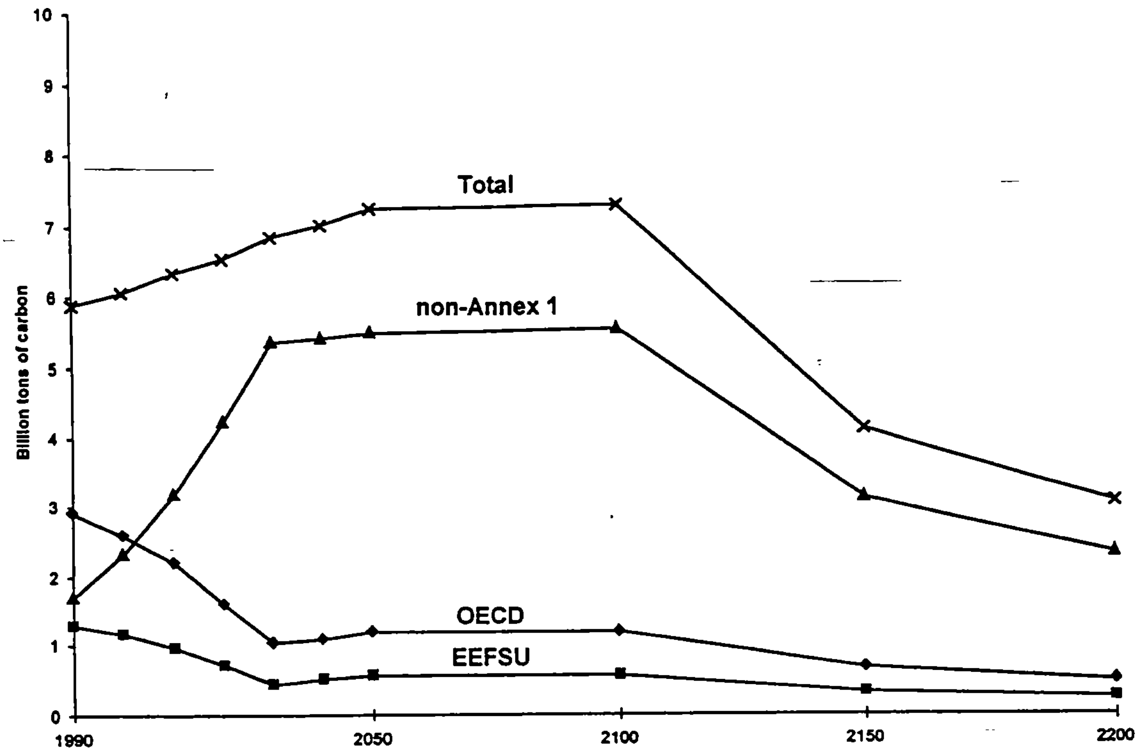


a) Alternative concentration profiles

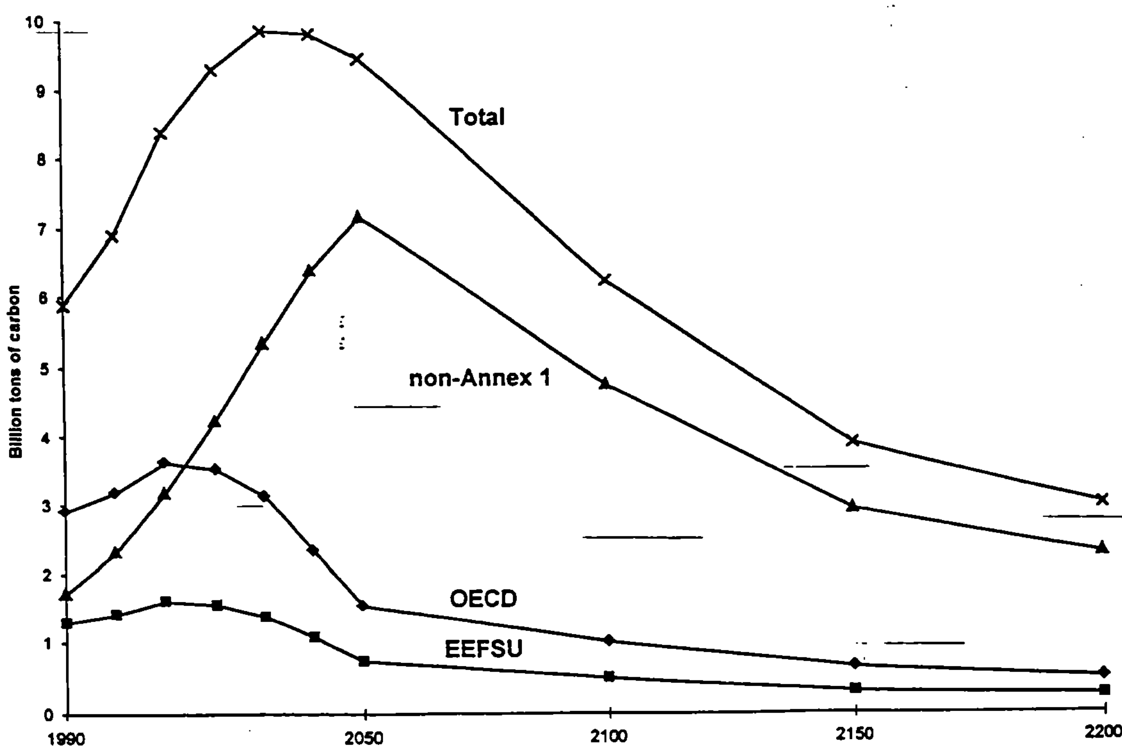


b) Alternative fossil fuel emisson paths

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%

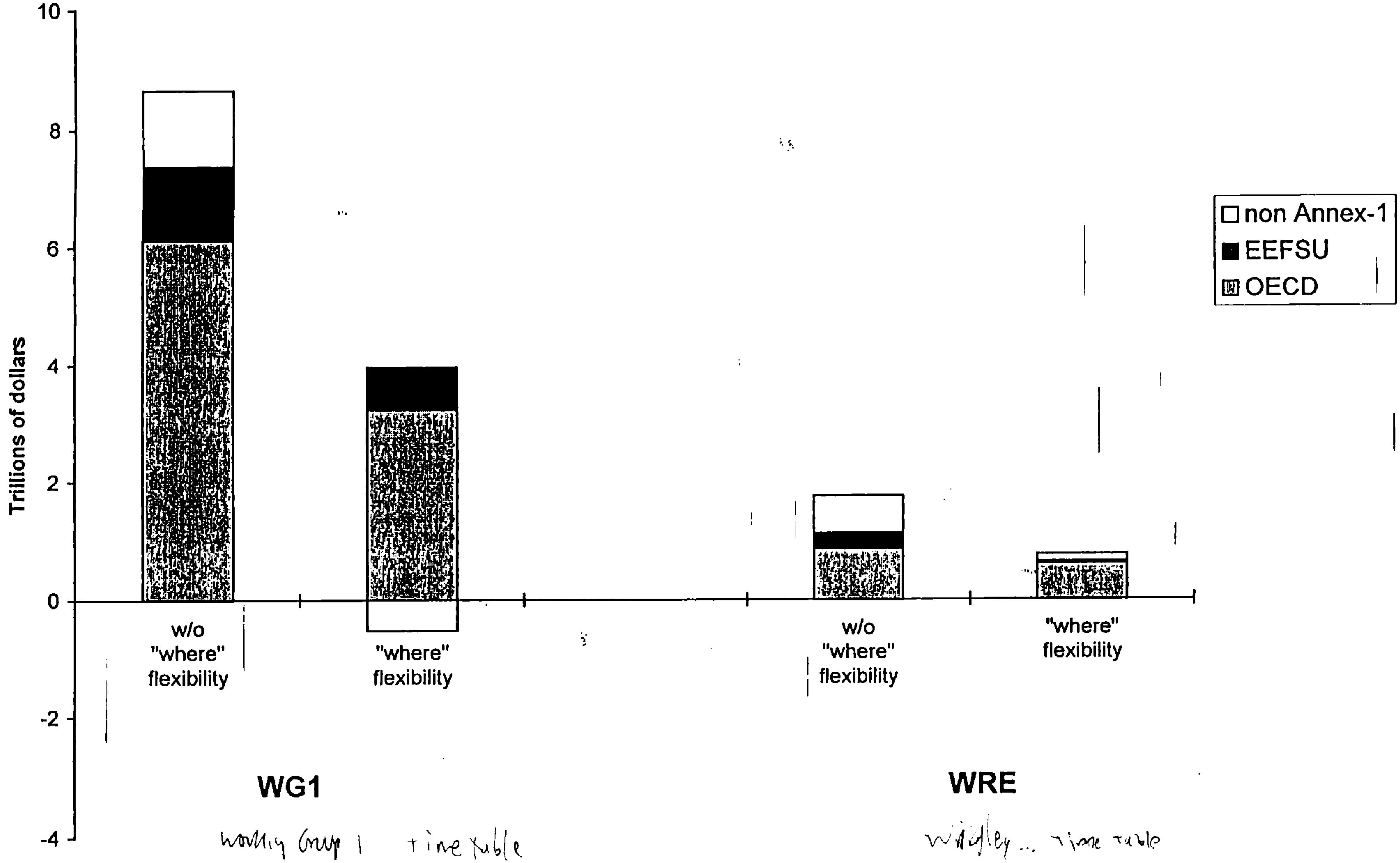


Figure 5.1 International Price of Crude Oil

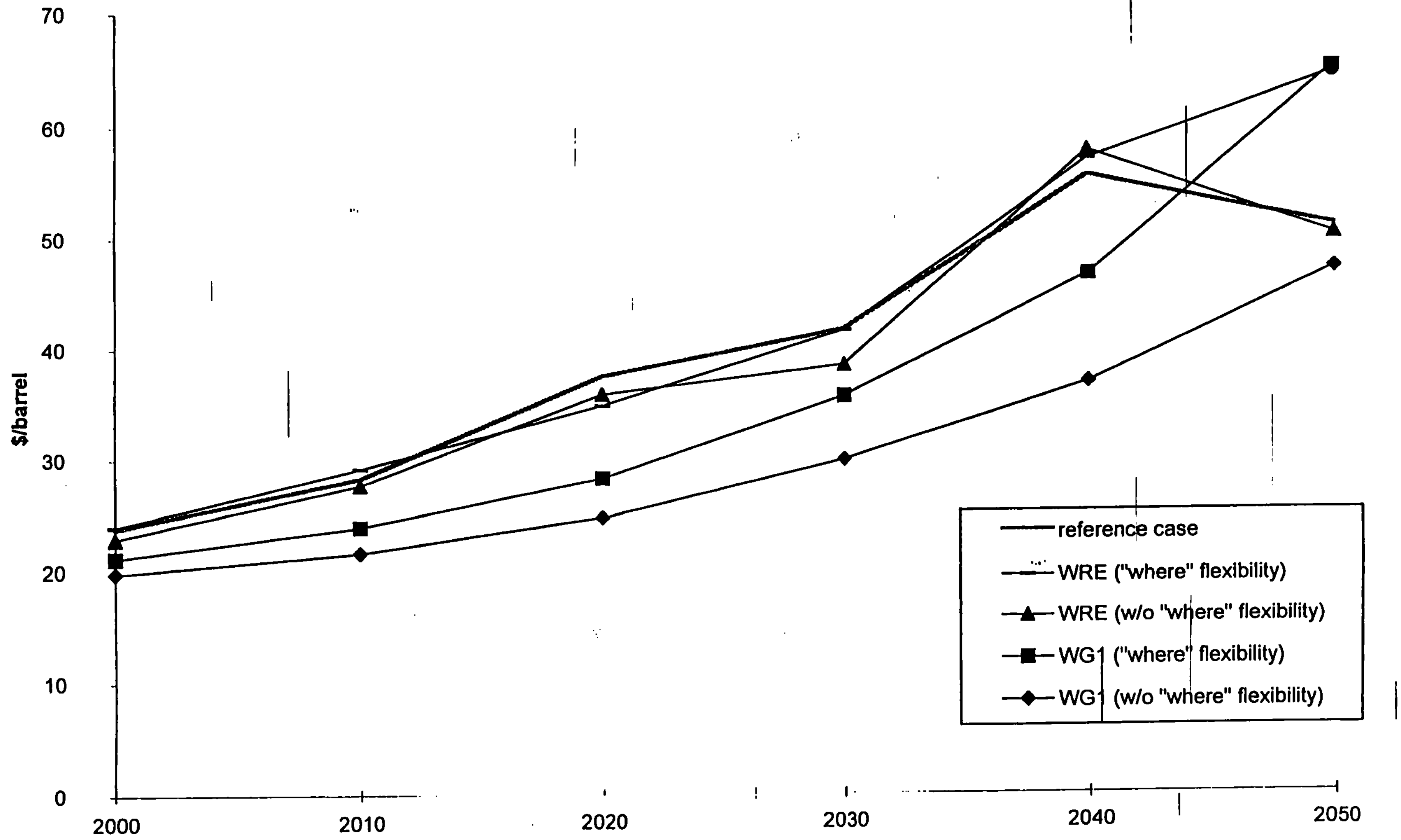
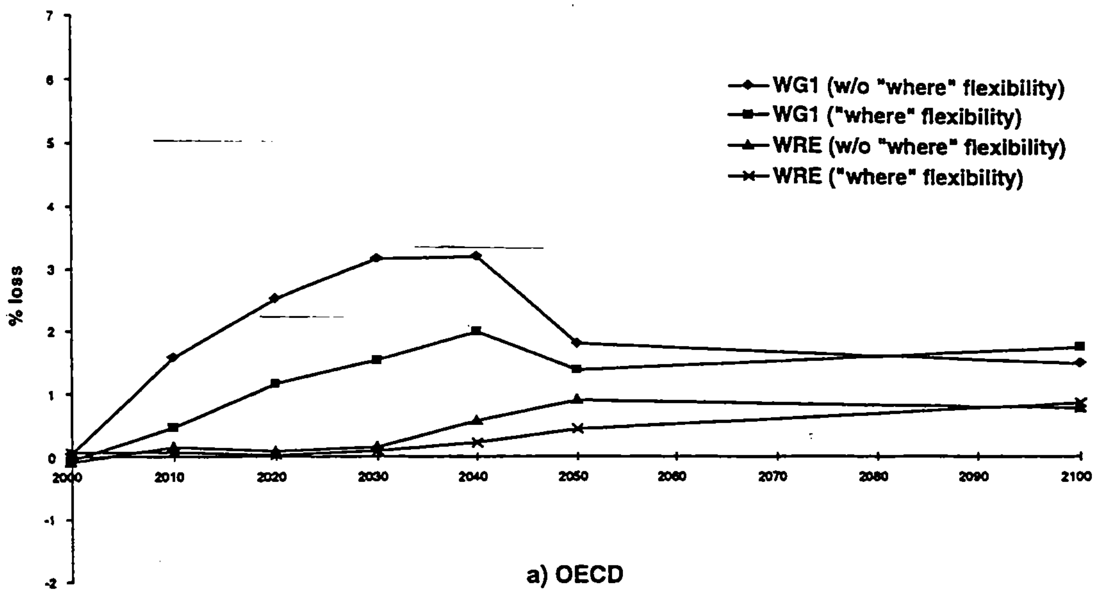
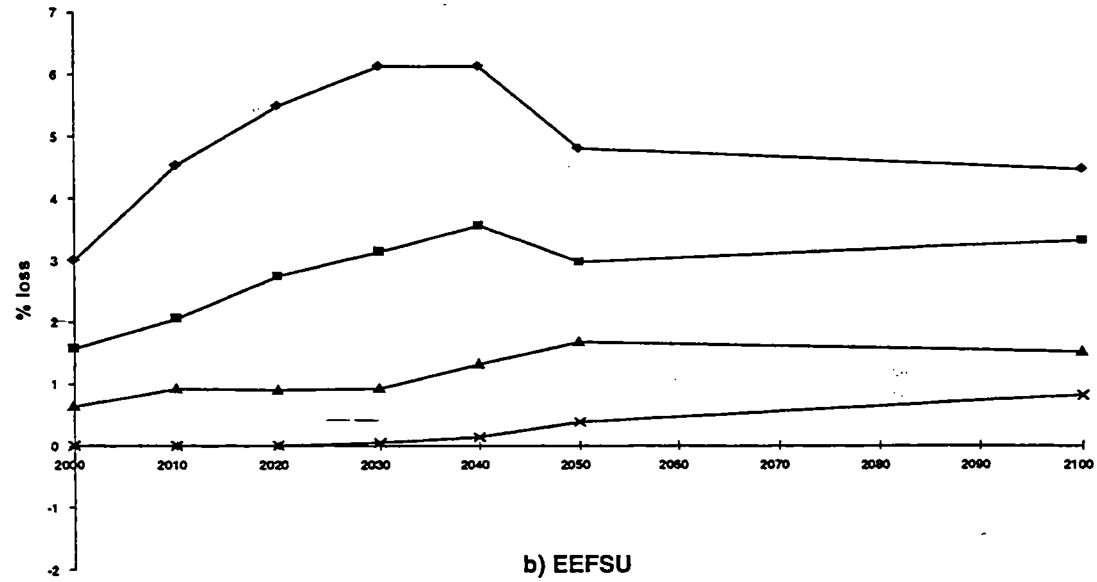


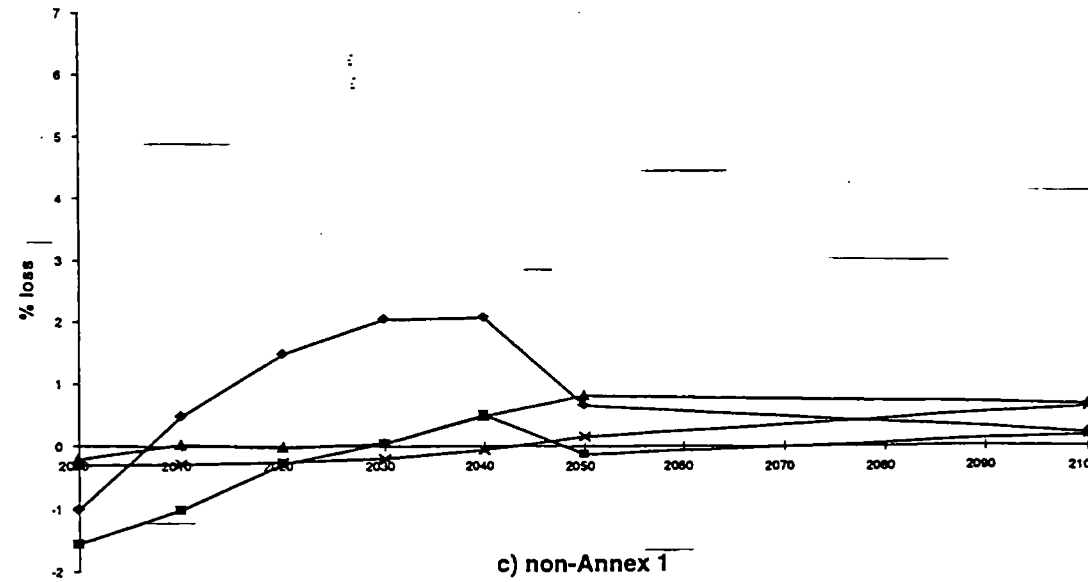
Figure 5.2 Annual % Consumption Losses



a) OECD



b) EEFSU



c) non-Annex 1

Figure 6.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

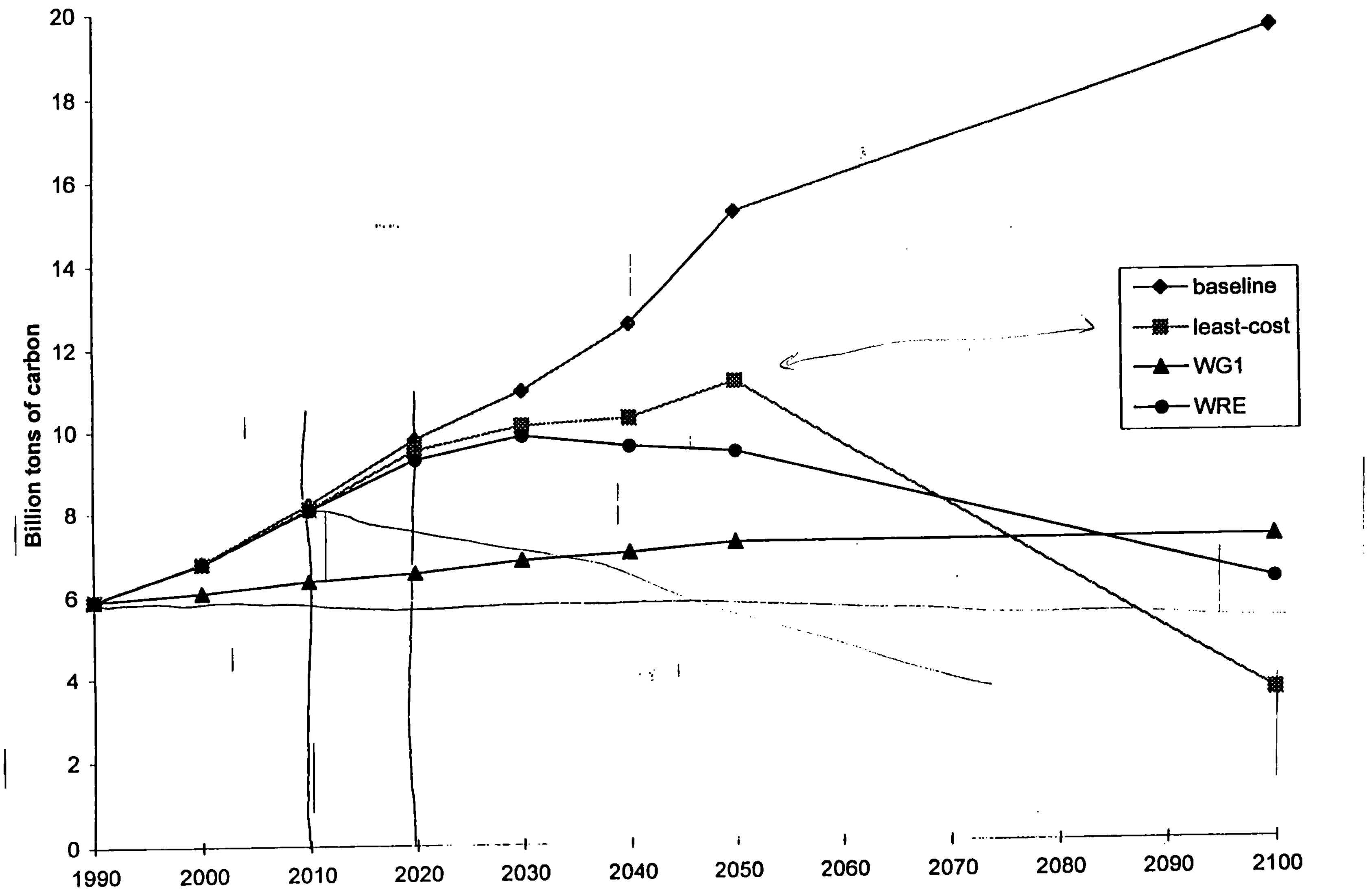


Figure 6.2 Global Costs of Stabilizing Concentrations at 550ppmv -- discounted to 1990 at 5%

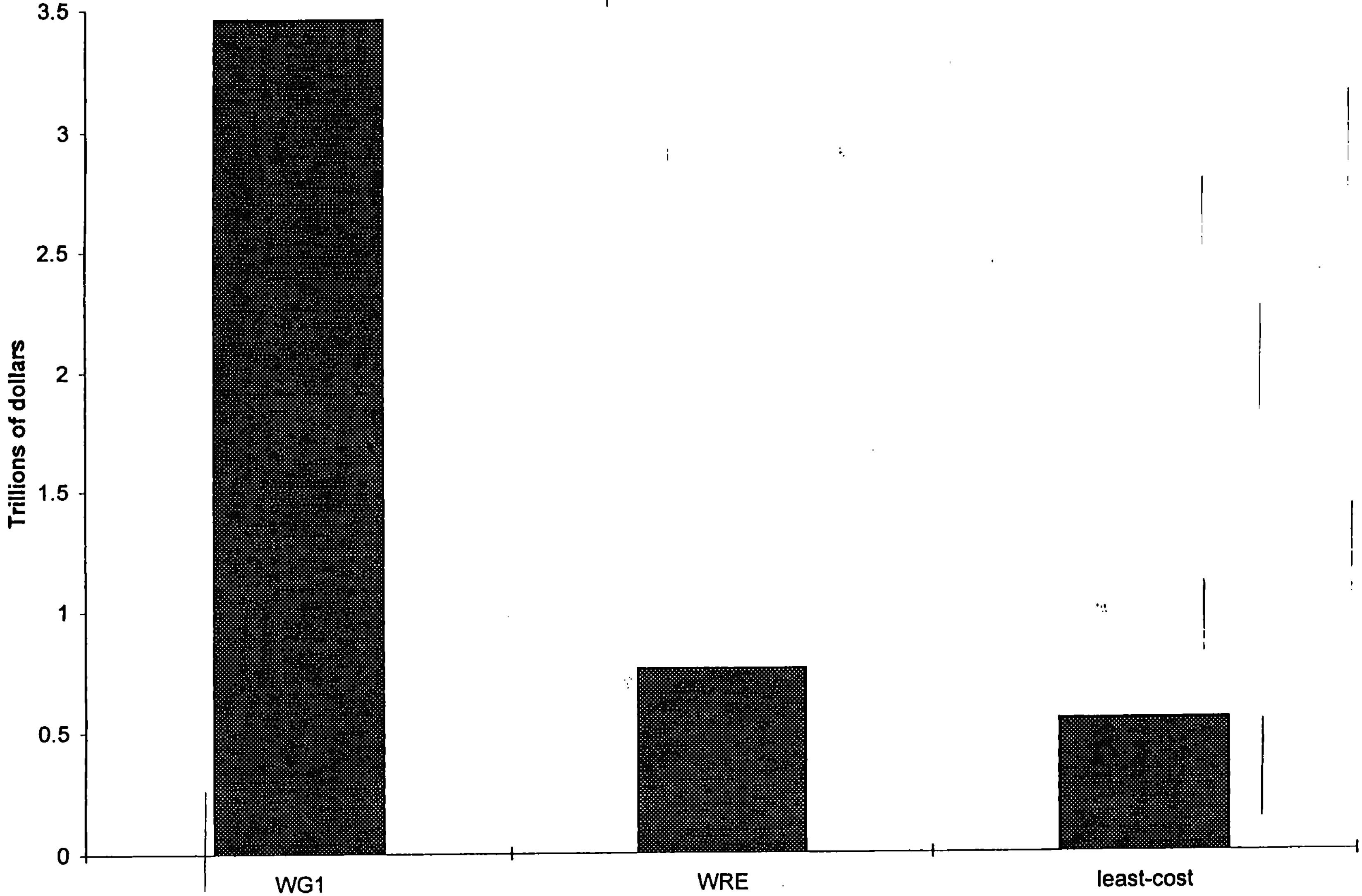
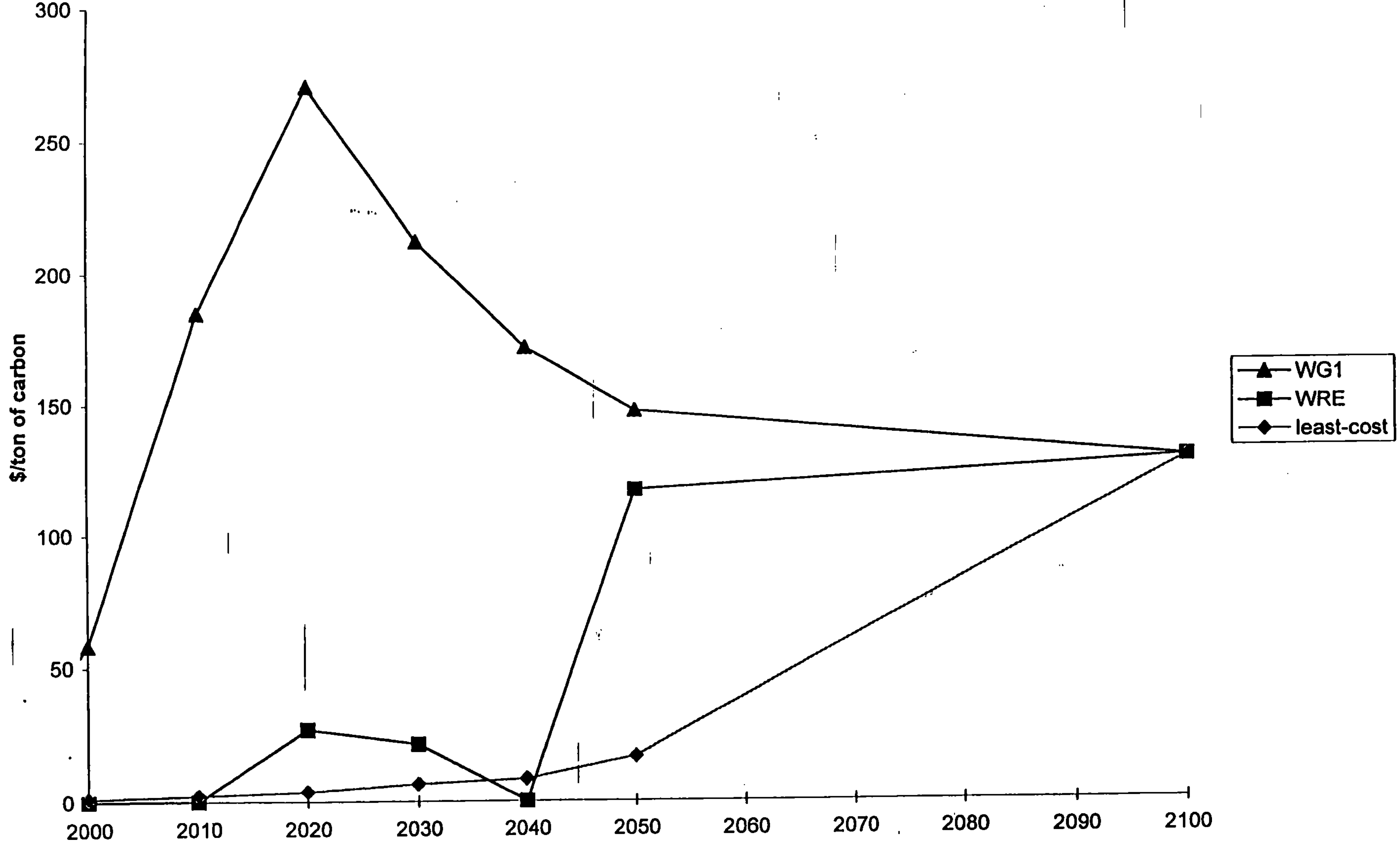


Figure 6.3 Value of Carbon Emission Rights with Alternative Pathways for Stabilizing Concentrations at 550ppmv



↑ Factor of 100 in 2020!

(costs are more sensitive to where flexibility and when (aggressive WG1 timetable, vs WRE) then to target concentration levels (even) 550-650

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

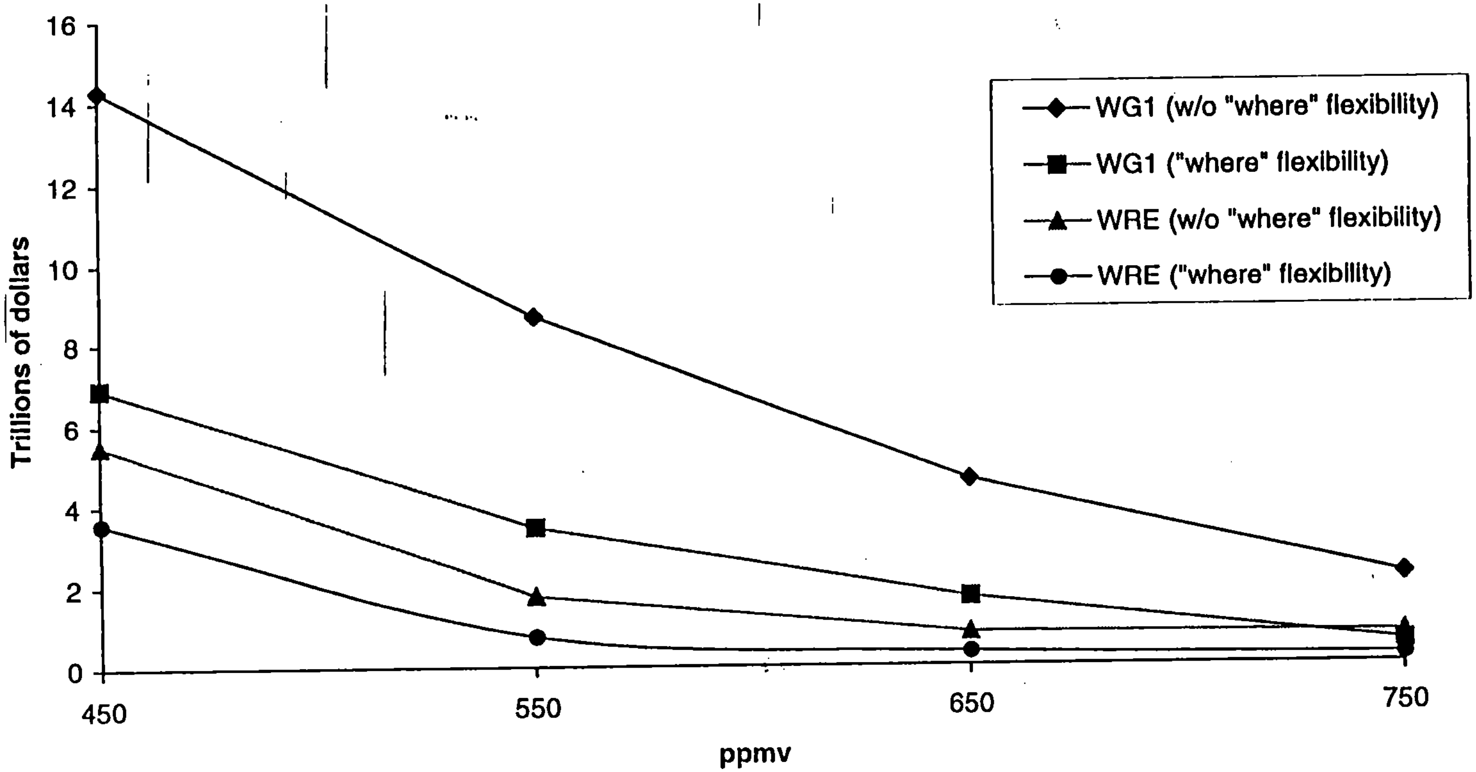
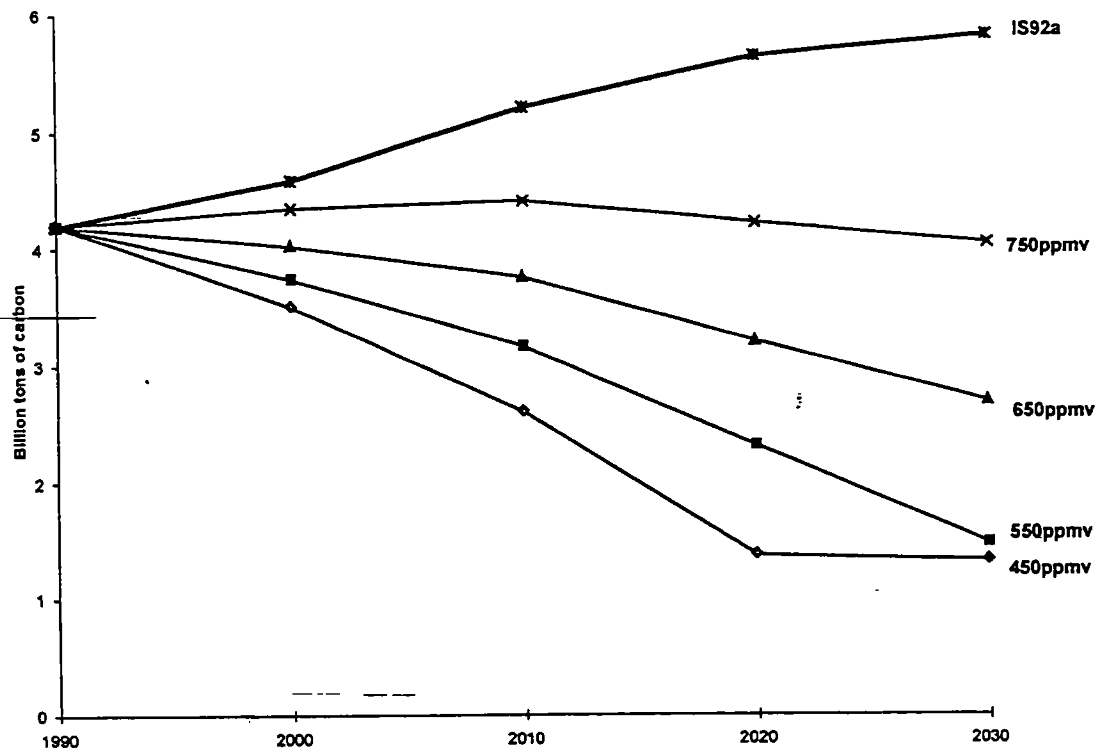
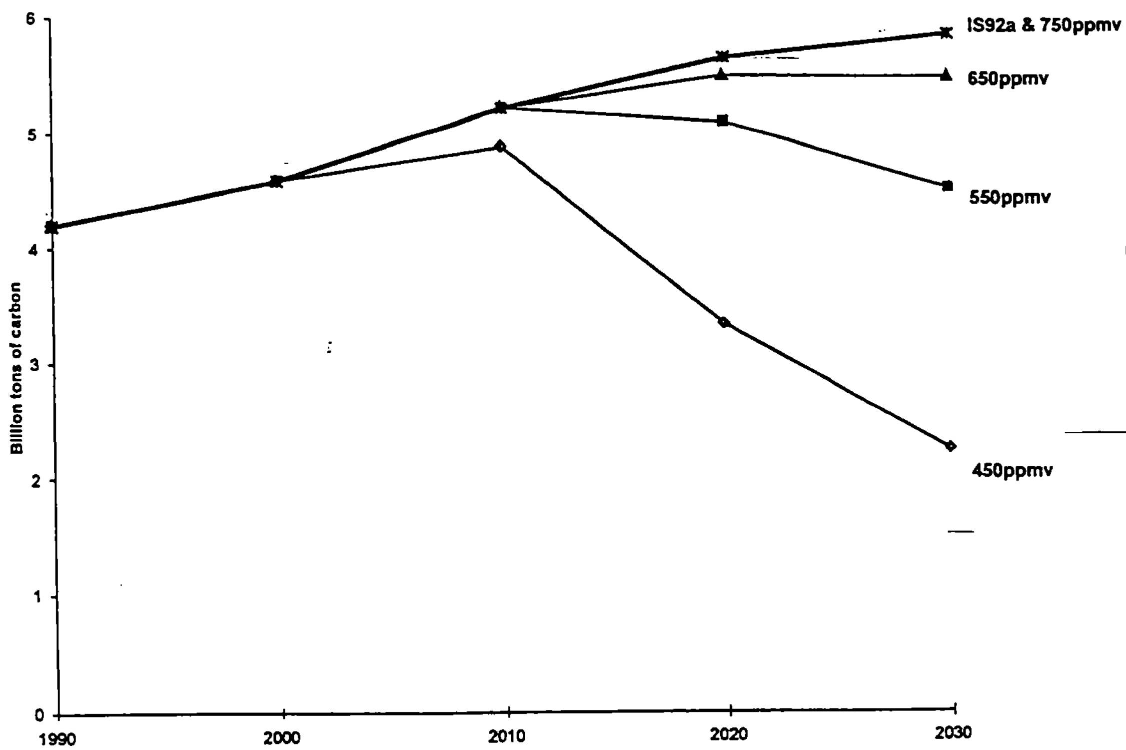


Figure 7.2 Annex 1 Emission Constraints under Alternative Concentration Targets



a) WG1



peaks in 2010
1990 level
later than 2030

peaks in 2010
1990 level by 2030

b) WRE