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Climate Change - Trading Models [1]

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## MEMORANDUM

To: Janet Yellen  
From: Joe Aldy and Randy Lutter  
Date: 10/8/97  
Subject: Sensitivity of permit prices to alternative economic assumptions

How sensitive are estimated carbon permit prices to alternative assumptions about GDP growth, autonomous energy efficiency improvement, and the opportunities for substitution across technologies and fuels? A preliminary assessment of the effects of varying these assumptions indicates that permit prices are unlikely to fall significantly. Since fuel switching is sensitive to elasticities embedded in models, we conducted our analysis with energy and carbon outputs from the Markal Macro and SGM models.

We find that for the permit price to be \$30/ton in the SGM model, AEEI would have to equal GDP growth. (This implies zero growth in energy use over the decade.) For the permit price to be \$30 in the Markal Macro model, AEEI would have to exceed GDP growth, implying that energy use would have to fall over this period. The only recent decade when energy consumption did not grow was from 1972 to 1982.

### Methodology

We assume that the price of carbon varies linearly with the emissions reduction required under a 1990 in 2010 stabilization case relative to a no policy baseline.

$$P_s = P_m \frac{\hat{C}_s}{\hat{C}_m},$$

where  $P_s$  is the forecast price under stabilization under our approach,  $P_m$  is the model output forecast price under stabilization,  $C_s$  is the change in carbon emissions required to achieve 1990 level in 2010 from a business as usual level (specified below), and  $C_m$  is the reduction in carbon relative to the models' estimated business as usual.

Emissions reductions can be written as

$$\hat{C}_s = \frac{\hat{C}_m}{\hat{E}_m} \hat{E}_s,$$

the product of a fuel switching factor, which is defined as the change in carbon under a stabilization policy divided by the change in energy under this policy (both relative to a business as usual projection for 2010) from a model, multiplied by the percentage change in energy consumption. (Note that since the fuel switching parameter is driven by the price of carbon, we

cannot vary it exogenously.) The change in total energy use between the stabilization case and business as usual in 2010 is determined by GDP growth and autonomous energy efficiency improvement inputs.

As a starting point, we use the results from SGM and Markal Macro with the IAT assumptions (AEEI = 1.25%, GDP growth of 2.06% and 1.91%) and permit prices of \$81/ton and \$145/ton in 2010. We use these to calibrate our spreadsheet. Note that our calibrations result in price estimates that differ from the model results by 5.8% and 2.6% -- this likely is a function of using rounded averages for GDP and AEEI.<sup>1</sup> SGM generates a fuel switching factor of 1.5, while Markal Macro assumes more fuel switching, so its factor is 1.64. We then calculated a set of permit prices by varying GDP and AEEI over the 1995-2010 period. We varied annual GDP growth by about 1.3% and 3% and AEEI by 0.7% and 1.75%. Note that the most recent GDP growth rate projection is about 2.4%, and a survey of energy economists indicates that AEEI likely falls between 0.5% and 0.7% (EIA employs a 0.9% energy efficiency improvement).

## Results

The assessment of the permit prices with varying input assumptions indicates that permit prices can vary significantly with the inputs. However, given that the IAT employed very optimistic AEEI (1.25%) and moderate economic growth (~2%), the variations of inputs imply that permit prices could easily be above the IAT forecast results. For example, assuming an AEEI of 0.9% (consistent with the Energy Information Administration) and the present projected GDP growth rate of 2.4%, the computed permit price with the SGM derived measure would be about \$130/ton while the Markal Macro derived measure would be about \$250/ton. The chart on the next page presents the estimated permit prices given the ranges of GDP growth and AEEI considered.

Low permit prices would require very slow growth and very optimistic AEEI. For example, assume that over the next 13 years, the economy experiences 8 years of zero growth (e.g., a prolonged recession) and five years of moderate growth (e.g., 2% per year). During this period, assume that autonomous energy efficiency improvements occur at an annual rate of 0.9%. Under this scenario, 2010 energy consumption would be roughly equal to 1995 energy consumption. The price of a carbon permit in 2010 would still be about \$30/ton with the SGM derived measure, and nearly \$60/ton with the Markal Macro measure.

Our sensitivity analysis indicates that prices can vary, but are more likely to vary upward relative to the IAT results. Note however that we only varied GDP growth and AEEI. The nature of the supply curve for emissions reductions also can affect the permit price. Modifying other assumptions may generate different results.

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<sup>1</sup> As a check on our proportionality assumption, we did a second calibration of SGM using an AEEI of 1.0%, GDP growth of 2.0%, a fuel switching factor of 1.39, and a permit price of \$108. This results in a predicted price of \$121, or 12% from the actual model result. Our assumption does not appear to be far off, but with higher emissions reductions, our approach generates permit prices slightly larger than the model estimates. With smaller emissions reductions, the error appears to be small. Note the attached chart that illustrates the marginal abatement cost curve for emissions reductions in 2010.

Estimated Permit Prices Under Various GDP Growth and AEEI Assumptions

Derived from:	GDP Growth Rate	AEEI	Permit Price (\$/ton)
SGM*	2.06%	1.25%	\$86
SGM, Best Estimate	2.4% <sup>1</sup>	0.9% <sup>1</sup>	\$128
SGM	1.25% <sup>2</sup>	0.7%	\$69
SGM	1.25% <sup>2</sup>	0.9%	\$55
SGM	1.25% <sup>2</sup>	1.25%	\$31 <sup>3</sup>
SGM	1.25% <sup>2</sup>	1.75%	\$0 <sup>3</sup>
Markal Macro*	1.91%	1.25%	\$149
Markal Macro, Best Estimate	2.4% <sup>1</sup>	0.9% <sup>1</sup>	\$250
Markal Macro	1.25% <sup>2</sup>	0.7%	\$135
Markal Macro	1.25% <sup>2</sup>	0.9%	\$108
Markal Macro	1.25% <sup>2</sup>	1.25%	\$60 <sup>3</sup>
Markal Macro	1.25% <sup>2</sup>	1.45%	\$31 <sup>3</sup>
Markal Macro	1.25% <sup>2</sup>	1.75%	\$0 <sup>3</sup>

\* Calibration estimates: SGM model result is \$81/ton, Markal Macro model result is \$145/ton.

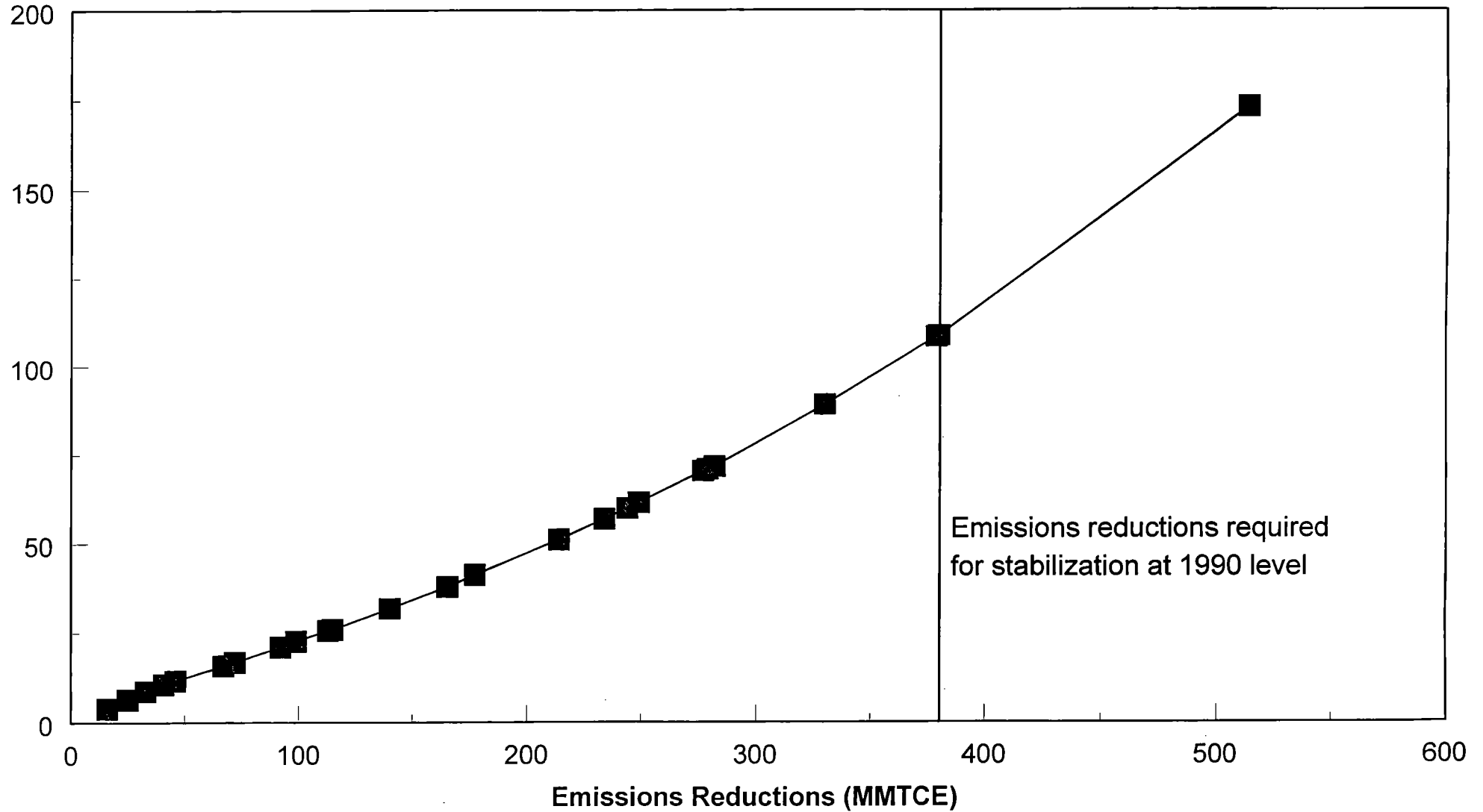
1: The 2.4% GDP growth rate corresponds to the Administration's most recent projection of GDP growth. The 0.9% AEEI corresponds to the Energy Information Administration's projection of AEEI over the next 20 years.

2: A growth rate average of 1.25% between now and 2010 would imply that during six of the next thirteen years, the nation would experience a GDP growth rate of zero (e.g., a prolonged recession) and annual GDP growth would average, during the remaining seven years, about 2%.

3: These estimates of permit prices assume that energy use remains flat or falls between now and 2010. An energy trend of this nature, over a period as long as a decade, has only occurred during the 1970s and early 1980s as a result of the OPEC oil shocks.

# Carbon Emissions Reductions Marginal Abatement Cost Curve, 2010

Carbon Price (\$/ton)



Model: SGM

ID	Scenario	Model	Modelers	Target	Timetable	Trading	Permit Allocation	Revenue Recycling	Burden Sharing	BAU Emissions Path Assumption	Paper Tons or Corresponding Reductions	AEEI	Ramp-up	Time Path	Outputs	
															PDV (5%; 2000-2050) Foregone Consumption	GDP in 2010 (deviation from BAU)
SGM1	BAU	SGM, MAGICC	Battelle	n/a	n/a	n/a	n/a	n/a	n/a	IAT	n/a	1.0	n/a	-->2050, -->2100 (climate)	\$121,650 billion (BAU consumption)	\$9,185 billion (BAU GDP)
SGM9	-10% of 1990 in 2010	SGM, MAGICC	Battelle	-10% 1990 emissions level	stabilize in 2010	Annex I	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	\$485 billion	\$9,155 billion (-\$30 billion)
SGM8	-10% of 1990 in 2010	SGM, MAGICC	Battelle	-10% 1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	\$980 billion	\$9,149 billion (-\$36 billion)
SGM10	-10% of 1990 in 2010	SGM, MAGICC	Battelle	-10% 1990 emissions level	stabilize in 2010	worldwide	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	\$50 billion	\$9,171 billion (-\$14 billion)
SGM36	1990 in 2020	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2020	Annex I	auction	lump-sum	no LDC part.	IAT	PT	1.0	yes	-->2050, -->2100 (climate)	\$195 billion	\$9,179 billion (-\$6 billion)
SGM39	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	Annex I	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$230 billion	\$9,172 billion (-\$13 billion)
SGM3	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	Annex I	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	\$225 billion	\$9,172 billion (-\$13 billion)
SGM18	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	Annex I	auction	lump-sum	LDC stabilizes at 2030 in 2030	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$255 billion	\$9,172 billion (-\$13 billion)
SGM21	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	Annex I	auction	lump-sum	LDC BAU to 2030, equal per capita in 2050	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$260 billion	\$9,172 billion (-\$13 billion)
SGM17	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	LDC stabilizes at 2030 in 2030	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$740 billion	\$9,164 billion (-\$21 billion)
SGM2	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	\$665 billion	\$9,165 billion (-\$20 billion)
SGM38	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$740 billion	\$9,164 billion (-\$21 billion)
SGM20	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	LDC BAU to 2030, equal per capita in 2050	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$740 billion	\$9,164 billion (-\$21 billion)
SGM40	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	worldwide	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$5 billion	\$9,180 billion (-\$5 billion)

ID	Scenario	Model	Modelers	Target	Timetable	Trading	Permit Allocation	Revenue Recycling	Burden Sharing	BAU Emissions Path Assumption	Paper Tons or Corresponding Reductions	AEEI	Ramp-up	Time Path	PDV (5%; 2000-2050) Foregone Consumption	GDP in 2010 (deviation from BAU)
SGM4	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	worldwide	auction	lump-sum	no LDC part.	IAT	PI	1.0	no	-->2050, -->2100 (climate)	\$5 billion	\$9,180 billion (-\$5 billion)
SGM22	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	worldwide	auction	lump-sum	LDC BAU to 2030, equal per capita in 2050	IAT	PI	1.0	in 2005	-->2050, -->2100 (climate)	\$25 billion	\$9,180 billion (-\$5 billion)
SGM19	1990 in 2010	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2010	worldwide	auction	lump-sum	LDC stabilizes at 2030 in 2030	IAT	PI	1.0	in 2005	-->2050, -->2100 (climate)	\$20 billion	\$9,180 billion (-\$5 billion)
SGM35	1990 in 2020	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2020	domestic only	auction	lump-sum	no LDC part.	IAT	PI	1.0	yes	-->2050, -->2100 (climate)	\$660 billion	\$9,172 billion (-\$13 billion)
SGM37	1990 in 2020	SGM, MAGICC	Battelle	1990 emissions level	stabilize in 2020	worldwide	auction	lump-sum	no LDC part.	IAT	PI	1.0	yes	-->2050, -->2100 (climate)	-\$1 billion	\$9,183 billion (-\$2 billion)
SGM6	1995 in 2010	SGM, MAGICC	Battelle	1995 emissions level	stabilize in 2010	Annex I	auction	lump-sum	no LDC part.	IAT	CR	1.0	no	-->2050, -->2100 (climate)	\$380 billion	\$9,175 billion (-\$10 billion)
SGM5	1995 in 2010	SGM, MAGICC	Battelle	1995 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	CR	1.0	no	-->2050, -->2100 (climate)	\$425 billion	\$9,174 billion (-\$11 billion)
SGM7	1995 in 2010	SGM, MAGICC	Battelle	1995 emissions level	stabilize in 2010	worldwide	auction	lump-sum	no LDC part.	IAT	CR	1.0	no	-->2050, -->2100 (climate)	\$30 billion	\$9,179 billion (-\$6 billion)
SGM33	1995 in 2020	SGM, MAGICC	Battelle	1995 emissions level	stabilize in 2020	Annex I	auction	lump-sum	no LDC part.	IAT	CR	1.0	yes	-->2050, -->2100 (climate)	\$410 billion	\$9,176 billion (-\$9 billion)
SGM32	1995 in 2020	SGM, MAGICC	Battelle	1995 emissions level	stabilize in 2020	domestic only	auction	lump-sum	no LDC part.	IAT	CR	1.0	yes	-->2050, -->2100 (climate)	\$445 billion	\$9,176 billion (-\$9 billion)
SGM34	1995 in 2020	SGM, MAGICC	Battelle	1995 emissions level	stabilize in 2020	worldwide	auction	lump-sum	no LDC part.	IAT	CR	1.0	yes	-->2050, -->2100 (climate)	-\$40 billion	\$9,180 billion (-\$5 billion)
SGM12	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	Annex I	auction	lump-sum	no LDC part.	IAT	PI	1.0	no	-->2050, -->2100 (climate)	\$55 billion	\$9,185 billion (\$0 billion)
SGM30	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	Annex I	auction	lump-sum	no LDC part.	IAT	PI	1.0	in 2005	-->2050, -->2100 (climate)	\$75 billion	\$9,185 billion (0 billion)
SGM24	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	Annex I	auction	lump-sum	LDC stabilizes at 2030 in 2030	IAT	PI	1.0	in 2005	-->2050, -->2100 (climate)	\$75 billion	\$9,185 billion (0 billion)

ID	Scenario	Model	Modelers	Target	Timetable	Trading	Permit Allocation	Revenue Recycling	Burden Sharing	BAU Emissions Path Assumption	Paper Tons or Corresponding Reductions	AEEI	Ramp-up	Time Path	PDV (5%; 2000-2050) Foregone Consumption	GDP in 2010 (deviation from BAU)
SGM27	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	Annex I	auction	lump-sum	LDC BAU to 2030, equal per capita in 2050	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$75 billion	\$9,185 billion (0 billion)
SGM11	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	domestic only	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	\$235 billion	\$9,185 billion (\$0 billion)
SGM29	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	domestic only	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$270 billion	\$9,184 billion (-\$1 billion)
SGM26	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	domestic only	auction	lump-sum	LDC BAU to 2030, equal per capita in 2050	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$270 billion	\$9,184 billion (-\$1 billion)
SGM23	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	domestic only	auction	lump-sum	LDC stabilizes at 2030 in 2030	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$270 billion	\$9,184 billion (-\$1 billion)
SGM25	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	worldwide	auction	lump-sum	LDC stabilizes at 2030 in 2030	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	-\$3 billion	\$9,185 billion (0 billion)
SGM31	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	worldwide	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	-\$5 billion	\$9,185 billion (0 billion)
SGM13	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	worldwide	auction	lump-sum	no LDC part.	IAT	PT	1.0	no	-->2050, -->2100 (climate)	-\$8 billion	\$9,185 billion (\$0 billion)
SGM28	Peak in 2015	SGM, MAGICC	Battelle	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	worldwide	auction	lump-sum	LDC BAU to 2030, equal per capita in 2050	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$1 billion	\$9,185 billion (0 billion)
SGM15	+10% of 1990 in 2010	SGM, MAGICC	Battelle	+10% 1990 emissions level	stabilize in 2010	Annex I	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$95 billion	\$9,181 billion (-\$4 billion)
SGM14	+10% of 1990 in 2010	SGM, MAGICC	Battelle	+10% 1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$460 billion	\$9,174 billion (-\$11 billion)

ID	Scenario	Model	Modelers	Target	Timetable	Trading	Permit Allocation	Revenue Recycling	Burden Sharing	BAU Emissions Path Assumption	Paper Tons or Corresponding Reductions	AEEI	Ramp-up	Time Path	PDV (5%; 2000-2050) Foregone Consumption	GDP in 2010 (deviation from BAU)
SGM16	+10% of 1990 in 2010	SGM, MAGICC	Battelle	+10% 1990 emissions level	stabilize in 2010	worldwide	auction	lump-sum	no LDC part.	IAT	PT	1.0	in 2005	-->2050, -->2100 (climate)	\$1 billion	\$9,184 billion (-\$1 billion)
MM1	BAU	Markal	DOE	n/a	n/a	n/a	n/a	n/a	n/a	IAT	n/a	~1.0	n/a	-->2025	n/a	\$9,205 billion (BAU GDP)
MM2	1990 in 2010	Markal	DOE	1990 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	n/a	~1.0	n/a	-->2025	n/a	\$9,137 billion (-\$68 billion)
MM3	1995 in 2010	Markal	DOE	1995 emissions level	stabilize in 2010	domestic only	auction	lump-sum	no LDC part.	IAT	n/a	~1.0	n/a	-->2025	n/a	\$9,152 billion (-\$53 billion)
MM4	1990 in 2020	Markal	DOE	1990 emissions level	stabilize in 2020	domestic only	auction	lump-sum	no LDC part.	IAT	n/a	~1.0	n/a	-->2025	n/a	\$9,197 billion (-\$8 billion)
MM5	Peak in 2015	Markal	DOE	2010 BAU emissions in 2015; 1990 level in 2040	stabilize in 2040	domestic only	auction	lump-sum	no LDC part.	IAT	n/a	~1.0	n/a	-->2025	n/a	\$9,201 billion (-\$4 billion)

ID	Permit Prices: 2010	Permit Prices: 2025	Permit Prices: 2050	Conc. (ppmv) in 2050 (Deviation from BAU)	Conc. (ppmv) in 2100 (Deviation from BAU)	Year Conc. (550 ppmv) Reaches 2x Pre-Ind. Level (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2050 (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2100 (Deviation from BAU)	Emissions Peak, mmtce (year)	Year Returns to 1990	Intl. Trade of Permits, U.S., 2010 (MMTCE), (\$)	Intl. Trade of Permits, U.S., 2050 (MMTCE), (\$)	Date Received Run	File (h:\jaldy\)
SGM1	\$0	\$0	\$0	502	711	2065	1.06	2.36	no peak: 2245 (2050)	n/a	n/a	n/a	08/21/97	cea90_~1.xls
SGM9	\$91	\$137	\$238	481 (-21)	645 (-66)	2074 (+9)	0.97 (-0.09)	2.11 (-0.25)	1637 (2005)	never returns	-180, (-\$16.4 billion)	-332, (-\$79.0 billion)	08/21/97	cea90m_~1.xls
SGM8	\$175	\$304	\$924	481 (-21)	645 (-66)	2074 (+9)	0.97 (-0.09)	2.11 (-0.25)	1637 (2005)	2010	n/a	n/a	08/21/97	cea90m_~1.xls
SGM10	\$33	\$37	\$45	481 (-21)	645 (-66)	2074 (+9)	0.97 (-0.09)	2.11 (-0.25)	no peak: 2060 (2050)	never returns	-332, (-\$11.0 billion)	-845, (-\$38.0 billion)	08/21/97	cea90m_~1.xls
SGM36	\$23	\$86	\$150	486 (-16)	656 (-55)	2072 (+7)	0.99 (-0.07)	2.16 (-0.20)	no peak: 1714 (2050)	n/a	-180 (-\$4.14 billion)	-364 (-\$54.6 billion)	09/10/97	case20~1.xls
SGM39	\$41	\$84	\$149	486 (-16)	656 (-55)	2072 (+7)	0.99 (-0.07)	2.16 (-0.20)	no peak: 1714 (2050)	never returns	-202, (-\$8.3 billion)	-364, (-\$54.2 billion)	09/10/97	case10~1.xls
SGM3	\$42	\$84	\$149	486 (-16)	655 (-56)	2072 (+7)	0.99 (-0.07)	2.15 (-0.21)	no peak: 1714 (2050)	never returns	-202, (-\$8.5 billion)	-364, (-\$54.2 billion)	08/21/97	cea90_~2.xls
SGM18	\$39	\$83	\$150	478 (-24)	565 (-146)	2091 (+26)	0.96 (-0.10)	1.82 (-0.54)	no peak: 1712 (2050)	never returns	-209, (-\$8.2 billion)	-362, (-\$54.3 billion)	08/27/97	case2.xls, 9/4/97 fax
SGM21	\$39	\$83	\$150	n/a	n/a	n/a	n/a	n/a	no peak: 1712 (2050)	never returns	-209, (-\$8.2 billion)	-362, (-\$54.3 billion)	08/27/97	case3.xls
SGM17	\$108	\$188	\$582	476 (-26)	564 (-147)	2092 (+27)	0.95 (-0.11)	1.82 (-0.54)	1550 (2000)	2010	n/a	n/a	08/27/97	case2.xls, 9/4/97 fax
SGM2	\$110	\$191	\$582	485 (-17)	658 (-53)	2072 (+7)	0.99 (-0.07)	2.16 (-0.20)	1637 (2005)	2010	n/a	n/a	08/21/97	cea90_~2.xls
SGM38	\$108	\$188	\$582	484 (-18)	656 (-55)	2073 (+8)	0.98 (-0.08)	2.15 (-0.21)	1550 (2000)	2010	n/a	n/a	09/10/97	case10~1.xls
SGM20	\$108	\$188	\$582	n/a	n/a	n/a	n/a	n/a	1550 (2000)	2010	n/a	n/a	08/27/97	case3.xls
SGM40	\$16	\$23	\$33	486 (-16)	656 (-55)	2072 (+7)	0.99 (-0.07)	2.16 (-0.20)	no peak: 2101 (2050)	never returns	-312, (-\$5.0 billion)	-751, (-\$24.8 billion)	09/10/97	case10~1.xls

ID	Permit Prices: 2010	Permit Prices: 2025	Permit Prices: 2050	Conc. (ppmv) in 2050 (Deviation from BAU)	Conc. (ppmv) in 2100 (Deviation from BAU)	Year Conc. (550 ppmv) Reaches 2x Pre-Ind. Level (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2050 (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2100 (Deviation from BAU)	Emissions Peak, mmtce (year)	Year Returns to 1990	Intl. Trade of Permits, U.S., 2010 (MMTCE), (\$)	Intl. Trade of Permits, U.S., 2050 (MMTCE), (\$)	Date Received Run	File (h:\jaldy)
SGM4	\$16	\$23	\$32	486 (-16)	655 (-56)	2072 (+7)	0.99 (-0.07)	2.15 (-0.21)	no peak: 2102 (2050)	never returns	-313, (-\$5.0 billion)	-752, (-\$24.1 billion)	08/21/97	cea90_~2.xls
SGM22	\$15	\$23	\$0	n/a	n/a	n/a	n/a	n/a	no peak: 2239 (2050)	never returns	n/a	n/a	08/27/97	case3.xls
SGM19	\$15	\$23	\$110	478 (-24)	565 (-146)	2091 (+26)	0.96 (-0.10)	1.82 (-0.54)	1883 (2040)	never returns	-316, (-\$4.7 billion)	-500, (-\$55.0 billion)	08/27/97	case2.xls, 9/4/97 fax
SGM35	\$71	\$192	\$582	484 (-18)	656 (-55)	2073 (+8)	0.98 (-0.08)	2.15 (-0.21)	1550 (2000)	2020	n/a	n/a	09/10/97	case20~1.xls
SGM37	\$9	\$24	\$33	486 (-16)	656 (-55)	2072 (+7)	0.99 (-0.07)	2.16 (-0.20)	no peak: 2101 (2050)	n/a	-246 (-\$2.21 billion)	-751 (-\$24.78 billion)	09/10/97	case20~1.xls
SGM6	\$74	\$119	\$202	483 (-19)	648 (-63)	2074 (+9)	0.98 (-0.08)	2.12 (-0.24)	1637 (2005)	never returns	36, (+\$2.7 billion)	-122, (-\$24.6 billion)	08/21/97	cea95_~1.xls
SGM5	\$62	\$131	\$317	483 (-19)	648 (-63)	2074 (+9)	0.98 (-0.08)	2.12 (-0.24)	1637 (2005)	never returns	n/a	n/a	08/21/97	cea95_~1.xls
SGM7	\$27	\$32	\$41	483 (-19)	648 (-63)	2074 (+9)	0.98 (-0.08)	2.12 (-0.24)	no peak: 2073 (2050)	never returns	-131, (-\$3.5 billion)	-593, (-\$24.3 billion)	08/21/97	cea95_~1.xls
SGM33	\$57	\$120	\$203	482 (-20)	648 (-63)	2074 (+9)	0.97 (-0.09)	2.12 (-0.24)	no peak: 1599 (2050)	n/a	20 (\$1.14 billion)	-119, (-\$24.16 billion)	09/10/97	case20~2.xls
SGM32	\$51	\$131	\$318	482 (-20)	648 (-63)	2074 (+9)	0.97 (-0.09)	2.12 (-0.24)	1550 (2000)	n/a	n/a	n/a	09/10/97	case20~2.xls
SGM34	\$21	\$33	\$41	482 (-20)	648 (-63)	2074 (+9)	0.97 (-0.09)	2.12 (-0.24)	no peak: 2072 (2050)	n/a	-122 (-\$2.56 billion)	-592 (-\$24.27 billion)	09/10/97	case20~2.xls
SGM12	\$0	\$47	\$155	491 (-11)	n/a	n/a	1.02 (-0.04)	n/a	1807 (2015)	never returns	0, (n/a)	-367, (-\$56.9 billion)	08/21/97	cea90_~1.xls
SGM30	\$11	\$56	\$153	489 (-13)	658 (-53)	2071 (+6)	1.00 (-0.06)	2.17 (-0.19)	1755 (2015)	never returns	-5, (-\$0.06 billion)	-367, (-\$56.2 billion)	08/27/97	case6.xls, 9/4/97 fax
SGM24	\$11	\$56	\$153	481 (-21)	568 (-143)	2089 (+24)	0.98 (-0.08)	1.84 (-0.52)	1755 (2015)	never returns	-5, (-\$0.06 billion)	-367, (-\$56.2 billion)	08/27/97	case4.xls, 9/4/97 fax

ID	Permit Prices: 2010	Permit Prices: 2025	Permit Prices: 2050	Conc. (ppmv) in 2050 (Deviation from BAU)	Conc. (ppmv) in 2100 (Deviation from BAU)	Year Conc. (550 ppmv) Reaches 2x Pre-Ind. Level (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2050 (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2100 (Deviation from BAU)	Emissions Peak, mmtce (year)	Year Returns to 1990	Intl. Trade of Permits, U.S., 2010 (MMTCE), (\$)	Intl. Trade of Permits, U.S., 2050 (MMTCE), (\$)	Date Received Run	File (h:\jaldy\)
SGM27	\$11	\$56	\$153	n/a	n/a	n/a	n/a	n/a	1755 (2015)	never returns	-5, (-\$0.06 billion)	-367, (-\$56.2 billion)	08/27/97	case5.xls
SGM11	\$0	\$84	\$559	489 (-13)	n/a	n/a	1.01 (-0.05)	n/a	1807 (2015)	2040	n/a	n/a	08/21/97	cea90_~1.xls
SGM29	\$12	\$99	\$563	489 (-13)	658 (-53)	2071 (+6)	1.00 (-0.06)	2.17 (-0.19)	1729 (2015)	2040	n/a	n/a	08/27/97	case6.xls, 9/4/97 fax
SGM26	\$12	\$99	\$563	n/a	n/a	n/a	n/a	n/a	1729 (2015)	2040	n/a	n/a	08/27/97	case5.xls
SGM23	\$12	\$99	\$563	481 (-21)	568 (-143)	2089 (+24)	0.98 (-0.08)	1.84 (-0.52)	1729 (2015)	2040	n/a	n/a	08/27/97	case4.xls, 9/4/97 fax
SGM25	\$4	\$16	\$111	481 (-21)	568 (-143)	2089 (+24)	0.98 (-0.08)	1.84 (-0.52)	1893 (2030)	never returns	-30, (-\$0.1 billion)	-500, (-\$55.5 billion)	08/27/97	case4.xls, 9/4/97 fax
SGM31	\$4	\$16	\$33	489 (-13)	658 (-53)	2071 (+6)	1.00 (-0.06)	2.17 (-0.19)	no peak: 2101 (2050)	never returns	-30, (-\$0.12 billion)	-751, (-\$24.8 billion)	08/27/97	case6.xls, 9/4/97 fax
SGM13	\$0	\$14	\$33	491 (-11)	n/a	n/a	1.02 (-0.04)	n/a	no peak: 2102 (2050)	never returns	0, (n/a)	-752, (-\$24.8 billion)	08/21/97	cea90_~1.xls
SGM28	\$4	\$16	\$0	n/a	n/a	n/a	n/a	n/a	no peak: 2241 (2050)	never returns	n/a	n/a	08/27/97	case5.xls
SGM15	\$17	\$56	\$113	489 (-13)	662 (-49)	2071 (+6)	1.00 (-0.06)	2.18 (-0.18)	no peak: 1824 (2050)	never returns	-172, (-\$2.9 billion)	-339, (-\$38.3 billion)	08/27/97	case1.xls
SGM14	\$60	\$128	\$310	488 (-14)	664 (-47)	2071 (+6)	0.99 (-0.07)	2.18 (-0.18)	1550 (2000)	never returns	n/a	n/a	08/27/97	case1.xls

ID	Permit Prices: 2010	Permit Prices: 2025	Permit Prices: 2050	Conc. (ppmv) in 2050 (Deviation from BAU)	Conc. (ppmv) in 2100 (Deviation from BAU)	Year Conc. (550 ppmv) Reaches 2x Pre-Ind. Level (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2050 (Deviation from BAU)	Change in Temp. (deg. C) from 1990 in 2100 (Deviation from BAU)	Emissions Peak, mmtce (year)	Year Returns to 1990	Intl. Trade of Permits, U.S., 2010 (MMTCE), (\$)	Intl. Trade of Permits, U.S., 2050 (MMTCE), (\$)	Date Received Run	File (h:\jaldy\)
SGM16	\$7	\$16	\$25	489 (-13)	662 (-49)	2071 (+6)	1.00 (-0.06)	2.18 (-0.18)	no peak: 2128 (2050)	never returns	-219, (-\$1.5 billion)	-643, (-\$16.1 billion)	08/27/97	case1.xls
MM1	\$0	\$0	n/a	n/a	n/a	n/a	n/a	n/a	no peak: 2066 (2025)	n/a	n/a	n/a	08/26/97	8_26run1.wk4
MM2	\$148	\$192	n/a	n/a	n/a	n/a	n/a	n/a	1586 (2005)	2010	n/a	n/a	08/26/97	8_26run1.wk4
MM3	\$136	\$146	n/a	n/a	n/a	n/a	n/a	n/a	1600 (2005)	n/a	n/a	n/a	08/26/97	8_26run1.wk4
MM4	\$0	\$198	n/a	n/a	n/a	n/a	n/a	n/a	1749 (2010)	2020	n/a	n/a	08/26/97	8_26run1.wk4
MM5	\$0	\$99	n/a	n/a	n/a	n/a	n/a	n/a	1767 (2015)	2040*	n/a	n/a	08/26/97	8_26run1.wk4

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*Fax 203-432-5779*

*June 20, 1997*

*see Figure 9*

Dr. Jay Shogren

Council of Economic Advisers

Dear Jay,

This is a refined version of the earlier paper. The RICE-model simulations have improved and do not look good for Rio-type schemes either from an economic or political point of view.

*book:  
when things  
bite back*

Sincerely,

*Bill*

**CLIMATE ALLOWANCES PROTOCOL (CAP):  
COMPARISON OF ALTERNATIVE GLOBAL TRADABLE EMISSIONS REGIMES**

William D. Nordhaus

June 17, 1997

Preliminary

**Abstract**

Recently, the U.S. government proposed an international emissions-trading protocol to cope with the threat of global warming due to emissions from greenhouse gases (GHGs). While such a proposal is superior to earlier approaches (such as the country-specific emissions targets of the Rio Treaty or the Berlin protocol), it leaves open a number of crucial questions. These include the appropriate objectives, the distribution of emissions budgets among countries, a mechanism to discover countries' perceived benefits from such an arrangement, as well as a set of incentive and enforcement procedures.

This paper develops a Climate Allowances Protocol (CAP) that addresses many of the outstanding issues. It is based on the view that the system should balance costs against benefits, be economically efficient, and respect *the realpolitik* fact that sovereign nations must find it in their self-interest. The CAP plan integrates climate policy with an underlying cost-benefit approach that maximizes global incomes and allows countries to arrive at a level of the public good that reflects an aggregation of individual country preferences.

Simulations of the efficiency and realism of the CAP plan using an updated version of the RICE model indicate that it has major economic advantages, leads to benefits for most participants, and has equivalent environmental benefits as compared to current international proposals.

**CLIMATE ALLOWANCES PROTOCOL (CAP):  
COMPARISON OF ALTERNATIVE GLOBAL TRADABLE EMISSIONS REGIMES**

William D. Nordhaus<sup>1</sup>

June 17, 1997

Preliminary

**1. Background and Motivation**

Recently, the U.S. government proposed an international emissions-trading protocol to cope with the threat of global warming due to CO<sub>2</sub> emissions from combustion of fossil fuels and other greenhouse gases (GHGs).<sup>2</sup> While a market mechanism is superior to earlier approaches (such as country-specific emissions targets), it leaves open a number of crucial questions. These include the appropriate ultimate concentrations and emissions targets, the distribution of allowable emissions among countries, a mechanism to discover countries' perceived benefits from such an arrangement, as well as the issues of incentive and enforcement procedures.

To date, there has been virtually no attention to the economic aspects of the design of such a protocol, and surprisingly little attention to making the design consistent with sound economic and political principles. This paper describes a regime (the "Climate Allowances Protocol" or CAP) that takes into account current economic theory of public goods and compares this approach with current proposals that are being discussed in government circles. The basic philosophy here is that the system should balance costs against benefits, be economically efficient, and respect the fact that the agreement must be among sovereign nations and must be in the self-interest of participating nations.

Global warming poses especially nasty obstacles to reaching efficient and effective policies. It is a public good over space and time in the sense that emissions in any place affect climate everywhere and for centuries in the future. There is no obvious technological fix. The scientific and economic uncertainties are sufficiently large that those who would be harmed by policies can easily generate a smokescreen to confuse people by arguing that the

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<sup>1</sup> The author is A. Whitney Griswold Professor of Economics and on the staff of the Cowles Foundation, 28 Hillhouse Avenue, Yale University, New Haven, CT 06520, USA.

<sup>2</sup> See U. S. Department of State, *U. S. Draft Protocol and Fact Sheet on Climate Change Proposal*, January 17, 1997.

scientific case is weak or trumped up. And the economic stakes are enormous, with the present value of costs and future damages of many proposals likely to run in the hundreds of billions of dollars annually. These features are exacerbated by the fact that there is no obvious anchor or “focal” point for policy. In this respect, global warming differs from other policies that have focal strategies, such as trade regimes (zero tariffs and trade barriers) or nuclear non-proliferation agreements (no weapons or weapons-grade material). Without focal policies, agreement is more difficult because reasoned disagreement is so easily sustained.

While this discussion is aimed at the threat of greenhouse warming, I think of it as a prototype for any important global economic public good. A global economic public good in one for which there are huge numbers of economic agents in a large numbers of countries and where the costs and benefits of action do not indicate any obvious focal policy or technological fix. While global warming might or might not turn out to be a critical issue for humanity or natural ecosystems, it is useful to think through how we might design a global economic regime when and if a crucial global economic public good appears on the radar screen. If you think global warming is a critical issue, this should interest you; if not, then imagine a global economic public good that is critical and apply these principles there.

This sketch will begin with a summary of the mechanisms and then proceed to see how it addresses the major design hurdles. It is meant only to sketch the major issues because a full treatment would be longer than the tolerance of most mortals.<sup>3</sup>

## 2. The Thorny Issues of Regime Design

Current international proposals for limiting greenhouse gases (such as those set out in the Rio Treaty or in the current U.S. proposal) are deeply flawed. They are based on arbitrary historical benchmarks for emissions limitations and make no attempt to link the path of emissions to any economic or environmental objective. They provide no incentives for countries to join or to follow the rules once they have joined. It is not surprising that every serious economic analysis of these proposals finds them highly inefficient.

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<sup>3</sup> This discussion will contain only a few references from the vast literature on the subject. An excellent overview with a bibliography to most of the literature is contained in B.S. Fisher, S. Barrett, P. Bohm, M. Kuroda, J.K.E. Mubazi, A. Shah, and R.N. Stavins, “An Economic Assessment of Policy Instruments for Combatting Climate Change,” Chapter 11 in James P. Bruce, Hoesung Lee, and Erik F. Haites, *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, Cambridge, U.K., 1996, pp 397-439. Many of the legal principles are laid out in Stewart???

What first principles would be look to in designing a regime that is economically efficient and politically viable? The most important characteristics are the following:

- The regime should be moderately efficient from an economic and administrative point of view.
- There must be positive incentives for countries to participate in the regime and to fulfill their obligations.
- The regime must contain a decision process which will induce countries to agree to efficient levels of greenhouse gas reduction.

I believe that the proposal discussed below satisfies the first three criteria reasonably well. The next three points are ones that are troubling and have no obvious solutions:

- The regime must recognize that countries with inept or corrupt governments may subvert the process or use it for personal gain.
- The regime must not injure other international agreements, particularly international trade agreements.
- The decision process should be simple and familiar to countries.

### 3. The Basic Mechanism

The alternative regime considered here — which is called the Climate Allowance Protocol (CAP) — would embed the price and quantity targets within a framework that considers both environmental and economic objectives and sets the policies to maximize net benefits. CAP proceeds by having a set of tradable emissions allowances or permits with carbon price ceilings and floors. The major innovation is that the emissions limits and carbon prices are derived from a dynamic cost-benefit analysis that incorporates all costs and benefits of slowing climate change. The costs are estimated from engineering and economic models, and will be tested in each accounting period. The benefits will be derived from a public goods mechanism of participating countries.

Participant countries will be allocated a number of emissions permits for each budget period. A major and fundamental difference between the CAP and current proposals is that the emission baselines for individual countries are rolling targets rather than ones set on the

basis of an arbitrary historical benchmark. In addition, there are expectations that countries will begin to participate as their economies develop. In CAP, countries will be expected to make small emissions reductions when their per capita incomes reach an "entry-level income" and to participate fully when their incomes reach "full-participation income."

In each budget period, the number of permits will be allocated according to a formula that reflects each country's uncontrolled emissions and its ability to pay. Because carbon prices are equalized across participating countries, there will be no need for tariffs or border tax adjustments among participants. The incentive to participate — and sanctions against violations — will come from import duties on the carbon content of imports of non-participants into participating countries. Unlike current proposals, there is no need for financial transfers among countries, which raise severe political complications. The balance of the paper describes these points in detail.

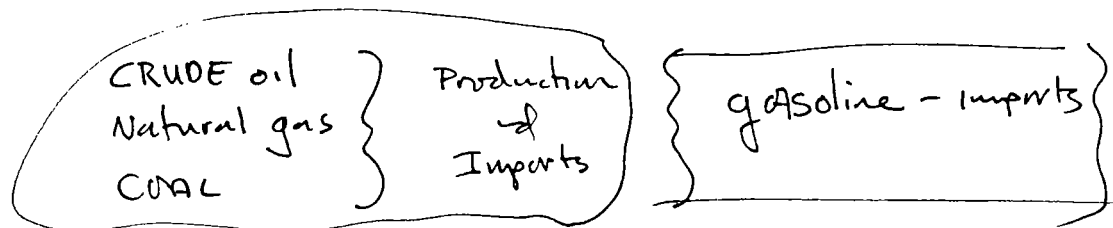
#### 4. The Trading Rules

The basic approach of the Climate Allowance Protocol is to have an agreement among the participating countries to limit the total annual emissions of greenhouse gases.

→ The overall limitation will be allocated to individual countries, who will receive their basic allowances of greenhouse gases. Nations will be allowed to buy, sell, barter, and borrow other countries' allowances as long as all the rules are obeyed. The fundamental rule is that a country's emissions shall not exceed the sum of its own allowances plus net purchases of allowances from other countries.

$$E_{\text{emissions}_i} = \bar{E}_i + \sum_{j \neq i} e_j \quad e_j \geq 0$$

CAP would initially include "covered fuels," which comprise the consumption of fossil fuels. For accounting purposes, consumption will be equal to domestic production of fossil fuels plus net imports. For example, for the U.S., consumption would include production of crude oil, natural gas, coal, as well as net imports of those fuels and net imports of petroleum products such as gasoline. Consumption would exclude derivative products such as petrochemicals, electricity, chemicals, as well as the fuels embodied in manufactured products. In the CAP, because emissions limits are pegged to uncontrolled emissions, there are no significant distributional or efficiency impacts of the exact definition



emission limits pegged to uncontrolled emissions

of covered fuels.<sup>4</sup> There is a complication for imports from non-participants, which is discussed later in the paper.

Each nation will be allowed to administer its emissions limitations in its own manner. In a market economy, it would be natural to require that each producer or importer of covered fuels purchase the requisite emissions allowances. For reasons discussed below, it is recommended that governments auction or sell their allowances. We estimate that the cost of the allowances would be shifted forward to consumers except for fuels that are highly price-inelastic in supply. ✗

### 5. Balancing Costs and Benefits in the Emissions Trading Regime

The fundamental philosophy of the CAP is that global emissions targets are chosen to balance costs and benefits of emissions reductions. This approach is radically different from current approaches in international negotiations (such as those under the Rio Treaty), which have targets and timetables for emissions limitations with no rationale for the targets and timetables. The Rio emissions limits are ones that occurred during a particular historical period in a particular country; they are easy to understand and explain. But they make no sense; there is no link between the targets and timetables, on the one hand, and the economic or environmental benefits. NO scientific or economic rationale

need to link the target and timetables to econ. & env. benefits.

The proposal here is to link the targets explicitly to economic and environmental benefits through the use of dynamic cost-benefit analysis. The state of the art in cost-benefit analysis of climate change are "integrated assessment" (IA) models, of which a wide variety are currently available and in use.<sup>5</sup> Most of the inputs into these models are of a scientific and technocratic nature. Such inputs include parameters of the carbon cycle, engineering and scientific data on global warming potential and carbon content of different fuels, and

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<sup>4</sup> The general principle is to define covered fuels in a manner that monitoring and enforcement costs are minimized. For that purpose, covered fuels are production of fossil fuels plus net imports of fuels and direct products. The only subtlety here is that consumption includes net imports, which will require some careful thought to ensure consistency and efficiency. Under the principles for allocation of allowances used here, the definition is of no importance for efficiency and is only of second-order importance for distribution. The definition would have great importance under current international proposals that have a fixed as opposed to a rolling base.

<sup>5</sup> An excellent overview of Integrated Assessment models by lead author John Weyant and collaborators is contained in Chapter 10 of James P. Bruce, Hoesung Less, and Erik F. Haites, eds., *Climate Change 1995 — Economic and Social Dimensions of Climate Change*, Cambridge University Press, 1996.

1. optimum ~~set~~ b/c
2.  $\Rightarrow$  optimal emissions over 5 year
- 3.

climate models. Two sets of non-technocratic data are, however, crucial for the results: the costs of emissions reduction and the damages from (or willingness-to-pay to avoid) climate change. Derivation of these will be described below.

The full output of the dynamic cost benefit analysis will be an "indicative plan" for global GHG emissions and carbon taxes. This indicative plan will be the basis of the overall limits on emissions. For each (accounting period (say five years), countries will be allocated emissions allowances whose sum equals the optimized emissions from the IA models.

The CAP mechanism relies on allocating emissions rather than carbon taxes because there is no mechanism for allocating carbon taxes. But carbon taxes or prices are a central part of the plan and will be introduced by having price ceilings and floors. Should emissions limits within a budget period be tighter than expected because of model mis-estimates, countries may buy emissions allowances at a ceiling price that is a premium (say, 150 percent) of the optimized carbon tax. Too-low prices will be ignored for the moment.

Deviations of prices or quantities from the levels projected in the IA planning models for the budget period will automatically be corrected by model revisions for the next budget period. This automatically incorporates a procedure by which the latest scientific and economic information and revised national priorities will be incorporated into the prices and quantities each period.

ADJUSTABLE TARGETS given new information on costs & benefits

## 6. Costs of Emissions Control

In our summary, we stated that the cost side of the cost-benefit analysis would be automatically revealed in the emissions-trading market. We explain that point in this section.

The revelation is seen most clearly for a private market economy. Suppose that the price of an emissions permit is  $\tau = \$10$  per ton of carbon. This means that firms can produce output using covered fuels at a marginal cost of  $P + \tau$  or substitute inputs at a cost of  $R$ . This implies that the marginal cost of reducing emissions is  $MC = R - P = \tau$ .

The revelation of marginal cost is illustrated in Figure 1. The curves  $MC^1$  and  $MC^2$  are the marginal cost curves for emissions reductions in regions 1 and 2. The efficient global cost-of-reduction curve is shown as  $MC^T$ . The vertical line at  $\bar{E}^T$  is the sum of the emissions limitations of the regions,  $\bar{E}^T = \bar{E}^1 + \bar{E}^2$ .

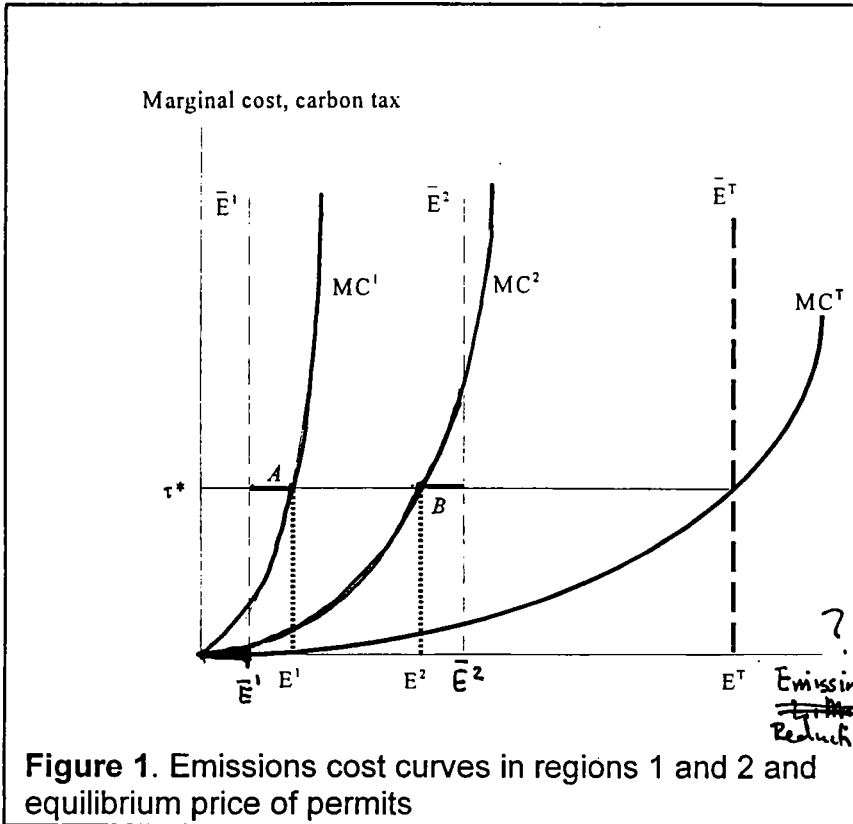
$$R = P + \tau$$

$$R - P = \tau$$

How are  $\bar{E}^1$  &  $\bar{E}^2$  chosen?

$$MC_{CF} = P + \tau$$

$$MC_{OTHER} = R$$



Firms in each regions will purchase or sell permits to the point where their MC of emissions reduction equals the permit price. The efficient allocation is shown in Figure 1 at a permit price of  $\tau^*$ . At that price, region 1 buys permits shown by the segment A, while region 2 sells segment B. The balancing condition is  $B + A = 0$ .

The key point to note is that (for cost minimizing entities), the permit price will be equal to the marginal cost of emissions reductions for each region. We will thus be able to observe the marginal cost curve

for emissions reductions as individual entities make their decisions.

INGA FREIDA

## 7. Public Goods Mechanism

In contrast to cost of controls, the value of emission reductions (or averted damages of climate change) cannot be determined by a market mechanism. Most of the damages will be felt far in the future, and indeed even the "experts" have only the haziest notions about what those costs may be and who will bear them. It is therefore necessary to design a process whereby reliable estimates of different countries' willingnesses to pay can be derived.

Slowing harmful climate change is a global public good. Individual people, countries, and generations make but a small contribution to slowing climate change, and this leads to the possibility of free-riding, posturing, temporizing, and insincere statements of position. On top of this intrinsic difficulty is the further complication that environmental policy is largely in the hands of environmentalists and large companies, neither of which adequately represents the interest of consumers. A final difficulty is that global warming involves countries with highly divergent incomes and priorities. The major difficulty in any plan, therefore, is to design a *public goods mechanism* that can find a tolerably good solution to this very nasty public goods problem.

The mechanism proposed here responds to these problems by containing two stages.

- The first stage is the *constitutional stage*. In this part, countries agree on the basic framework of the process. This stage involves the choice of international instrument, the accounting framework, the voting procedure, setting sanctions for non-participation or infractions, and the legal ratification and amendment processes. Given the long time horizon of the global warming problem, this stage effectively operates behind a Rawlsian veil of ignorance because costs and particularly benefits lie far in the future compared to most current investments and elections. Given the nature of the public good, this stage is largely distributional and could easily lead to protracted impasses.
- The second stage contains the *decision-administrative processes*. Given the constitution of the global warming agreement, heterogeneous country preferences will have to be aggregated into a single global level of emissions. Among the alternative processes we suggest that a voting mechanism is likely to be the most fruitful.

Before discussing the constitutional and decision-administrative phases, some background comments are necessary. The mechanism proposed here treats the massive public goods problem by having nations serve as trustees of future generations and by separating the costs today from the benefits in the future. The central idea is that countries will vote a given "value" of reducing climate change (or the willingness to pay [WTP] to reduce slow climate change). When the different values are aggregated, this will imply an efficient level of emissions control and an associated carbon emissions price or carbon tax today. None of these numbers will be a surprise to the countries who are voting on the decision -- rather the final outcome will be the result of negotiations, persuasion, recalibration, models runs, bargaining, and further negotiations until an agreed level of control and carbon price is agreed upon.

It should be emphasized that the design of the public goods mechanism is both the core of the proposal and its most problematic feature. While countries routinely use voting mechanisms to decide upon national public goods, there are a very few supranational examples of functional public goods mechanism. Those used by the European Union may be the closest in nature to the proposal here.

## 8. The Constitutional Stage

Before voting, countries need to know how they will be "taxed" to pay for the public good of slowing climate change. The mechanism outlined here presumes that nations are

likely to vote resources to emissions reductions primarily out of concern for the future rather than because they believe that they are likely to be differentially affected. Nations which have high willingness to pay and low discount rates will select higher control rates and carbon emission prices than those who are primarily concerned with today's economic and political issues.

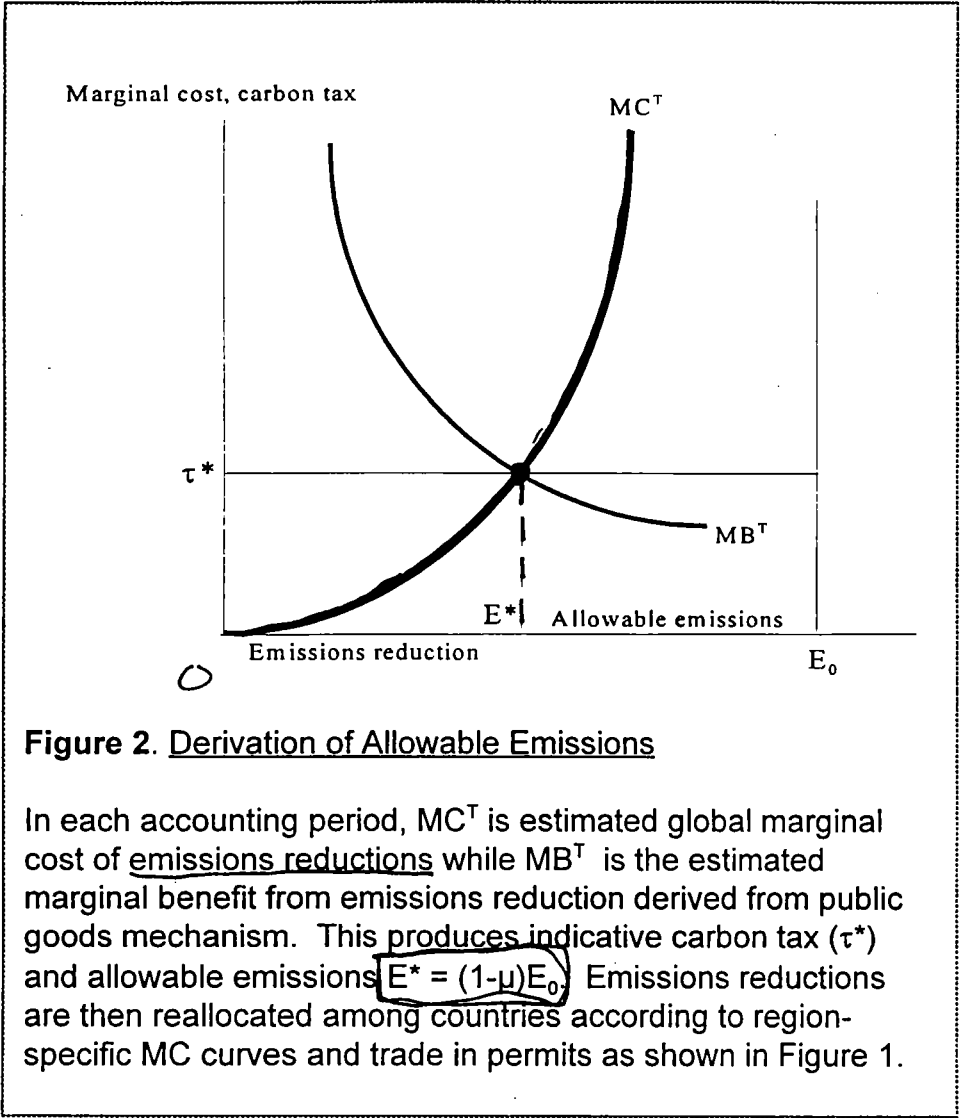
The payment mechanism will start with a zero base of uncontrolled emissions. This initial condition reflects the realistic fact of life that the status quo of doing nothing has a privileged position under custom and international law. Starting from the status quo, countries then pay according to both horizontal and vertical equity principles.

- The *horizontal equity* principle is that countries with the same per capita incomes should contribute proportionally to their current emissions. Assuming that price elasticities of supply and demand are equal across countries, this implies that each horizontally equivalent country shall receive permits that are a fixed fraction of baseline or uncontrolled emissions; equivalently, this means that the expected emissions reduction rate is equal for all horizontally equivalent country. If the elasticities are equal, this implies that the cost of participating in and complying with such a mechanism will be an equal fraction of national income for all countries that have the same level of emissions.
- The *vertical equity* principle would be that poor countries should be required to pay less than rich countries. The formula that is explored below proposes a floor of \$5000 per capita (below which a nation would have no expectations of emissions reduction) and a ceiling of \$15,000 per person (above which a nation would be expected to have full participation). The participation rate would then vary linearly over that range. (I consider alternative progressivity schedules below.)

Formally, nation  $i$  would in accounted period  $t$  receive a number of emissions permits equal to  $E_{i,t} = E_{0,i,t} [(1-f(y_{i,t}))\mu_t^*]$ . Here  $E_{0,i,t}$  is the baseline or uncontrolled level of emissions in period  $t$ ,  $f(y_i)$  is a fraction running from 0 to 1 as a function of the country's per capita income ( $y_i$ ), and  $\mu_t^*$  is the agreed target level of global emissions reduction for full participants in period  $t$ . The actual level of global emissions reduction ( $\mu_t^{act}$ ) will be less than the maximum level ( $\mu_t^*$ ) depending upon the degree of participation, the progressivity of the vertical equity schedule  $f$ , and the degree of compliance. The total  $\sum E_{0,i,t} f(y_i)$  is the amount of emissions that is subject to control and is called "reducible emissions."

The functioning of the mechanism is sketched in Figure 2. Estimates of the marginal costs of emissions are based on engineering and economic models for the first period. In

seems backwards?



subsequent periods, more reliable estimates will be obtained as countries begin reducing emissions and the price of permits rises above zero. The marginal benefit function is derived from the voting mechanism described below. These two fundamental building blocks are then used to generate the associated allowable emissions  $[(1 - \mu^{act})E_0]$  and carbon permit price ( $\tau^*$ ) as shown in Figure 2.

With no uncertainty, we could in principle use either the tax or emissions limitations. In fact, the tax approach is unworkable because it cannot be accurately verified against a background of other

**Figure 2. Derivation of Allowable Emissions**

In each accounting period,  $MC^T$  is estimated global marginal cost of emissions reductions while  $MB^T$  is the estimated marginal benefit from emissions reduction derived from public goods mechanism. This produces indicative carbon tax ( $\tau^*$ ) and allowable emissions  $E^* = (1 - \mu)E_0$ . Emissions reductions are then reallocated among countries according to region-specific MC curves and trade in permits as shown in Figure 1.

policies (such as fuel taxes and coal subsidies). We therefore use the emissions limitation approach as the most easily administered.

Given the uncertainty about the cost function, it is not sensible to ignore prices, however. To avoid costly mistakes, it is suggested that a cap on carbon prices be set at some premium (say 50 percent) over the estimated efficient price. (It may be possible to determine the optimal premium from IA models.) The revenues from the sale of extra permits at the premium price can be used as determined by the participating countries. For the case of prices that fall below the estimated price, it is suggested that countries be allowed to “bank” the excess permits for future use. We leave open the question of whether it would be useful to have a fund for stabilization purposes.

## 9. The Voting Mechanism

The second stage of the process is the decision-administrative process in which the revelation of the value of the public good is the essential issue. From an analytical perspective, there are many proposals for mechanisms to facilitate revelation of preferences for public goods. Most share the feature that they are “one-dimensional” in the sense that agents vote for a level of public goods with a payment mechanism in place. The major desideratum of an effective public goods mechanism is that it be *incentive compatible*. An incentive compatible mechanism is one in which agents have an incentive to reveal their true preferences.

There are a large number of potential ways that countries can decide upon a global emissions-reduction target.<sup>6</sup> (a) One approach is simply to allow countries to decide on their own. In the case of a *Nash equilibrium* where countries pursue only their own self-interest, calculations indicate that the degree of emissions reduction would be minuscule. (b) The *Lindahl equilibrium* asks countries to reveal their own individual prices and then sets the global rate of emissions reduction to maximize global welfare. This is defective because countries have strong incentives to misstate their own preferences. (c) One approach is simply allow countries to *bargain* until they reach agreement. Under the so-called Coase theorem, this process would reach an efficient outcome. (The transactions costs here are trivial relative to the economic costs and benefits.) While bargaining might reach a solution, it seems more likely to get bogged down and to be subject to serious free riding by non-participants. (d) A theoretically attractive approach is to use the *Clarke-Groves mechanism*. In this approach, countries bid the value of different global warming strategies. They are then taxed on the basis of their bids, with individual taxes calculated as the contribution of each country to the net cost imposed on other countries. This mechanism has attractive theoretical properties but is extremely complex, is far too intricate to explain to busy politicians, and has never to my knowledge been implemented.

NOT  
TRUE

The approach proposed here is to use a voting mechanism. This has the advantage that it is incentive compatible, is likely to come close to the efficient outcome (as long as tastes are not too skewed), and is familiar to most people. The major disadvantage compared to efficient public-goods mechanisms or bargaining is that it can impose significant costs on those whose preferences deviate significantly from the mainstream. The basic idea is the following:

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<sup>6</sup> I omit what seem fruitless or highly inefficient approaches like moral suasion and mandatory technical standards. While these are highly popular among politicians and can sometimes be useful supplements, they cannot form the core of an efficient and effective global public goods mechanism.

**Voting Mechanism.** The rate of emissions reduction is determined on the basis of the globally aggregated willingness to pay for reducing climate change. The willingness to pay is aggregated from the individual willingnesses to pay of different countries as expressed by their votes. The individual willingnesses are then averaged across participants on the basis of their reducible emissions.

In other words, the targeted emissions reduction is decided by voting of participants in the plan. Each country expresses its willingness to pay (call it parameter  $\omega_i$ ). The individual countries willingnesses are then aggregated into a global willingness ( $\Omega$ ) by averaging across the participants. Using the globally averaged willingness, then, we can estimate the optimal emissions reduction and carbon tax or permit price.

To make this more concrete, we would define the willingness to pay parameter as the annual willingness to pay to avoid the damages accompanying an equilibrium doubling of  $\text{CO}_2$  (or alternatively of a 3 degrees C warming). For example, a country might express a willingness to pay 2 percent of GDP to prevent the equilibrium climate change associated with a doubling of atmospheric  $\text{CO}_2$ . To obtain the economically correct emissions reduction, we would use the global average willingness to pay ( $\Omega = \sum \omega_i \lambda_i$ ) which is obtained by averaging the individual country willingness to pay ( $\omega_i$ ) by their shares of a world income ( $\lambda_i$ ). Unfortunately, this presents serious incentive problems. Weighting WTP by future incomes or total emissions (which is the appropriate measure of damage) would allow rapidly growing countries or countries with low emission reductions fractions ( $f$ ) to free ride on current emitters.

To avoid free riding, we need to work with a variant of global WTP that is incentive compatible. To do this, we weight each nation's expressed WTP by its share of reducible emissions. This mechanism will give an unbiased estimate of current WTP if WTP is uncorrelated with  $f(y_i)$ . Weighted median voting is simple, robust to strategic distortions, and prevents free riding:

*Weighted median voting*

**Voting Mechanism.** The voting mechanism in the plan would be to set the global willingness to pay ( $\Omega$ ) equal to the median WTP. In this calculation, each unit of reducible emissions would have an equal vote.

This mechanism is incentive compatible because there is no advantage for any country with single-peaked preferences<sup>7</sup> to vote anything other than its most preferred policy. To do

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<sup>7</sup> All studies of the damage from climate change indicate that countries have single-peaked preferences with respect to the willingness-to-pay parameter.

otherwise would either have no effect if it did not change the outcome or would lower its economic welfare if it did change the outcome.

Huh?

## 10. Calculation of Baseline Emissions

Baseline emissions play a critical role in the mechanism because determine the economic interests of countries, affect the equity of the system, and have a major impact upon incentive compatibility. One of the major flaws in current proposals (such as the Rio Treaty or the 1996 U.S. emissions-trading protocol) is that they rely on historical emissions to determine future allowances. This leads to growing inequities among countries and provides a major roadblock to reaching an agreement. Under current proposals, countries have emissions limits that are determined by their 1990 emissions levels. This penalizes efficient countries (like Sweden) or rapidly growing countries (like Korea). It also gives a premium to slow-growing countries (like Britain) while historically inefficient countries (like Russia or Germany after unification) are rewarded by having too high a base. This point can be illustrated as follows. We estimate that industrial CO<sub>2</sub> emissions for the U.S. in 2000-2009 will be about 1.64 billion tons of carbon per year. This represents a growth of 18 percent over the prior decade and an increase of about 20 percent over 1990 emissions. Under current proposals, the U.S. would continue to live with its 1990 base in the indefinite future. By contrast, Russia and Germany had emissions in 1994 of about 20 percent less than 1990 levels; they would receive large windfalls if the 1990 base were continued in the future.

One of the major distinguishing features of the CAP is the calculation of each country's base emissions.

*Emissions base:* Each country's emissions base would be equal to its uncontrolled emissions in each budget period. This base would roll forward with the change in each country's growth in output and population.

Under CAP, a country's base for reductions would be its uncontrolled level of emissions. This base would then roll forward with each budget period. Countries that experience rapid growth in their economies would not thereby be penalized, nor would countries receive windfalls if they were historically inefficient. There definitely would be penalties from higher emissions, but penalty would be proportional to the level of emissions rather than some irrelevant historical experience.

Aside from better equity properties, the CAP approach of a rolling base also improves the possibilities of reaching an agreement. As noted above, the CAP approach has the

feature that it would lead to a unanimous decision if countries have the same demand and supply elasticities and the same damages from climate change (even if their growth rates differ). The historical base has the unfortunate feature that the decision will depend upon the growth rate; indeed, some countries (like Germany or Russia) might vote for very large emissions reductions because they have such large emissions bases relative to their actual emissions that this would drive up the price of their emissions allowances. Other countries like the U.S. or Japan with growing emissions would find themselves with a severe relative disadvantage. Indeed, they might even find that their optimum would be for *negative* emissions reductions given their small base.

One problem with the rolling base is the possibility of countries having an incentive to “ratchet” up their emissions in one period to increase the base in the next period. The “ratchet effect” is a phenomenon observed in planning systems wherein individual agents have incentives to increase spending (or in this case emissions) to increase their base for the next planning period. Two points are important here. First, ratchet effects at the individual or *explicit collusion* firm level are minuscule because these agents have such a tiny impact upon national emissions levels. Second, while the rolling base definitely attenuates the incentive to reduce emissions at the country level, it does not give the wrong incentives as long as the real price of allowances is not rising too rapidly. For constant emissions reduction rates, the ratchet effect will be neutral when the carbon permit price is rising at the real interest rate. In the more likely case where the carbon permit price is rising more slowly than the real interest rate, the value to a country of an additional unit of emissions is negative. Again, note that the ratchet effect applies only to countries, who receive permits, and not to individuals, who must buy them.<sup>8</sup>

## 11. Participation and Sanctions

Whatever the moral imperative to protect the planet, it seems likely that the present costs will outweigh future benefits for most countries unless there is a cooperative arrangement with sanctions on disinclined and wayward countries. One indication of the tendency for free-riding is the estimate of the Nash-equilibrium. If countries take into account only their own national interests, the control rates and carbon prices are likely to be only a small fraction of the cooperative prices. Countries are unlikely to benefit from global

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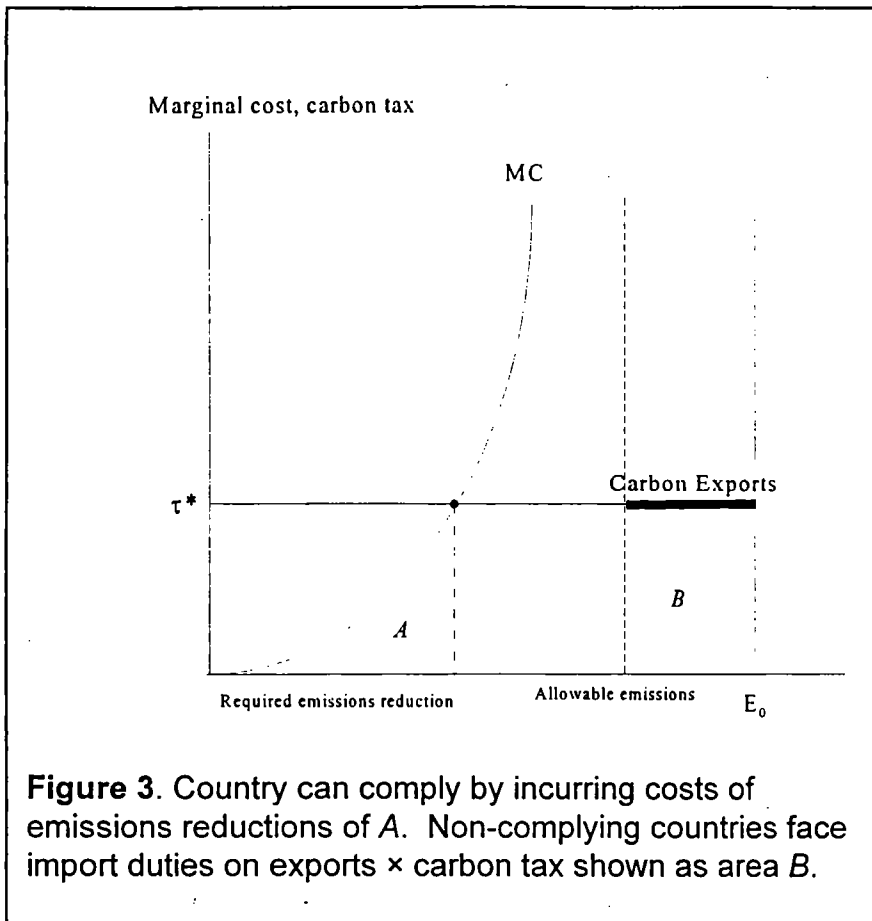
<sup>8</sup> The present value of a unit of emissions in period  $t$  is  $-\tau_t + [\tau_{t+\theta}(1-\mu_{t+\theta})]/[(1-\mu_t)(1+r)]$ . In this expression,  $\tau_t$  is the price of permits in accounting period  $t$ ,  $\mu_t$  is the emissions control rate,  $r$  is the real interest rate, and  $\theta$  is the length of the accounting period. This value is negative as long as the permit price is rising less than the real interest rate and as long as the control rate is not falling. These conditions are met in virtually all simulations.

warming policies for at least half a century.<sup>9</sup> To make joining such an agreement for individual countries worthwhile, therefore, not only must it impose reasonable, efficient, and equitable burdens, but it must also impose serious and proportional sanctions on the wayward and those who will not participate.

The most workable sanction would be carbon import duties levied on non-participating and non-complying countries. There would be a number of different sanction designs, but the simplest would be to have participating countries impose duties equal to the current price of emissions permits times the carbon content of the imports of non-complying countries into participating countries. For example, suppose that the U.S. were a participant which persistently ignored its targets, which were a 10 percent reduction from a base emissions of 1640 million tons of carbon. If the carbon emissions fee were \$10 per ton, the U.S. would face an import duty of that amount on its exports into participating countries. If the U.S. exported one-fifth of its carbon output, then this would amount to duties of  $\$10 \times 0.2 \times 1640 = \$3.28$  billion annually. The estimated annual cost of compliance is, by my estimate, \$0.85 billion, so it would definitely pay for the U.S. to comply rather than face the import duties.

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<sup>9</sup> This point is clearly shown in W. Nordhaus and Z. Yang, "A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy," *American Economic Review*, September 1996.



The tradeoff is shown in Figure 3 for a country considering whether or not to join the plan. Compliance costs are area *A* under the marginal cost curve. Noncompliance would cost the country the current carbon price times the carbon content of exports, shown as area *B* in Figure 3. For small open economies, relatively low emissions reductions, and a large group of participating countries, the incentives to participate are likely to be quite strong. Numerical calculations indicate that if the plan gets off the ground by including more than half of countries, and if it is not overly ambitious, the incentive to participate would be

powerful except for very closed economies.

## 12. Corruption and Standards for Country Behavior

A mechanism for emissions trading contains a troubling paradox. While it imposes present costs on countries by requiring them to reduce emissions, it also creates valuable assets in the form of tradable emissions permits. Because limiting emissions creates a scarcity where none previously existed, such a plan allows “green revenues” to flow to the owners of the permits. The fact of wealth creation is troubling because the value of the permits might be dissipated or used for corrupt purposes.

We can think of three different ways that the valuable permits could be allocated: (a) auction, (b) building political consensus, and (c) corruption.

- The optimal approach would be for governments to auction these permits and use the revenues for worthwhile purposes -- to lower existing taxes, reduce budget

deficits, or expand valuable programs. Such use would be the fairest way to dispose of the revenues and would enhance efficiency if the revenues were used to lower other taxes. If the permits are auctioned and the revenues recycled, the net impact on the country could be quite low.

- Given political imperfections and the need to buy political support, a government might give permits to those politically powerful groups who were adversely affected by the plan. This occurred when the U.S. instituted its sulfur emissions-trading regime, where the permits were allocated to polluters on the basis of historical emissions. This approach is defective for a number of reasons: it overcompensates polluters, it sets up terrible incentives for firms to ratchet up their emissions, and it unnecessarily increases the deadweight loss of taxation. While the plan might strongly recommend against such allocations, they would probably not constitute a violation of the agreement.
- The real difficulty arises with respect to non-democratic and corrupt regimes. In a polar case, we might imagine a venal dictator who sells most of the permits (perhaps to another country), pockets the proceeds, turns the screws tightly on the population by severely limiting fuel imports, and moves the assets abroad to Riviera villas and fine Bordeaux wines. This might even worsen the environmental condition of the country and world by encouraging desperate foraging for firewood and increased deforestation.

As examples, consider the cases of Iraq and Nigeria, each of which had emissions of around 30 million tons of industrial CO<sub>2</sub> emissions in 1994. These could easily sell for \$300 million or more each year of hard currency on the open market (or \$3 billion annually if the environmentalist plans were imposed). We would clearly want such countries to participate, but we could not be confident that the revenues from the permits would not be used for acquiring nuclear materials or bolstering Swiss bank accounts. To avoid antisocial activities, we would probably impose conditionality requirements on the sale and use of emissions permits; for example, renegade countries (however that is defined) might not be permitted to sell permits to other countries. Of course, the more burdensome are the “ethical” restrictions on the disposition of the permits, the less attractive participation becomes for countries, so there is a delicate tradeoff here.

### 13. Simulations Using the RICE Model: The Setup

An important question is the relative efficiency of different climate-policy regimes. For this analysis, I use an updated version of the “RICE model” of global warming<sup>10</sup> as modified for this analysis. The RICE model is an integrated assessment model that includes output, emissions, concentrations, climate change, and climate-change damages for a number of world regions. The model uses the data for 13 regions of the world for the estimates (U.S., Europe, China, India, Russia, and 8 other groups of countries). Most of the parameters are from the original RICE model, but the data are updated to 1994 levels of output and emissions. Using the model, we can calculate both the costs of compliance and the benefits of slowing climate change in each region for the different policy proposals.

The model is then run for a number of different policy proposals.

- A baseline is the “market” or “no-control” case where no climate policies are in place.
- The “optimal” policy corresponds to complete participation with lump-sum redistribution.
- There are three CAP regimes with three different schedules for participation. The one described above is the “middle progressivity.” There are in addition a regressive and a more progressive plan.<sup>11</sup>

Finally, we investigate three proposals that correspond to plans that are currently under discussion.

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<sup>10</sup> See Nordhaus and Yang, *op. cit.* for a complete discussion.

<sup>11</sup>The “middle progressive” CAP protocol assumes an entry-level income of \$5000 per capital and full-participation income of \$15,000. More precisely, the percent participation (the  $f$  function) goes linearly from 0 at a per capita income of \$5000 to 100 percent at \$15,000. Alternative progressivity schedules have entry levels and full participation of (\$10,000 and \$20,000) for a “progressive” approach and (\$0 and \$5000) for a “regressive” approach. For the simulations, we assume that there is perfect compliance and that countries do not join ahead of schedule. We have simplified the calculations by using the actual damage function rather than the median-allowable-emissions voting function. In addition, we assume that the economic and technological variables are known with certainty.

- The Rio Treaty plan, which has emissions limits at 1990 levels for the OECD region.
- The U.S. proposal, or Rio limits with emissions trading among the OECD countries.
- The “Berlin mandate,” which follows the Rio Treaty but has 20 percent cuts in emissions from 1990 levels starting in 2010 and does not allow trading.

The basic point is to investigate the comparative performance of the different regimes. That is, what fraction of the benefits of the optimal control policy is captured by the emissions regime, and how well do the different regimes attain the ultimate goal of slowing climate change?

#### **14. Empirical Results**

The enclosed figures and tables show the major results. Figures 4 and 5 shows the emissions under different plans. Figures 6 and 7 show the levels of concentration and temperature change for the different proposals. There are significant reductions in emissions, concentrations, and global temperature change in all the plans. Current approaches in the Rio and Berlin plans do relatively well for the next century or so in terms of the environmental objectives. In the longer run, they lag behind the CAP plans because they have no mechanism to bring in big developing-country emitters in the future. Under the CAP plans, all important countries (including India and China) incur reduction obligations in the next century, so most emissions are covered relatively quickly.

While the environmental picture does not differ much among the different approaches, there is an enormous difference in the economics. Figure 8 shows the net benefits of the alternative plans. These measure the present value of control costs and climate damages from 1990 on, in 1994 prices, discounted at a goods discount rate of 5 percent annually (the measurement convention is that costs are negative and measured relative to no controls). Table 1 shows the basic data, with 1A showing the absolute levels and 1B showing the impacts as a share of national outputs. The bottom half of the tables show the impact relative to no controls for each region and for the world.

Two fundamental findings emerge from these simulations:

- *Economic turkey.* The three current proposals on the international agenda (Rio, the U.S. modification of Rio, and the Berlin protocol) have negative net benefits, and substantial ones. These plans impose more than \$100 billion of discounted costs for

the Rio approaches and \$1 trillion of discounted costs for the Berlin approach. By contrast, the CAP proposals all have positive global benefits. The Rio-based plans suffer from limiting emissions to a small fraction of emissions, by having rigid targets, and (except for the U.S. plan) by proscribing emissions trading.

• *Political clunker.* The three Rio-style options are politically inept and cannot survive the political market place in most democracies. They impose enormous costs on the major participants — the high-income countries — and confer large benefits on those who do nothing. The U.S. fares extremely poorly under all three of the current proposals, including its own. These plans would be rejected by countries acting in their self-interests. By contrast, the CAP plans have positive or at worst small negative net benefits for all countries.

Figure 9 shows the distribution of gains and losses under two plans -- the middle CAP plan and the U.S. plan of Rio targets with trading. This shows the difference in the distribution of benefits of the different approaches. Figure 10 shows the carbon emissions prices that are estimated for the different plans. The Rio-with-trading and the Berlin mandate have extremely high emissions prices, reaching \$100 quickly and heading north from there very quickly. These carbon taxes are unrealistically high from an administrative and political point of view. For example, the mine-mouth price of U.S. coal would rise by between 60 and 2000 percent over current prices depending on the time period and plan. The carbon tax in the CAP plan, by contrast, starts around \$6 per ton carbon and rises to \$35 per ton by 2100.

Table 2 summarizes the economic impacts and efficiencies of the different approaches relative to the optimal emissions reduction, which has a benchmark of 100 percent economic and environmental efficiency. The first two columns show the overall net economic impacts. The three current proposals have benefit-cost ratios well below 1. Trading improves the benefit-cost ratio of the Rio approach, but does not raise it anywhere near unity. Focusing on the long term concentration and temperature effects in the middle and right-hand columns, we see that — in addition to having much better economic efficiency — the CAP plans also have better long-term environmental benefits than the Rio-style proposals. Finally, Table 3 shows the impact of different plans on the United States. The U.S. has little net gain or loss under the CAP plans but is a major loser under the Rio-style proposals.

The most important conclusions that come from these simulations are (a) that current approaches are no-starters in any negotiations in which countries take actions based on their self-interest and the (b) current approaches are highly inefficient in their design. In short, they are both bad politics and bad economics.

## 15. Conclusions

The CAP proposal described here is an attempt to flesh out a emissions-trading proposal in the context of the global public good of global warming. In principle, it satisfies most of the design criteria discussed in section 2. An efficient trading regime would have the advantage of integrating policy with an underlying cost-benefit approach that maximizes global incomes. Further, it would allow countries to arrive at a level of the public good that reflects individual country preferences.

Model simulations indicate that the CAP plan would achieve between 40 and 75 percent of the potential economic benefit — and more than 96 percent of the long-term environmental benefit — depending upon the time frame and progressivity schedule. These compare with current proposals — such as the original Rio targets, the Berlin mandate, and the U.S. modification of the Rio targets to allow emissions trading — which have less favorable long-run environmental impacts and have significantly negative economic impacts.

At the same time, we must register some important reservations about the proposal. Many will think that the proposal to have sanctions linked to punitive import duties for non-participants is a dangerous and unwarranted distortion of international trade. Additionally, the mechanism for determining country preferences is complicated and may seem arcane to political decision makers (although it is simple compared to many “familiar” issues such as tax or real-estate law). And the treatment of inept and corrupt countries poses particular problems. Most of these issues will, however, necessarily arise in any effective plan. Notwithstanding these difficulties, the CAP proposal or some relative has the advantage of being both economically advantageous and politically workable whereas all current proposals are politically unrealistic and economically wasteful while conveying no environmental advantage over the CAP plan.

Figure 4

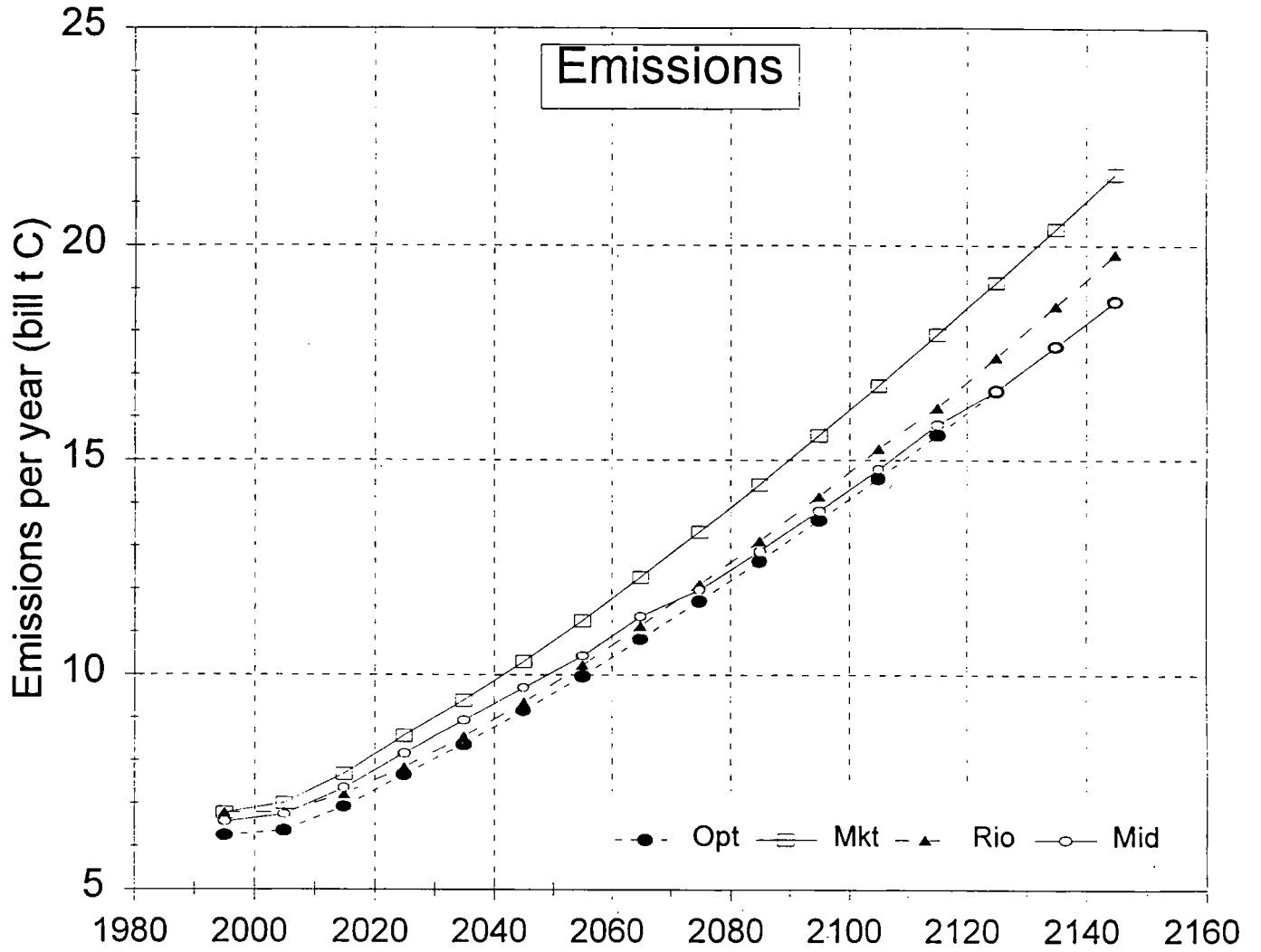


Figure 5

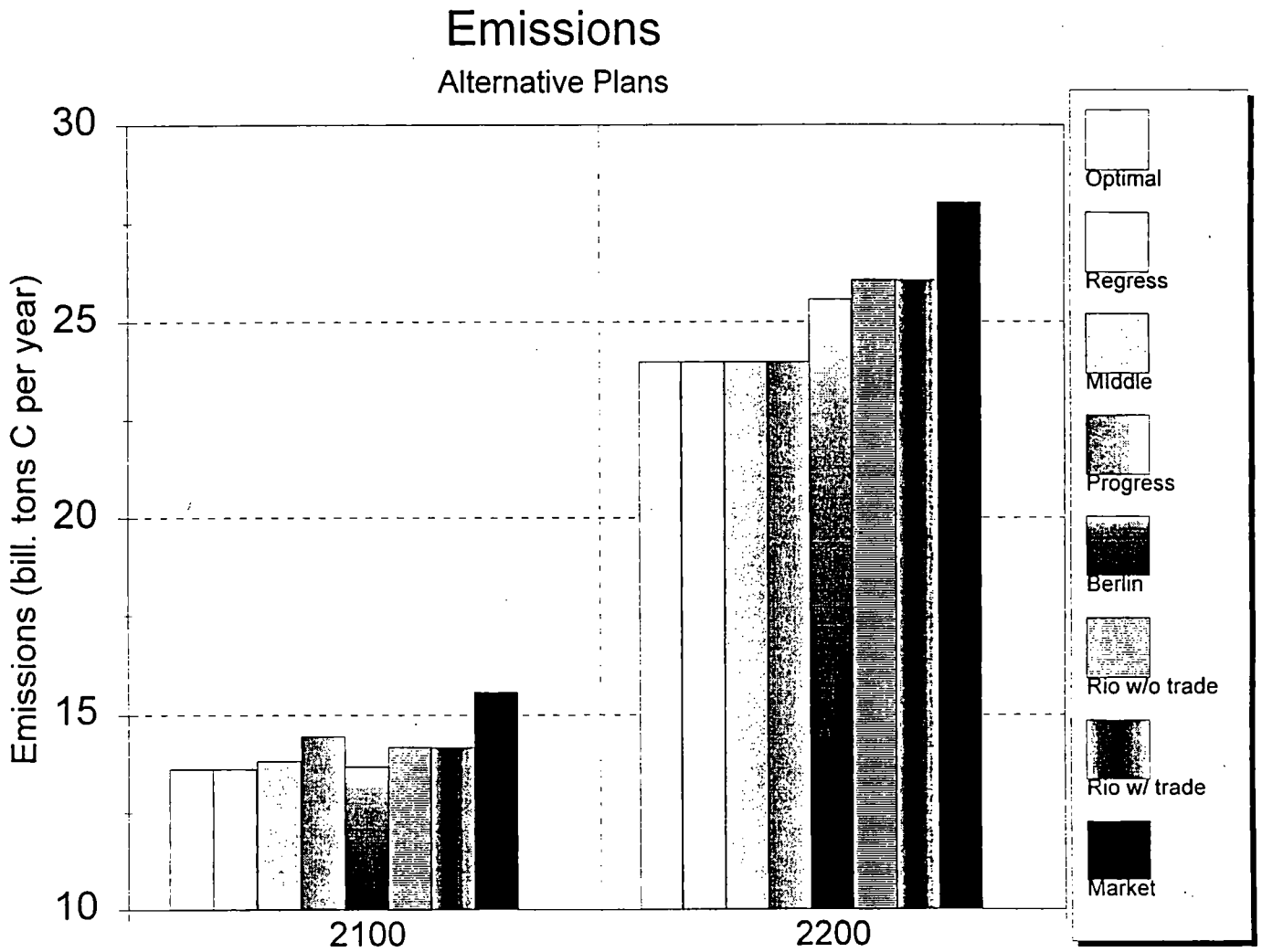


Figure 6

# Concentrations

## Alternative Plans

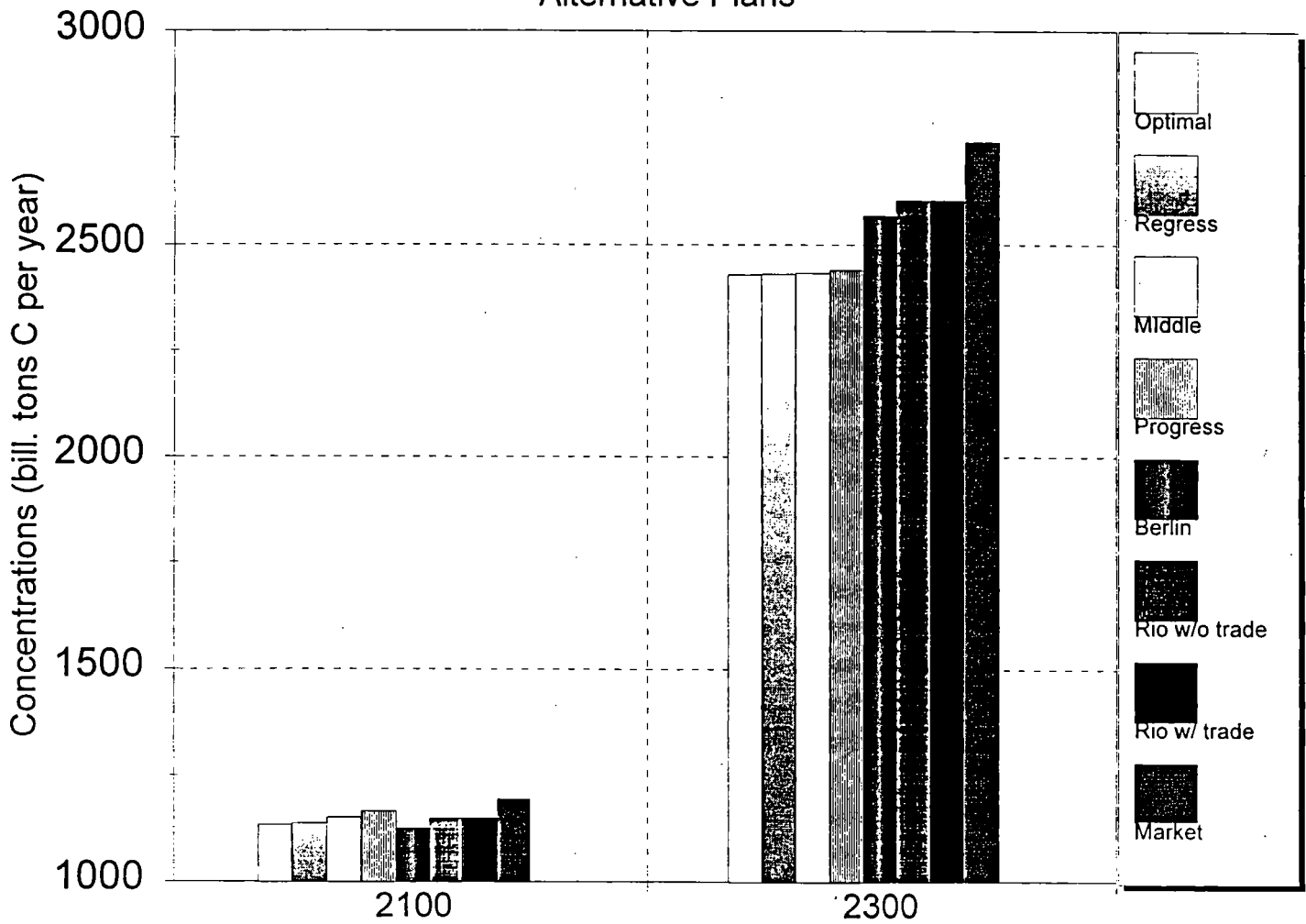


Figure 7

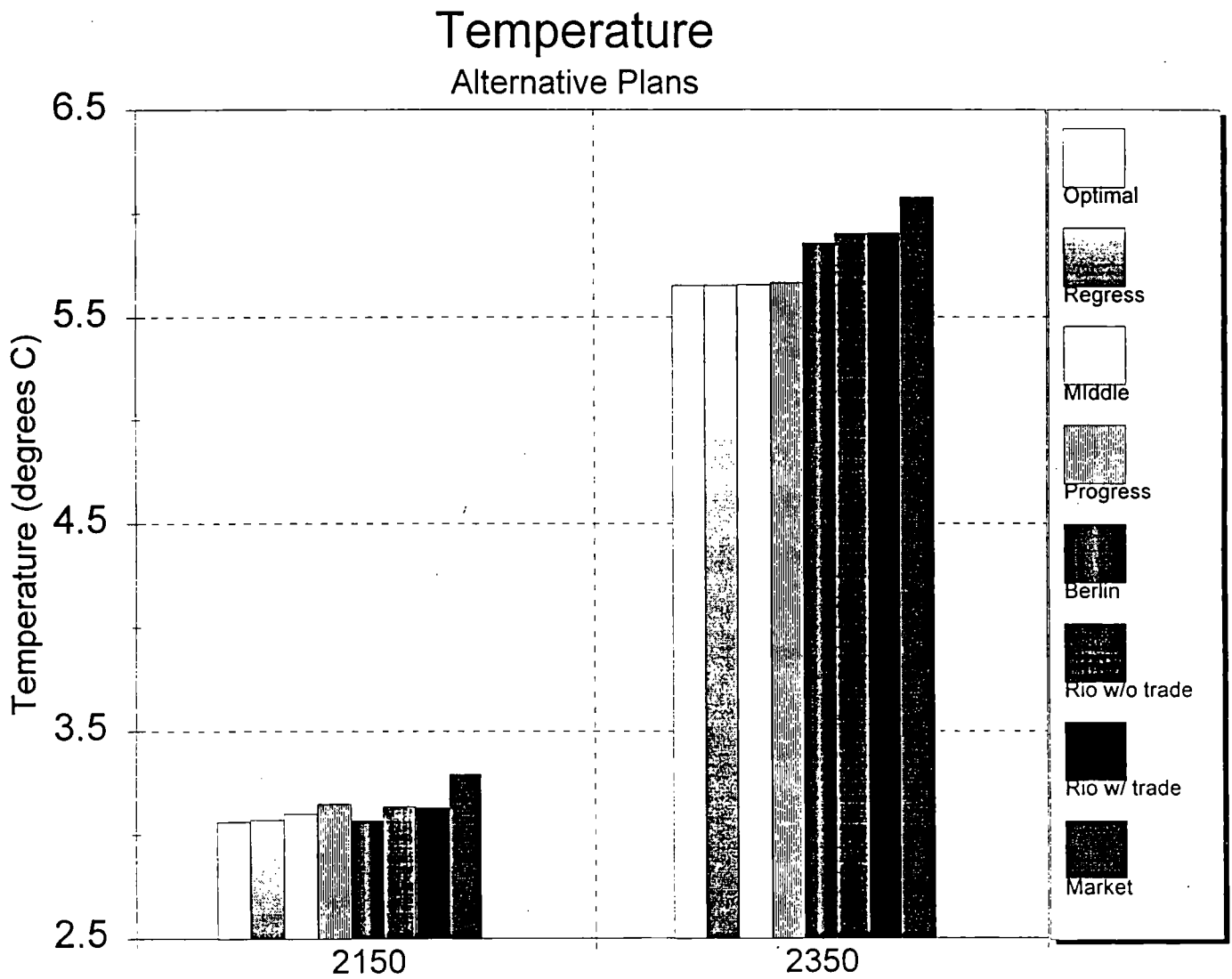


Figure 8

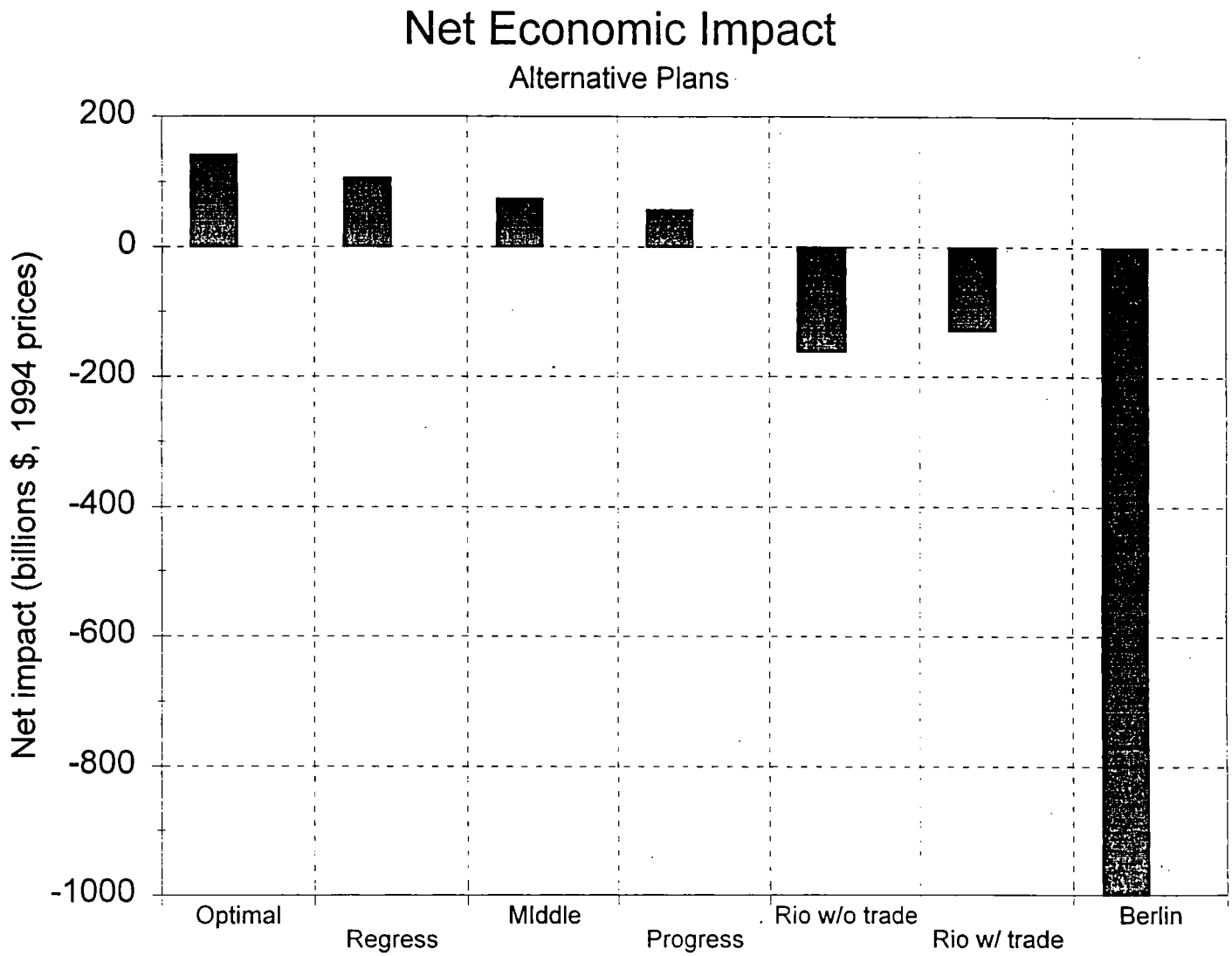


Figure 9

### Gainers and Losers Alternative Plans

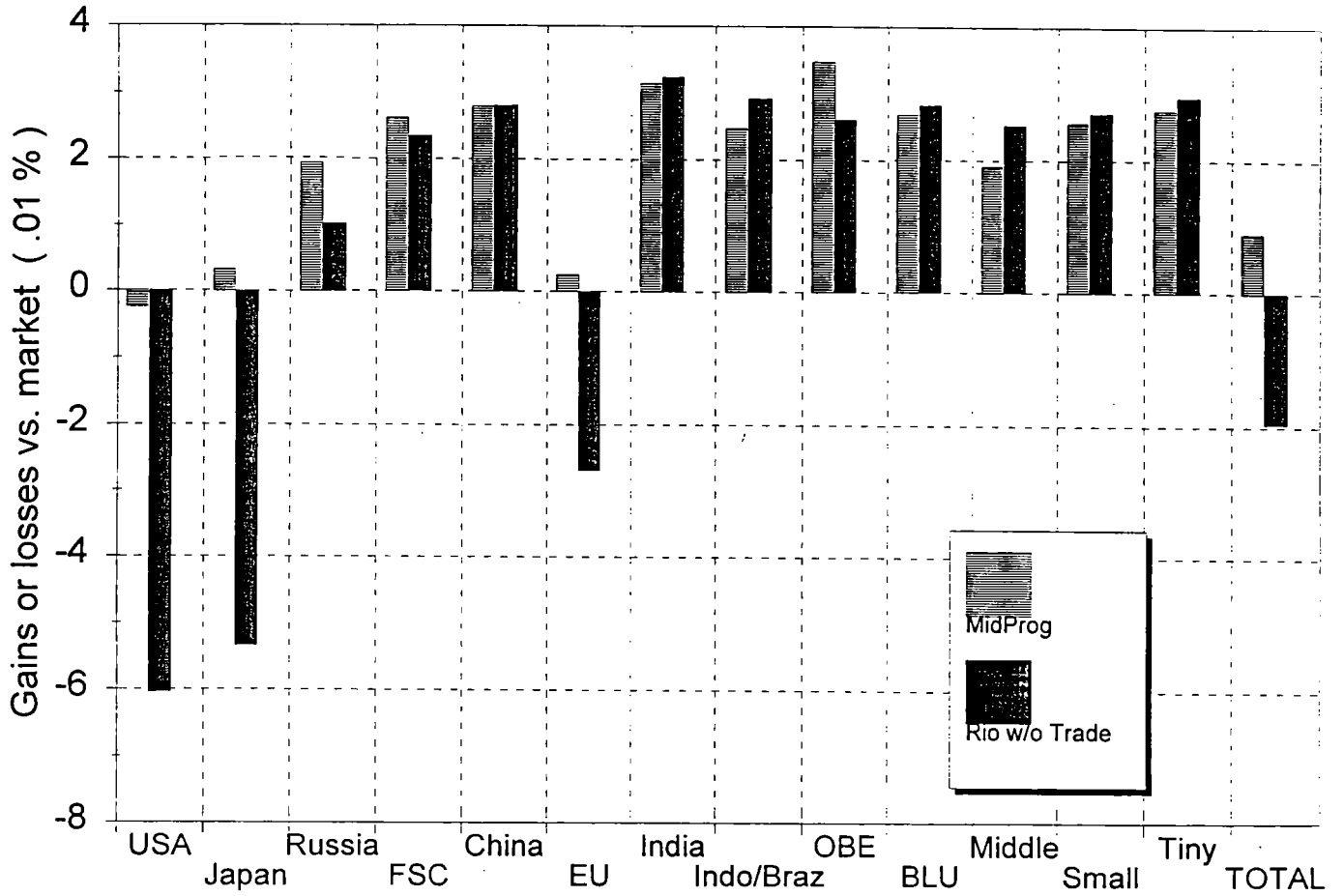


Figure 10

### Carbon Tax Rates in Different Plans

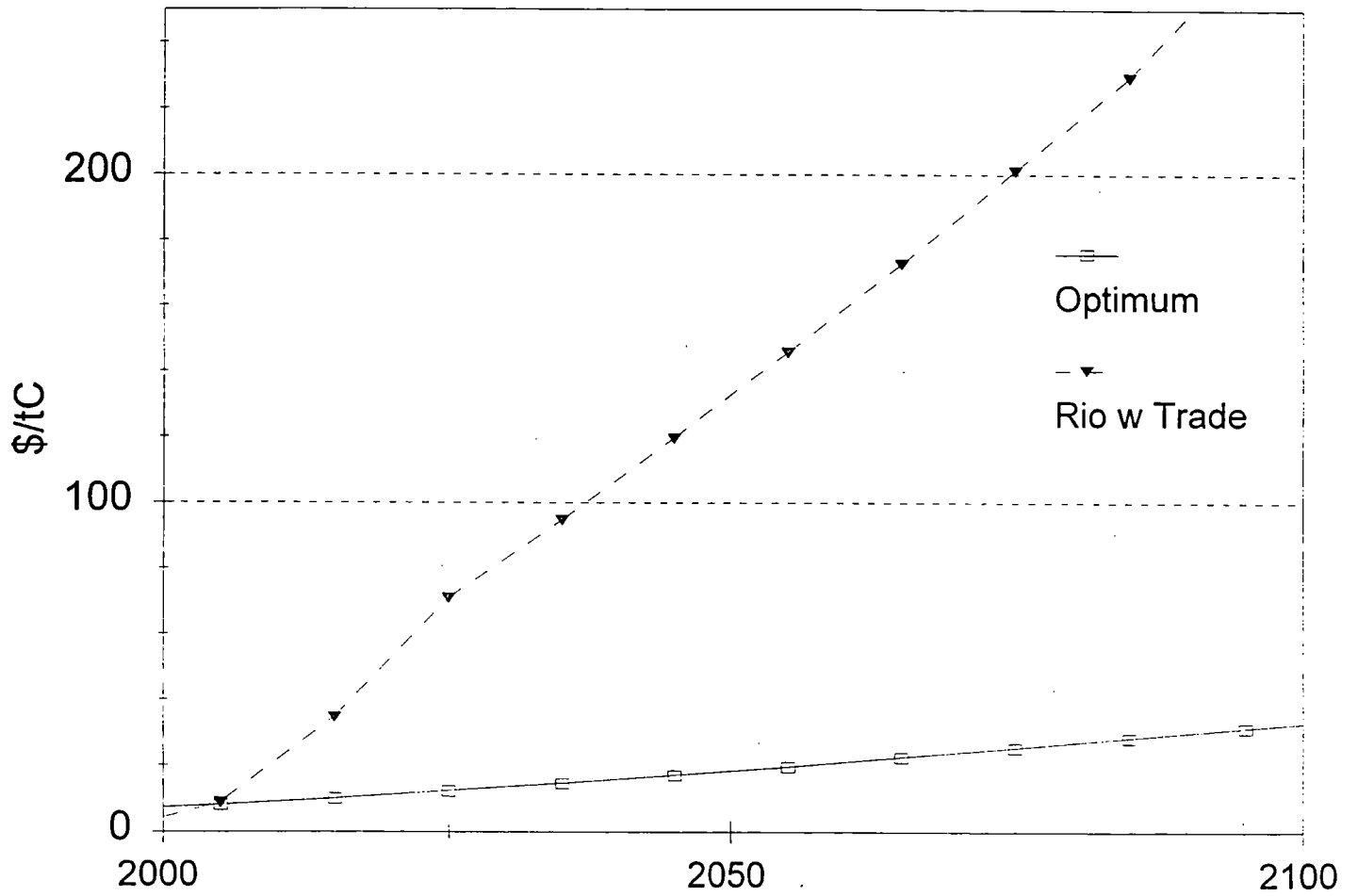


Table IA

## Net Benefits of Alternative Trading Regimes

	Billions of 1994 US dollars													
<i>Relative to No Global Warming</i>								Indon/						
	USA	Japan	Russia	FSC	China	EU	India	Brazil	OBE	BLU	Middle	Small	Tiny	TOTAL
Market	-520.8	-336.4	-32.2	-39.3	-232.9	-695.4	-123.7	-228.7	-56.8	-104.2	-695.6	-260.0	-116.1	<b>-3442</b>
Optimal	-504.9	-318.9	-36.5	-40.7	-231.2	-661.3	-119.9	-214.7	-57.8	-98.6	-659.7	-246.5	-109.1	<b>-3300</b>
Regress	-520.1	-328.7	-29.3	-35.7	-218.5	-681.3	-115.7	-219.3	-51.2	-98.6	-678.6	-248.1	-110.0	<b>-3335</b>
Middle	-525.2	-332.7	-29.8	-37.6	-222.2	-689.5	-118.5	-220.6	-53.8	-100.2	-675.1	-250.1	-111.6	<b>-3367</b>
Progress	-523.6	-333.8	-31.0	-38.2	-225.4	-690.9	-119.9	-222.4	-55.0	-101.2	-677.8	-252.5	-112.7	<b>-3385</b>
Rio w/o trade	-636.5	-396.1	-30.9	-37.8	-222.1	-759.1	-118.3	-219.2	-54.5	-100.0	-668.5	-249.5	-111.2	<b>-3604</b>
Rio w/ trade	-617.5	-382.1	-31.0	-37.9	-222.4	-757.1	-118.4	-219.4	-54.6	-100.1	-669.3	-249.8	-111.3	<b>-3571</b>
Berlin	-1057.3	-578.7	-29.7	-36.4	-213.3	-1064.5	-113.7	-210.6	-52.4	-96.1	-642.7	-239.9	-106.9	<b>-4442</b>
<i>Relative to No-Control Solution</i>								Indon/						
	USA	Japan	Russia	FSC	China	EU	India	Brazil	OBE	BLU	Middle	Small	Tiny	TOTAL
Market	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<b>0</b>
Optimal	15.8	17.4	-4.3	-1.4	1.8	34.1	3.8	14.0	-1.1	5.6	35.8	13.4	7.0	<b>142</b>
Regress	0.6	7.7	2.8	3.6	14.5	14.1	8.0	9.3	5.6	5.7	17.0	11.9	6.1	<b>107</b>
Middle	-4.4	3.6	2.4	1.7	10.8	5.8	5.2	8.1	3.0	4.1	20.5	9.9	4.5	<b>75</b>
Progress	-2.8	2.6	1.1	1.1	7.5	4.5	3.8	6.3	1.7	3.0	17.7	7.5	3.4	<b>57</b>
Rio w/o trade	-115.8	-59.8	1.3	1.5	10.8	-63.7	5.4	9.5	2.2	4.3	27.1	10.5	4.9	<b>-162</b>
Rio w/ trade	-96.8	-45.8	1.2	1.4	10.6	-61.7	5.3	9.3	2.2	4.2	26.3	10.2	4.7	<b>-129</b>
Berlin	-536.5	-242.3	2.4	2.9	19.7	-369.1	10.0	18.1	4.3	8.1	52.8	20.1	9.2	<b>-1000</b>
<b>Item: Discounted GDP (trillions)</b>	<b>191.6</b>	<b>111.7</b>	<b>12.2</b>	<b>6.3</b>	<b>38.5</b>	<b>236.0</b>	<b>16.6</b>	<b>32.5</b>	<b>8.6</b>	<b>15.2</b>	<b>107.4</b>	<b>38.7</b>	<b>16.5</b>	<b>831.9</b>

Table 1B

<b>Net Benefits of Alternative Trading Regimes</b>															
	Percent of Discounted GDP (x 100)														
<i>Relative to No Global Warming</i>								Indon/							Stand.
	USA	Japan	Russia	FSC	China	EU	India	Brazil	OBE	BLU	Middle	Small	Tiny	TOTAL	Dev.
Market	-27.2	-30.1	-26.4	-62.1	-60.4	-29.5	-74.5	-70.3	-65.9	-68.7	-64.7	-67.2	-70.5	-41.4	18.3
Optimal	-26.3	-28.6	-29.9	-64.2	-60.0	-28.0	-72.2	-66.0	-67.1	-65.0	-61.4	-63.7	-66.2	-39.7	17.3
Regress	-27.1	-29.4	-24.1	-56.4	-56.7	-28.9	-69.7	-67.5	-59.4	-64.9	-63.2	-64.1	-66.7	-40.1	17.0
Middle	-27.4	-29.8	-24.4	-59.5	-57.6	-29.2	-71.3	-67.9	-62.4	-66.0	-62.8	-64.6	-67.7	-40.5	17.3
Progress	-27.3	-29.9	-25.4	-60.4	-58.5	-29.3	-72.2	-68.4	-63.9	-66.7	-63.1	-65.3	-68.4	-40.7	17.5
Rio w/o trade	-33.2	-35.5	-25.3	-59.7	-57.6	-32.2	-71.2	-67.4	-63.3	-65.9	-62.2	-64.5	-67.5	-43.3	15.6
Rio w/ trade	-32.2	-34.2	-25.4	-59.8	-57.7	-32.1	-71.3	-67.5	-63.3	-65.9	-62.3	-64.6	-67.6	-42.9	15.9
Berlin	-55.2	-51.8	-24.4	-57.5	-55.3	-45.1	-68.5	-64.8	-60.8	-63.3	-59.8	-62.0	-64.9	-53.4	11.0
<i>Relative to No-Control Solution</i>								Indon/							Stand.
	USA	Japan	Russia	FSC	China	EU	India	Brazil	OBE	BLU	Middle	Small	Tiny	TOTAL	Dev.
Market	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Optimal	0.8	1.6	-3.5	-2.1	0.5	1.4	2.3	4.3	-1.3	3.7	3.3	3.5	4.2	1.7	2.4
Regress	0.0	0.7	2.3	5.7	3.8	0.6	4.8	2.9	6.5	3.8	1.6	3.1	3.7	1.3	1.9
Middle	-0.2	0.3	1.9	2.6	2.8	0.2	3.1	2.5	3.5	2.7	1.9	2.6	2.8	0.9	1.1
Progress	-0.1	0.2	0.9	1.7	1.9	0.2	2.3	1.9	2.0	2.0	1.6	1.9	2.1	0.7	0.8
Rio w/o trade	-6.0	-5.4	1.0	2.3	2.8	-2.7	3.2	2.9	2.6	2.8	2.5	2.7	3.0	-1.9	3.2
Rio w/ trade	-5.0	-4.1	1.0	2.3	2.7	-2.6	3.2	2.8	2.5	2.7	2.4	2.6	2.9	-1.5	2.8
Berlin	-28.0	-21.7	2.0	4.6	5.1	-15.6	6.0	5.6	5.0	5.4	4.9	5.2	5.6	-12.0	11.6

Table 2

<i>Regime</i>	<i>Efficiency</i>					
	<i>Economic</i>		<i>Temperature*</i>		<i>Concentrations*</i>	
	Percent of Optimum*	Benefit/Cost Ratio**	2150	2350	2100	2300
<b>Market</b>	0	0.00	0.0	0.0	0.0	0.0
<b>Optimal</b>	100	2.88	100.0	100.0	100.0	100.0
<b>Regress</b>	75	2.87	96.2	99.6	93.0	99.8
<b>Middle</b>	53	2.87	82.7	98.5	70.7	98.8
<b>Progress</b>	40	2.87	61.9	96.3	46.3	96.5
<b>Rio w/o trade</b>	-114	0.44	67.7	41.0	73.8	44.2
<b>Rio w/ trade</b>	-91	0.49	69.4	40.1	72.8	43.6
<b>Berlin</b>	-704	0.20	97.3	51.9	111.5	55.5

\* Percentage gain in net benefits, temperature, or concentrations as percent of optimal relative to market.

\*\*Ratio of reduction in climate damages to abatement costs.

Table 3

*Costs and Benefits for the United States*

[Billions of dollars, 1994 prices; costs and damages measures negatively\*]

<b>Relative to no controls</b>	<i>Costs</i>	<i>Benefits</i>	<i>Net Benefits</i>	<i>Benefit-Cost Ratio</i>
Market	0.0	0.0	0.0	na
Optimal	-14.0	29.9	15.8	2.13
Regressive	-20.8	21.4	0.6	1.03
Middle	-19.4	14.9	-4.4	0.77
Progressive	-14.3	11.5	-2.8	0.80
Rio w/o Trading	-131.9	16.2	-115.8	0.12
Rio with Trading	-112.3	15.6	-96.8	0.14
Berlin with 20 percent cuts	-571.1	34.6	-536.5	0.06

\* Calculations are from the 1997 version of the RICE model. All numbers cover the period 1990 through 2400 and include the present value of the costs of compliance (including both resource costs and permit purchases) and the climate damages discounted at a 5 percent discount rate back to 1990 in 1994 prices. The "Costs" column measures the compliance costs and the "Benefits" column measures the averted climate damage.

**On Stabilizing CO<sub>2</sub> Concentrations -  
Cost-Effective Emission Reduction Strategies**

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Richard Richels, Electric Power Research Institute

February 25, 1997

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## Abstract

With the adoption of the Berlin Mandate, developed countries are being asked to set emission limits for the early decades of the next century. The size of the reductions is currently the subject of international negotiations. This paper is intended to contribute to the analysis and assessment phase leading up to the adoption of new targets and timetables. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO<sub>2</sub> 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."<sup>1</sup> 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.<sup>2</sup>

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

This paper is intended to contribute to the process of analysis and assessment. However, we take a somewhat different approach than that suggested by the Berlin Mandate. Rather than focus exclusively on the next steps by developed countries, we view the issue from the perspective of the Convention's ultimate objective, the stabilization of atmospheric concentrations. We examine what might constitute cost-effective strategies for limiting CO<sub>2</sub> concentrations to alternative levels. We then explore the implications for near-term mitigation decisions and for long-term participation by the developing countries.

There are several reasons why a broader perspective is desirable. The Intergovernmental Panel on Climate Change (IPCC) has demonstrated that if CO<sub>2</sub> 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.<sup>3</sup> 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.<sup>4</sup> It will, however, have profound effects on who pays. Consistent with the Framework Convention, we adopt a burden sharing scheme that initially places the onus on developed countries. We then discuss the implications for international negotiations.

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

Finally, we emphasize that our analysis is confined to mitigation costs. We recognize that this is not the whole story, but it is an important part. Article 3 of the Framework Convention states that "policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible costs."<sup>5</sup> 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.<sup>6,7</sup> The present version of the model, known as MERGE 3.0, divides the world into nine regions: 1) the USA, 2) OECD (Western Europe), 3) Japan, 4) CANZ (Canada, Australia and New Zealand), 5) EEFSU (Eastern Europe and the former Soviet Union), 6) China, 7) India, 8) MOPEC (Mexico and OPEC) and, 9) ROW (the rest of world). The further disaggregation provides better alignment with the Annex 1/non-Annex 1 structure of the Framework Convention. It provides more details concerning winners and losers under alternative burden sharing schemes, and it distinguishes between the major oil importing and exporting regions.

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

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

Figure 2.1 Per Capita GDP

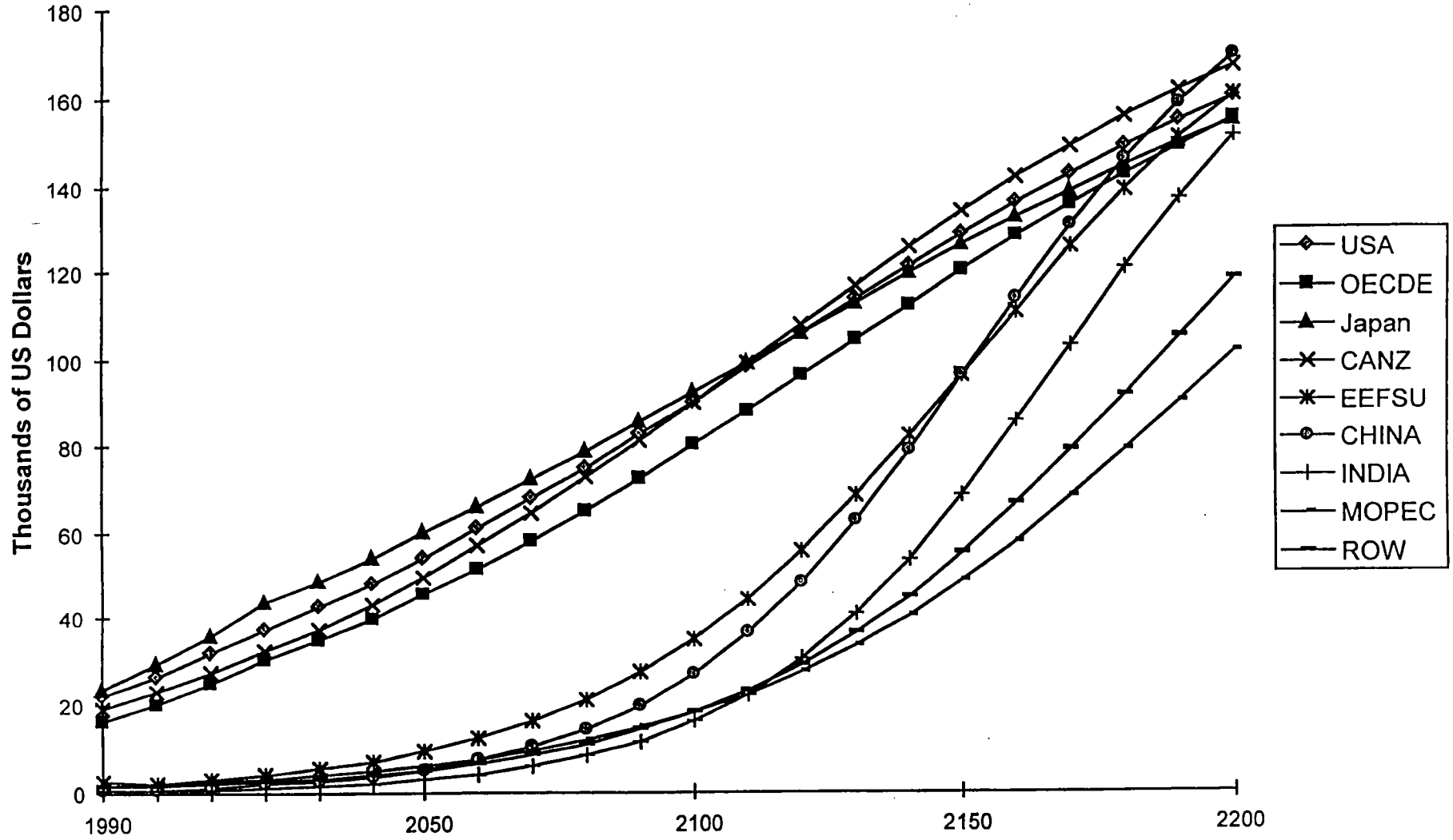


Figure 2.2 Regional Carbon Emissions

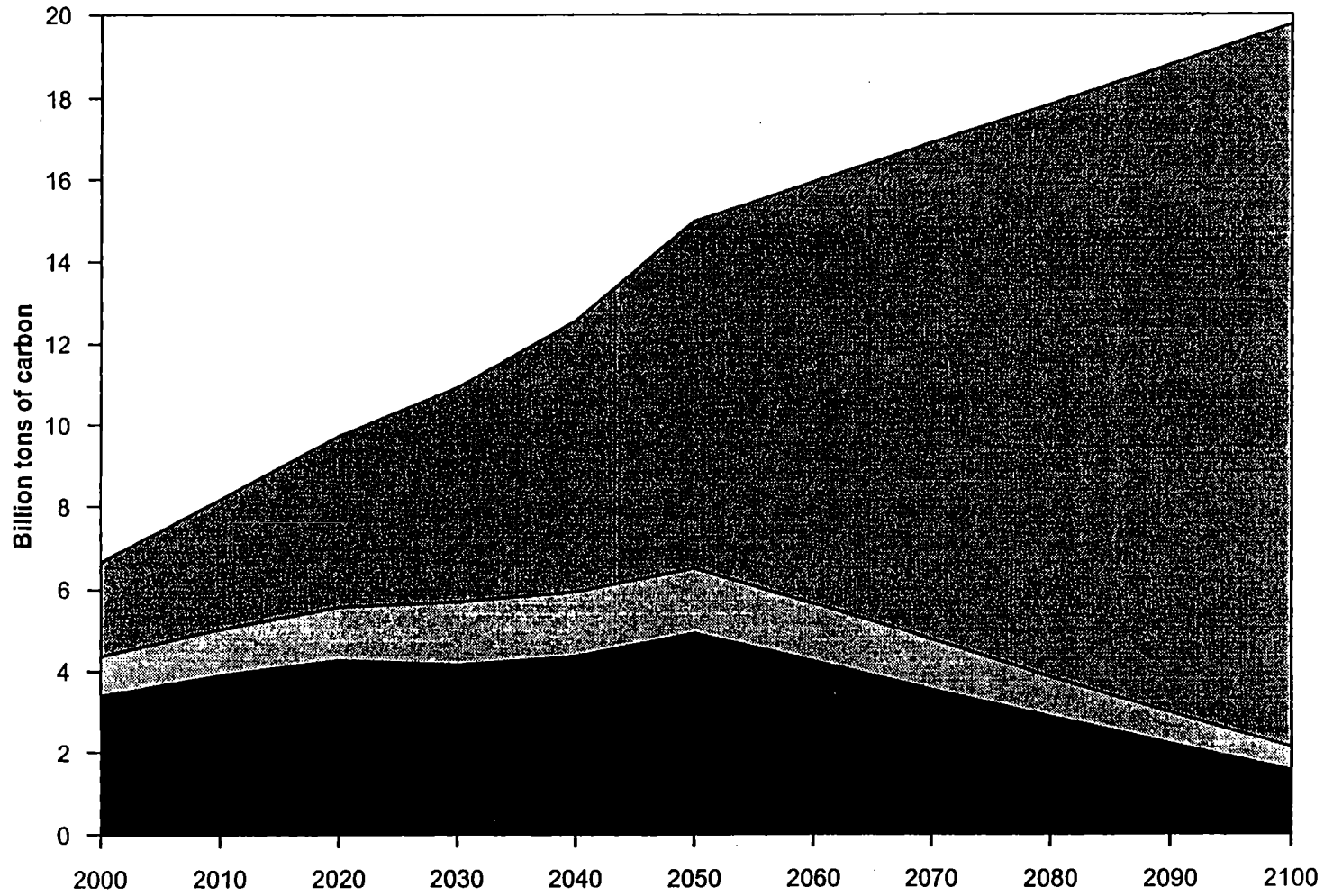
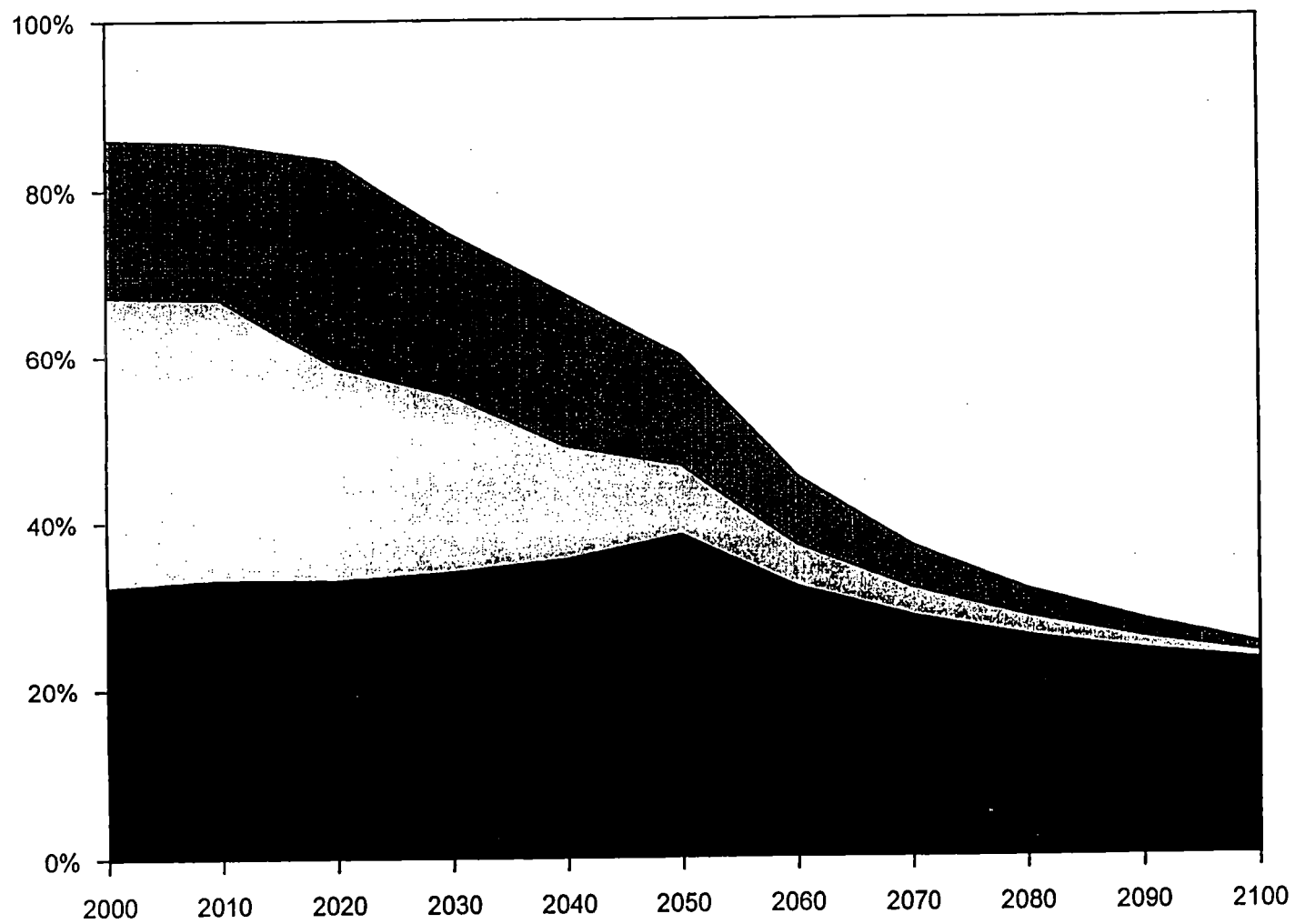


Figure 2.3 Total Primary Energy Use - Basecase



CO2 mitigation costs are determined by 1) the emissions baseline -- i.e., how emissions are apt to grow in the absence of policy interventions, 2) the cost and availability of alternative supply and demand-side options, and 3) the magnitude of the CO2 constraint. For the present analysis, several supply and demand parameters of the energy-economy submodel have been adjusted so that the baseline tracks the IPCC IS92a<sup>9</sup> scenario through the year 2100. Figure 2.2 shows carbon emissions for the OECD, EEFUSU 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.<sup>1</sup>

### 3. Scenario design

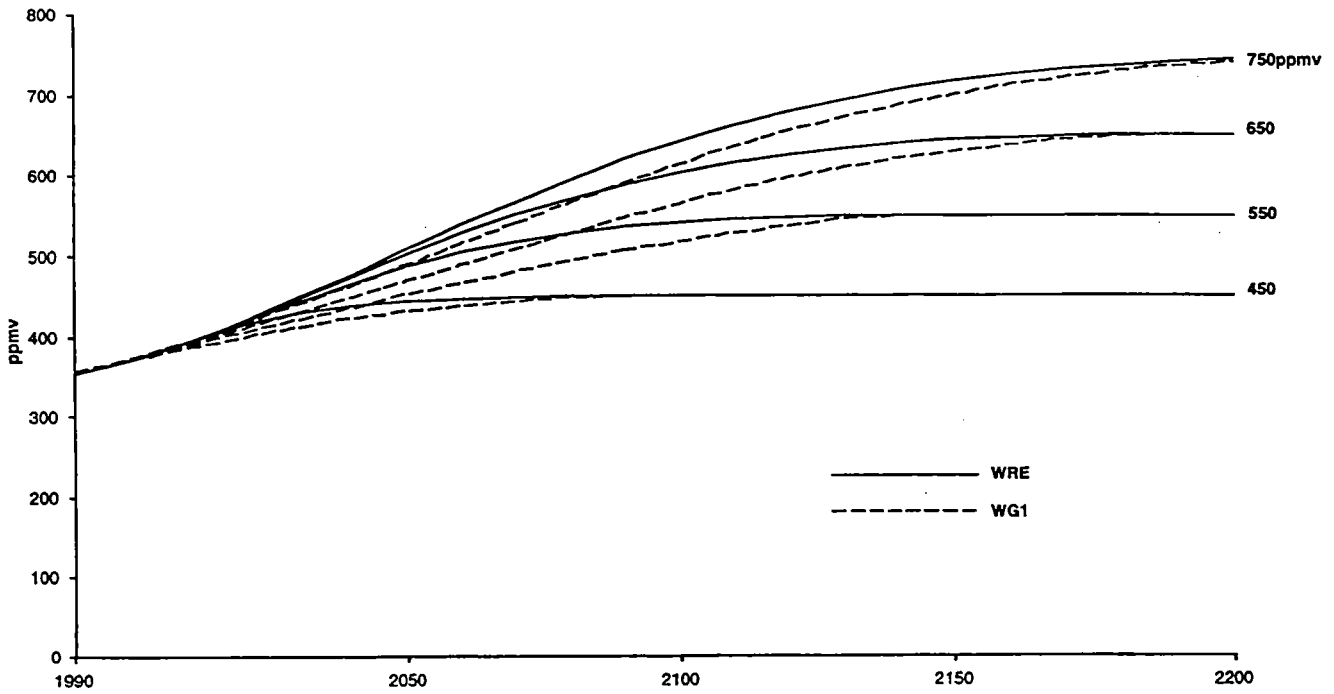
We focus on three factors critical to determining the costs of stabilizing concentrations at a particular level: the choice of global emissions pathway, the degree of international cooperation and the burden sharing scheme. In this section, we describe our assumptions with regard to each.

**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.<sup>10</sup> 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.<sup>11</sup> 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.<sup>12</sup>

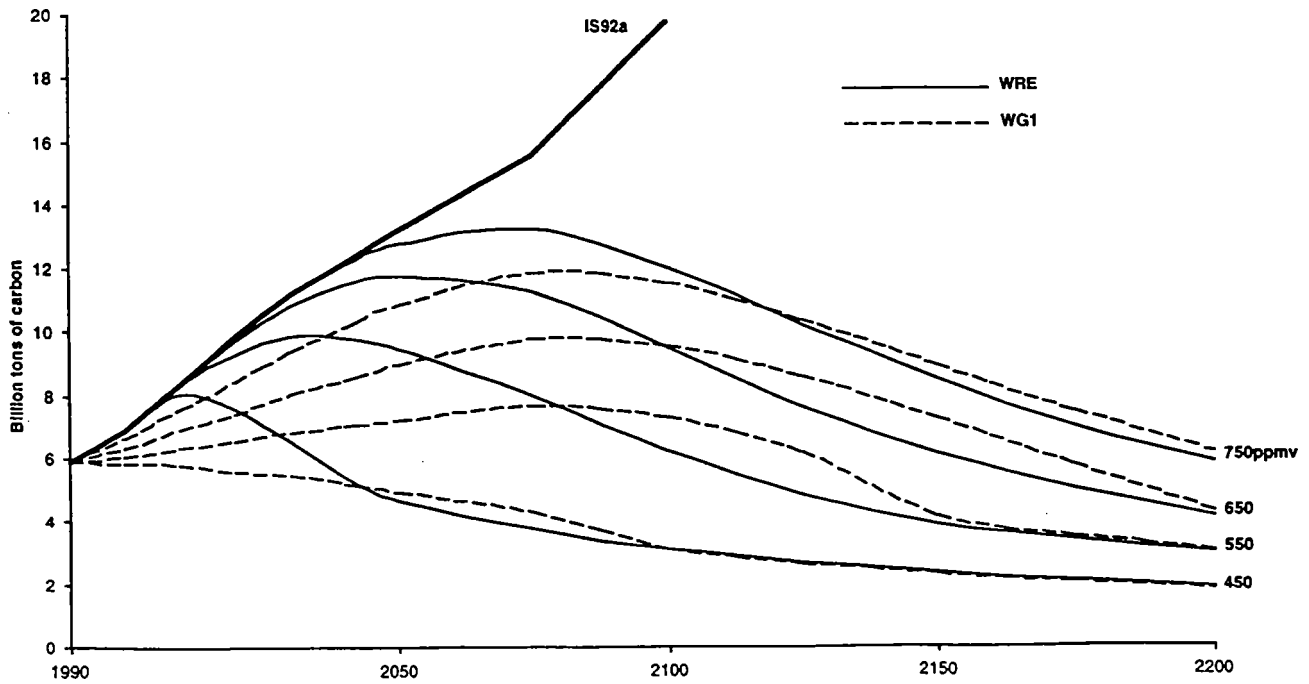
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<sup>1</sup> Contact rrichels@epri.com

Figure 3.1 Alternative Routes to CO<sub>2</sub> Stabilization



a) Alternative concentration profiles



b) Alternative fossil fuel emission paths

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

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

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

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

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

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

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

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

**Table 3.1 Structure of Burden Sharing Scheme**

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

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

#### 4. Global costs of stabilization at 550ppmv

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

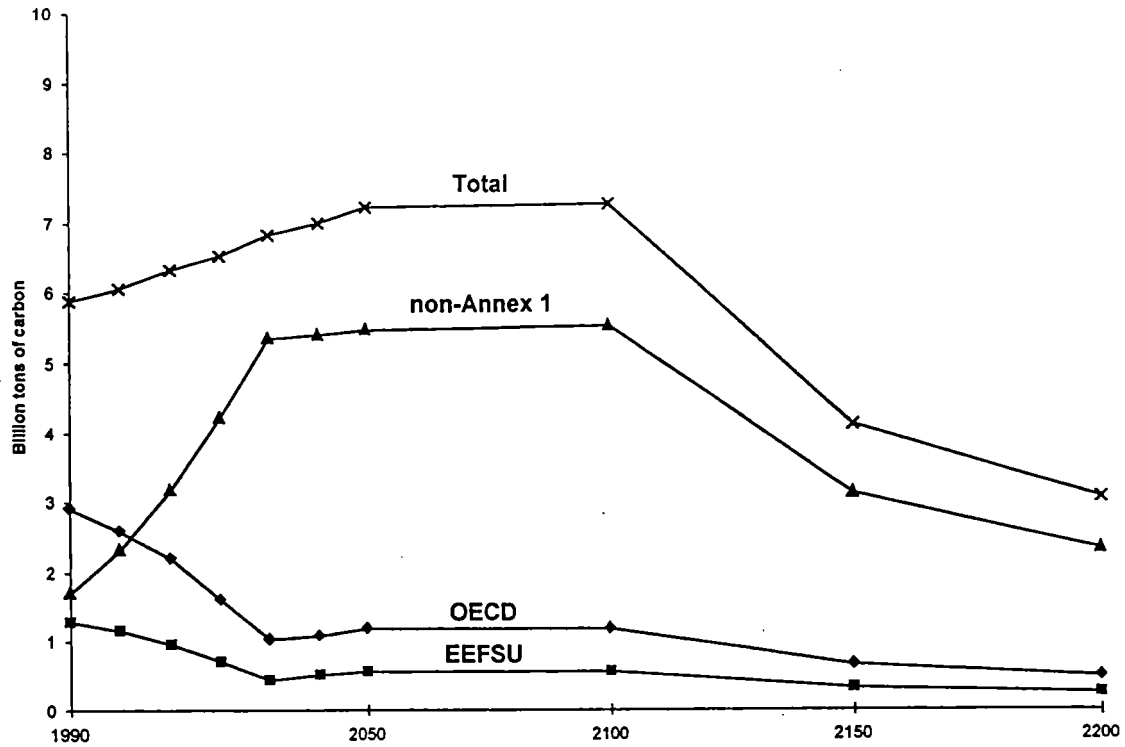
With MERGE, we can calculate how mitigation costs vary with the choice of concentration profile. At the present time, there is little consensus on what constitutes an appropriate concentration target. There is even less consensus on the choice of a pathway to stabilization. We shall begin by focusing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

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

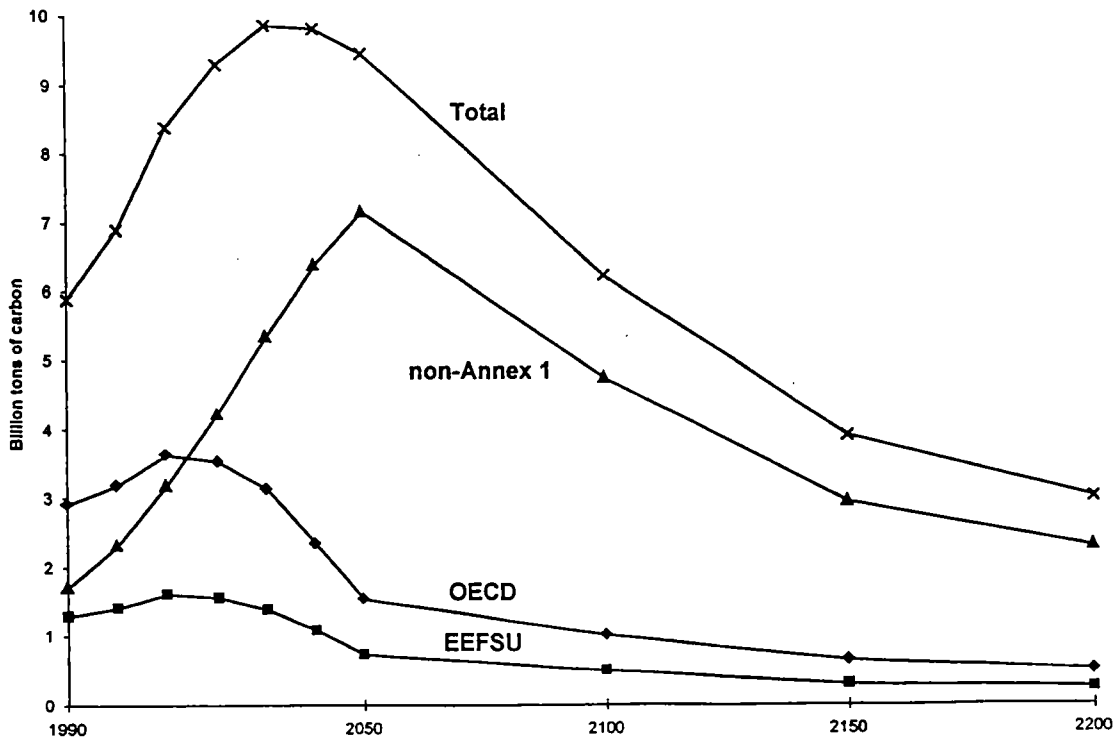
Figure 4.1 shows the implications of the burden sharing rule for these three regional groupings. The figure provides some insight into both global and regional costs. Under the WRE scenario, Annex 1 countries have some room for emissions growth, at least during the early decades of the 21st century.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

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

Figure 4.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv

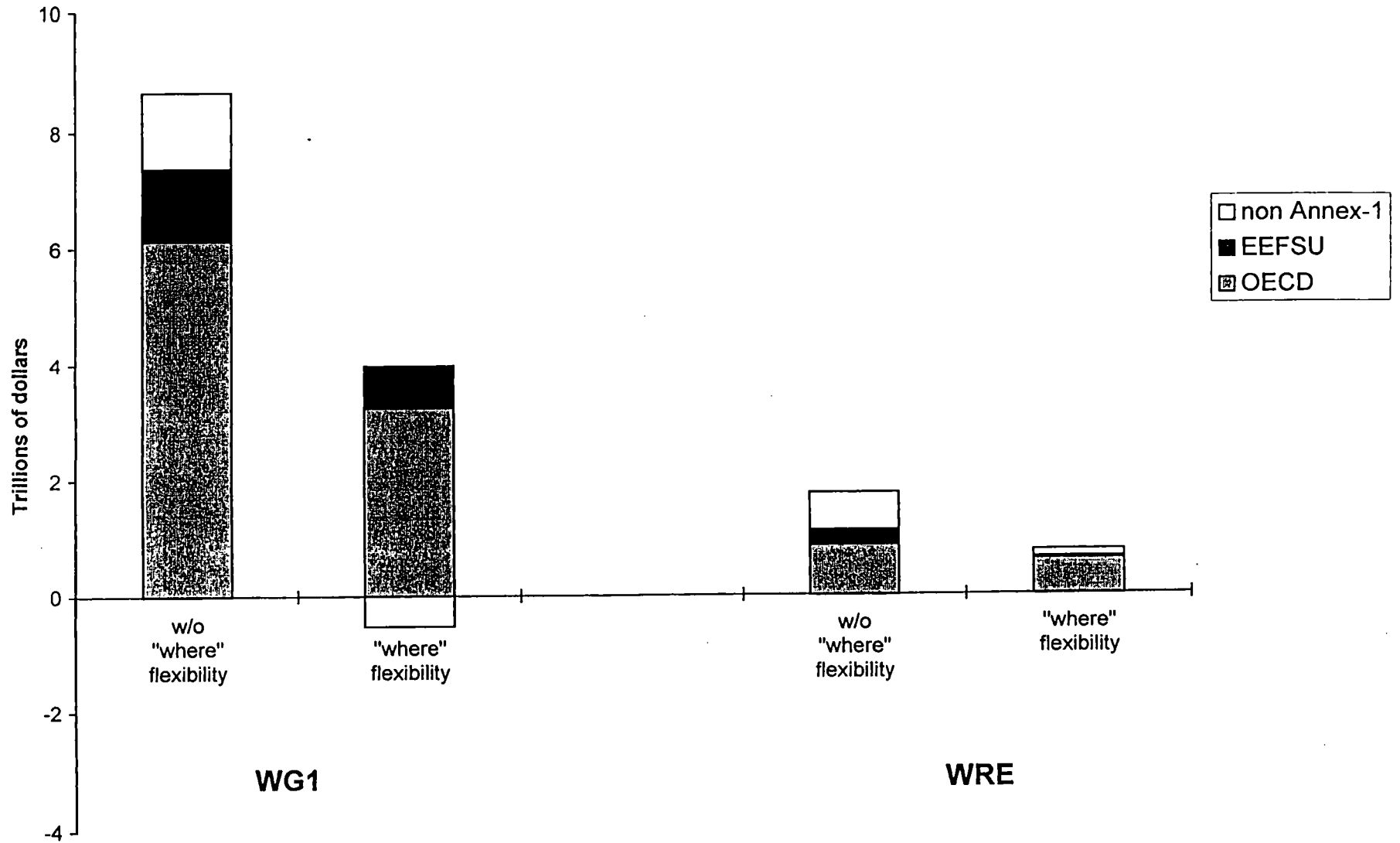


a) WG1



b) WRE

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



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

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

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

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

## **5. Annual losses when stabilizing concentrations at 550ppmv**

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

Figure 5.1 International Price of Crude Oil

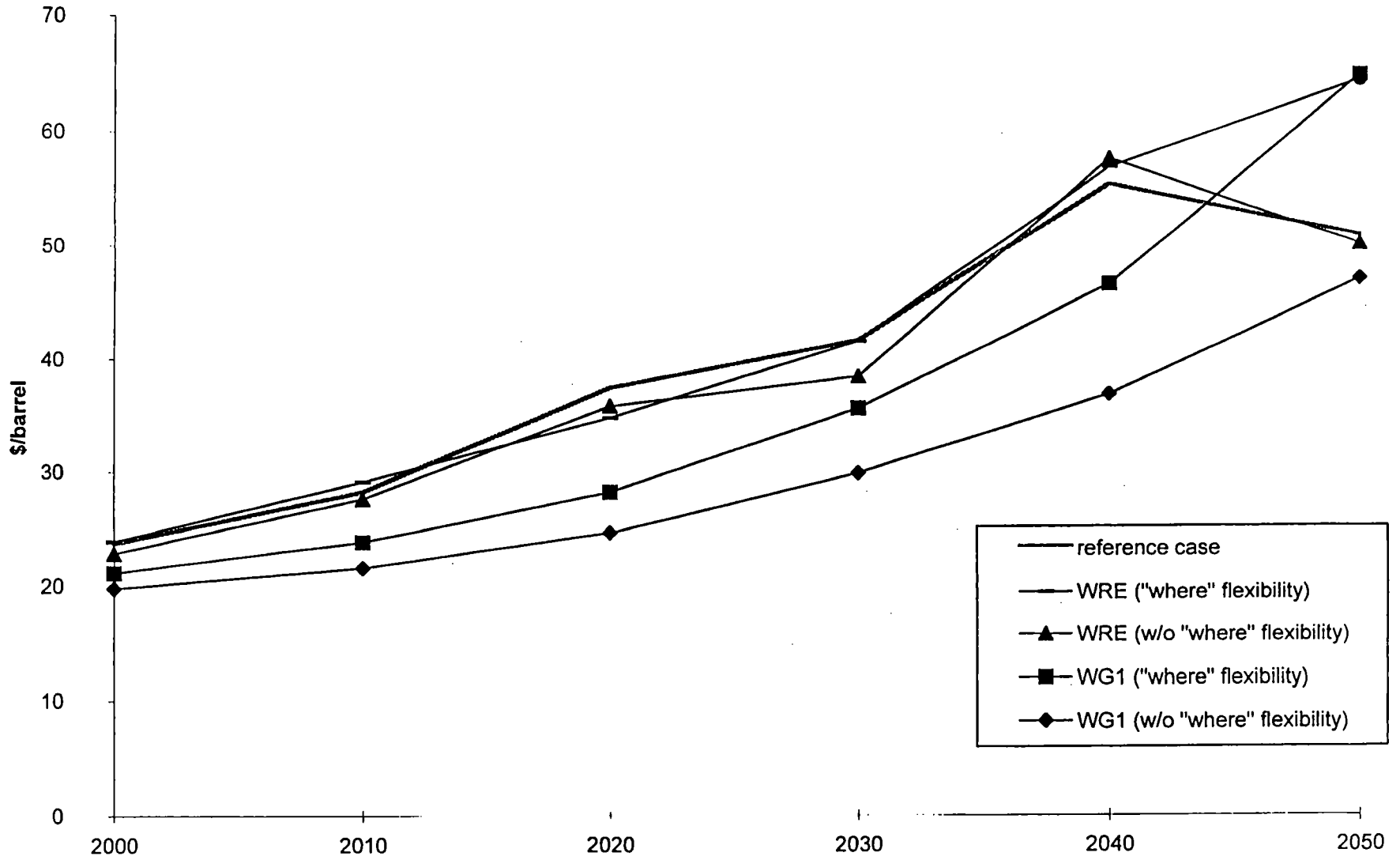
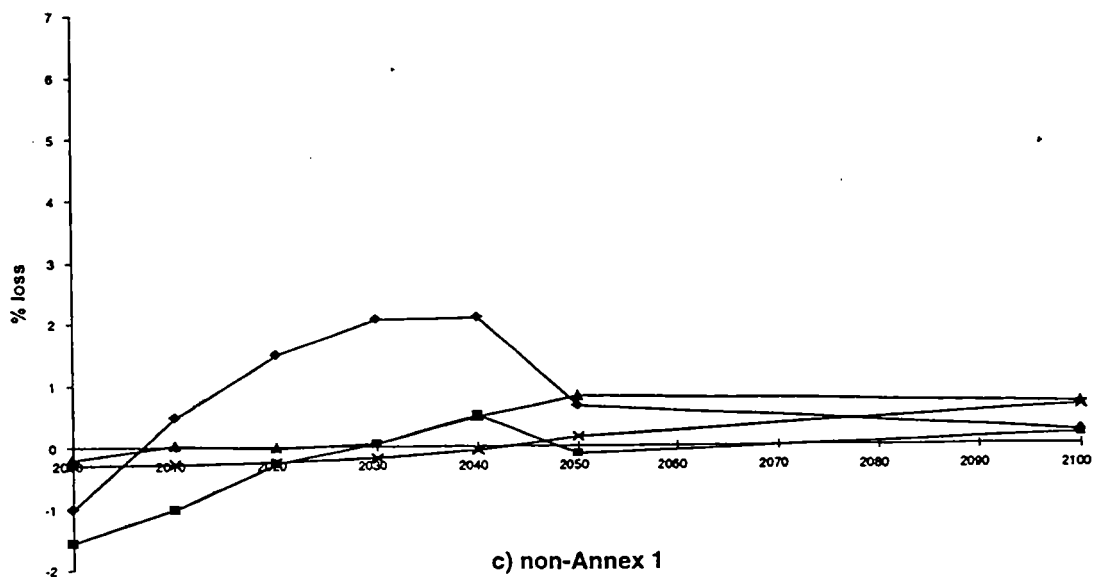
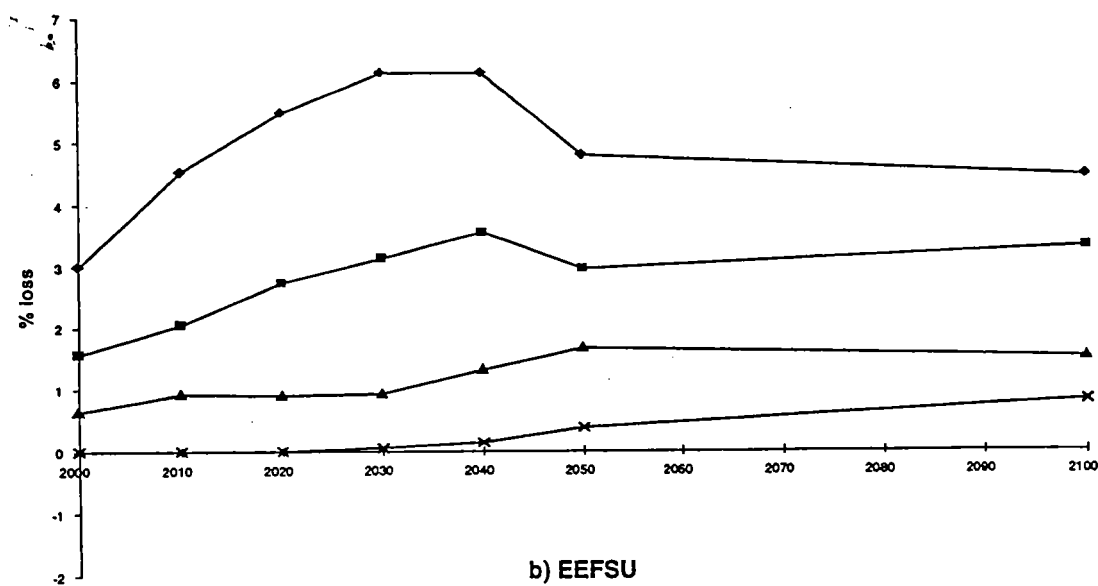
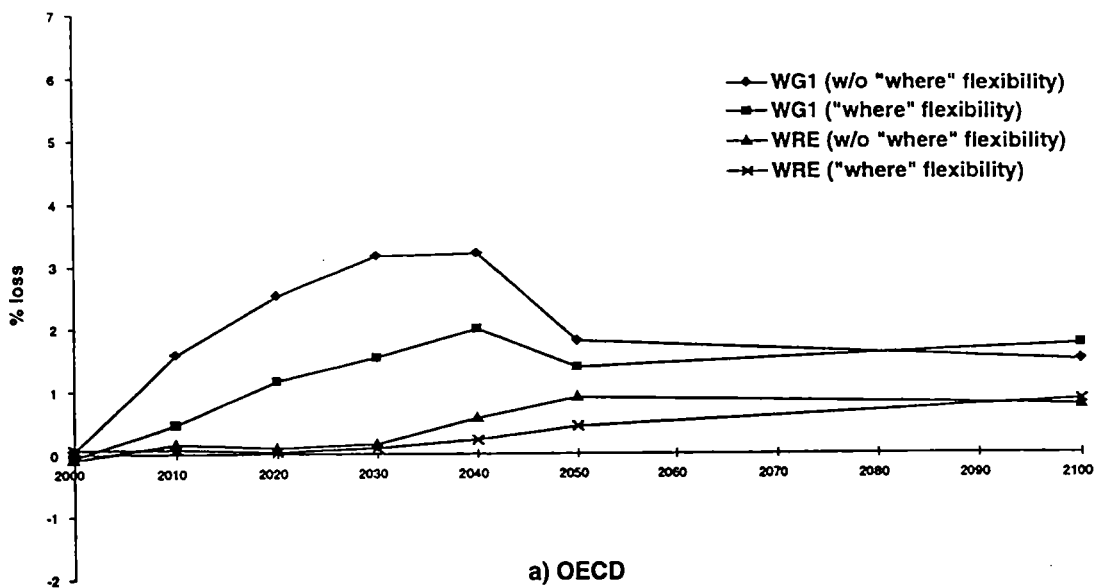


Figure 5.2 Annual % Consumption Losses



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

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

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

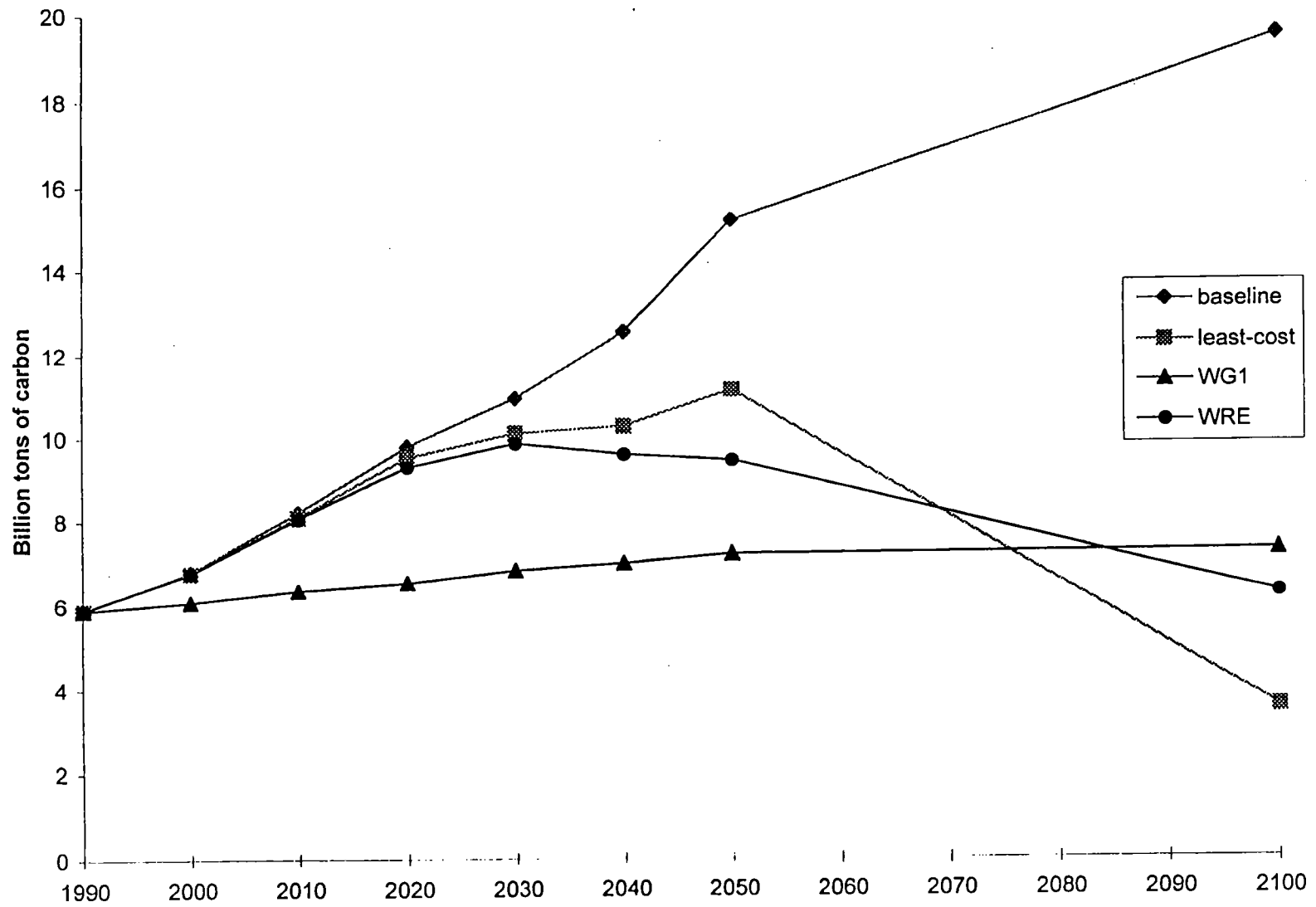
The non-Annex 1 region consists of both oil exporting and oil importing countries. Under the burden sharing scheme described in Table 3.1, the WG1 proposal leads to substantial net benefits in the early years, particularly with "where" flexibility. A tight near-term global emissions constraint would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

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

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

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

Figure 6.1 Alternative Emission Pathways for Stabilizing Concentrations at 550ppmv



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

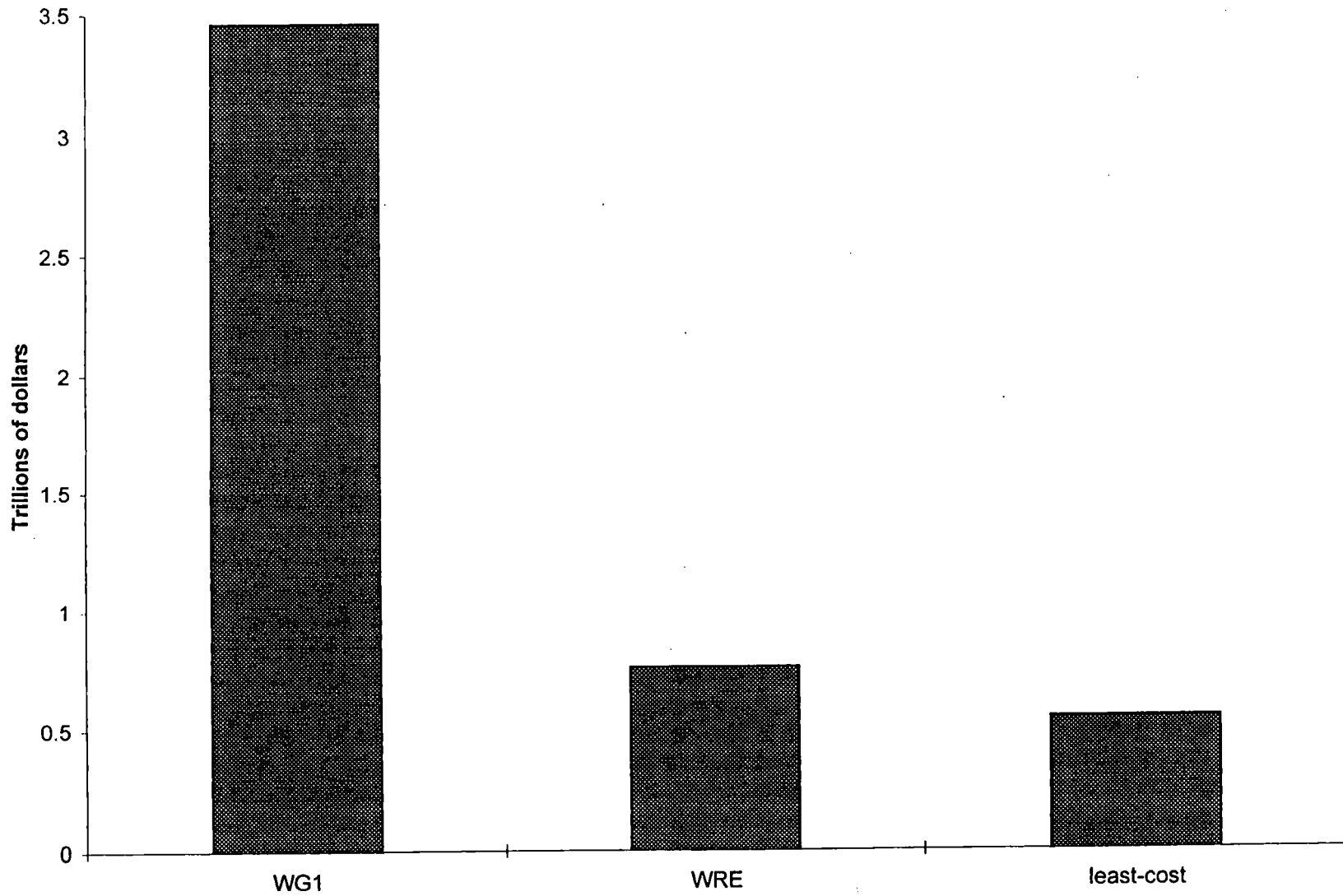
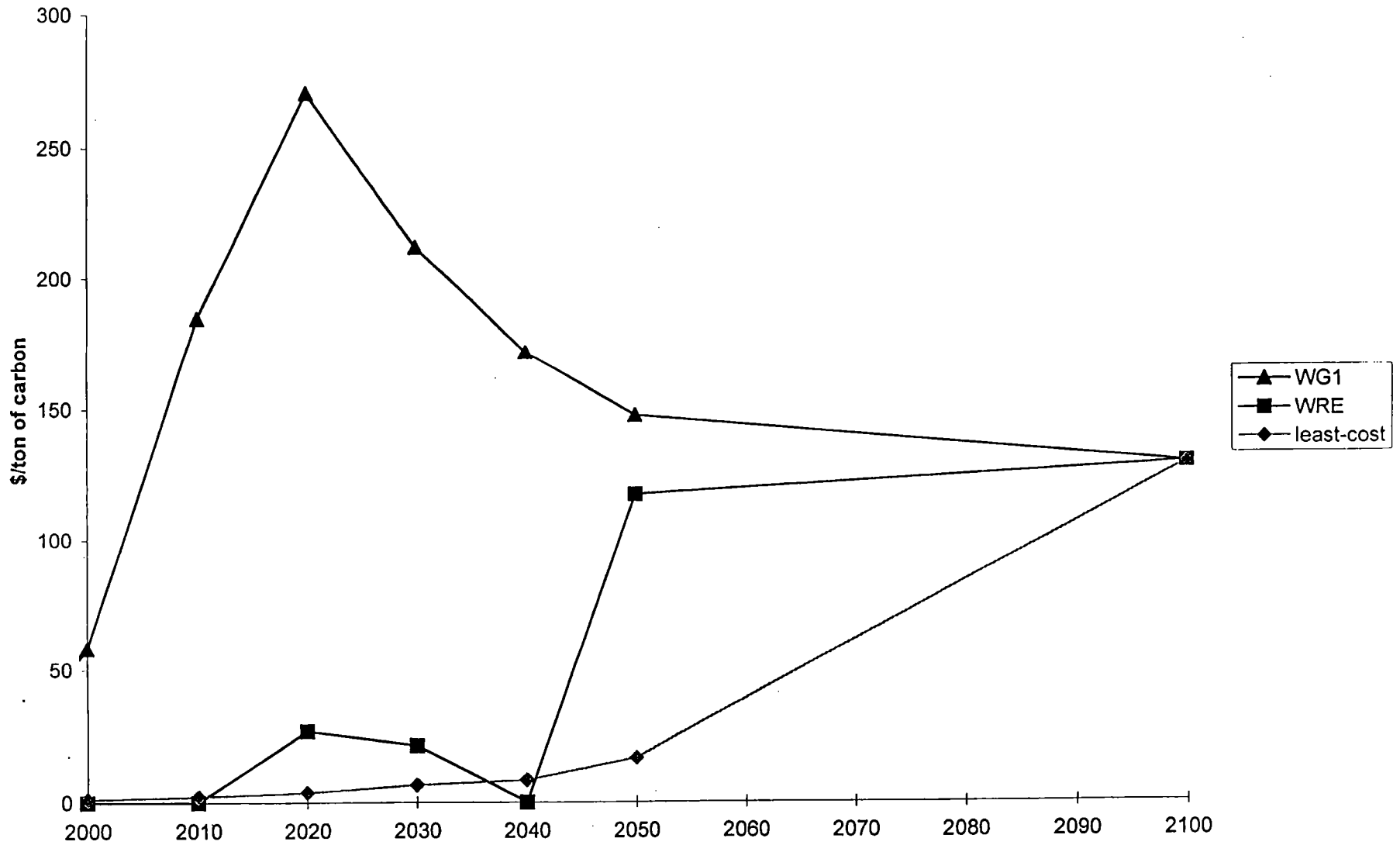


Figure 6.3 Value of Carbon Emission Rights with Alternative Pathways for Stabilizing Concentrations at 550ppmv



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

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

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

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

## 7. The costs of stabilizing concentrations at alternative levels

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

Figure 7.1 summarizes the results of the MERGE analysis. As would be expected, mitigation costs are a declining function of the stabilization target. Recall that a concentration target places an upper limit on the amount of CO<sub>2</sub> to be released into the atmosphere between now and the date at which the target is to be achieved. This in effect defines an emissions budget. The lower the target, the smaller the emissions budget.

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

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

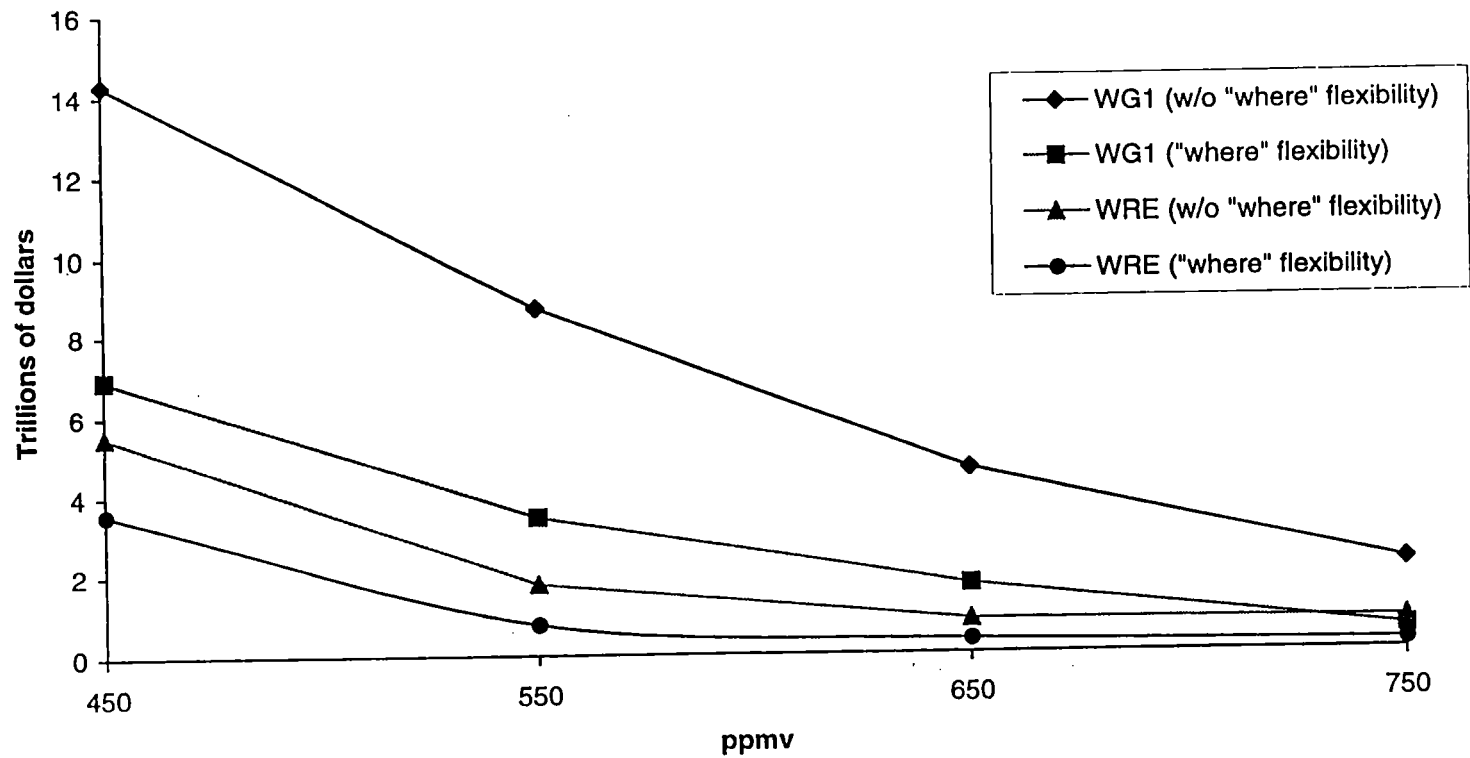
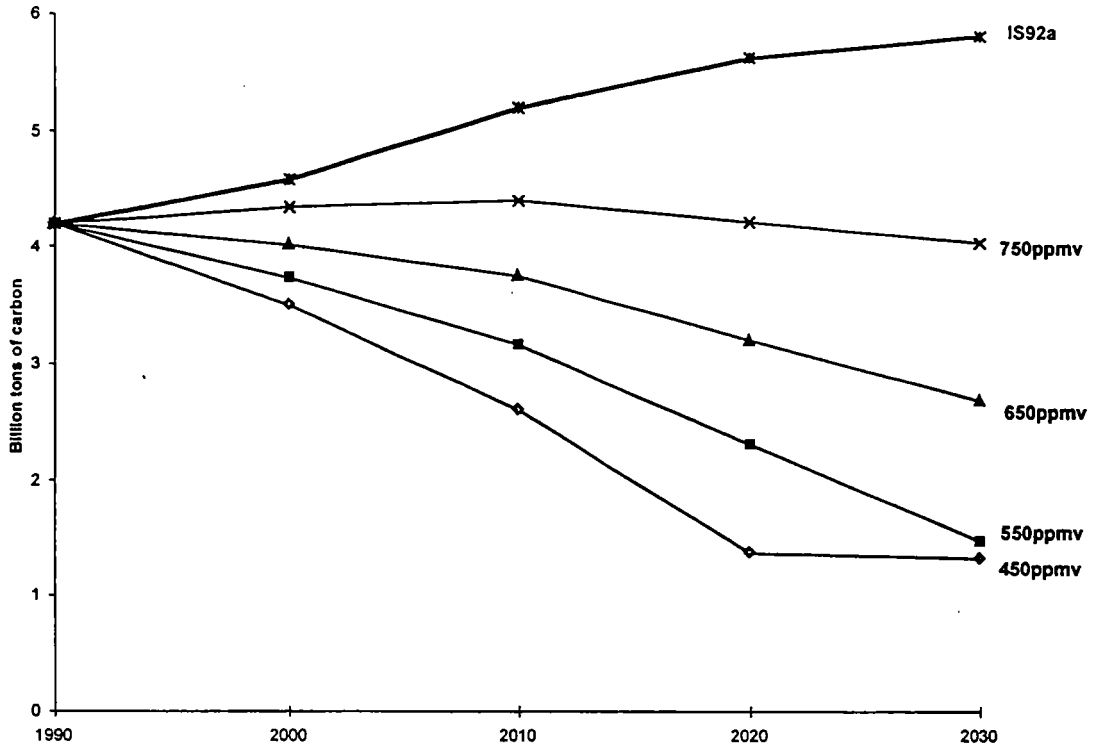
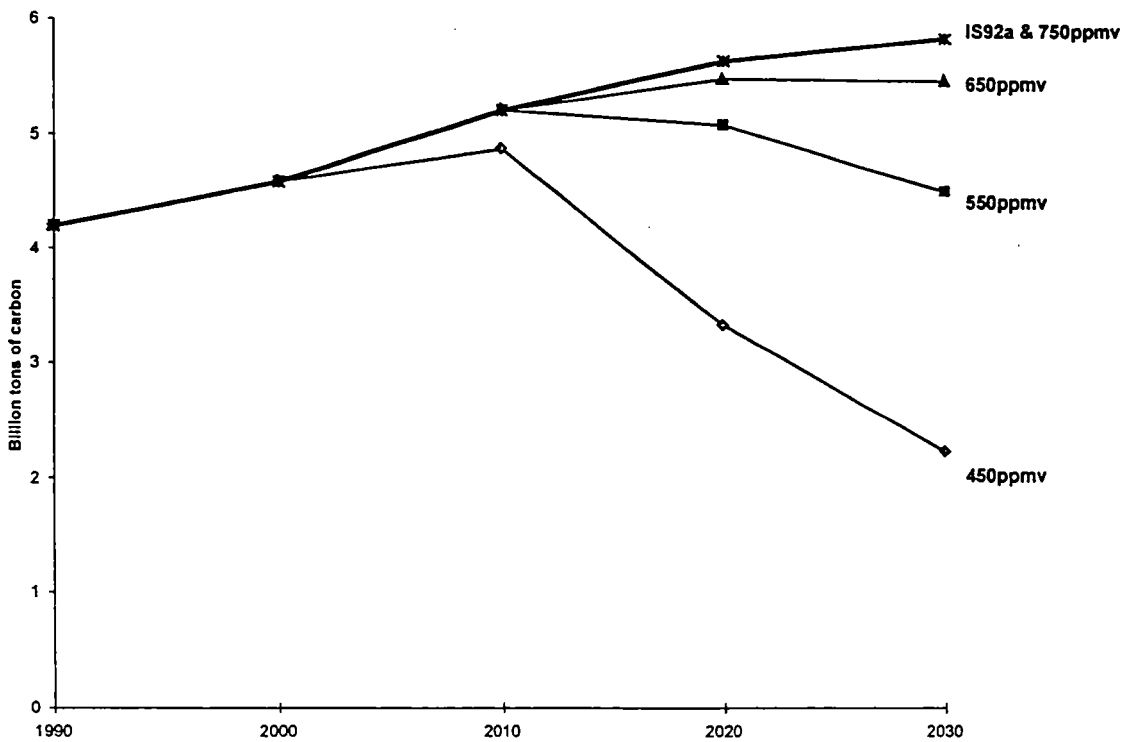


Figure 7.2 Annex 1 Emission Constraints under Alternative Concentration Targets



a) WG1



b) WRE

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

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

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

## 8. The choice of near-term mitigation strategy

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

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

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

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

## 9. Some concluding comments

The above analysis suggests that a more gradual transition away from fossil fuels is likely to be less expensive in terms of mitigation costs. This should not be interpreted as suggesting a "do nothing" or "wait and see" strategy. Mitigation may mean action, but action does not necessarily mean mitigation. As pointed out in the IPCC 1995 Report<sup>20</sup>, 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."<sup>21</sup>

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.<sup>22</sup>

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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## References

- <sup>1</sup> Intergovernmental Negotiating Committee for A Framework Convention on Climate Change (1992). Fifth Session, Second Part, New York, 30 April-9 May.
- <sup>2</sup> United Nations Climate Change Bulletin, Issue 7, 2nd Quarter 1995, published by the interim secretariat for the UN Climate Change, Convention, Geneva.
- <sup>3</sup> IPCC (1994). *Climate Change 1994*, Cambridge University Press.
- <sup>4</sup> Coase, R. (1960). "The Problem of Social Cost." *Journal of Law and Economics*, 3.
- <sup>5</sup> Intergovernmental Negotiating Committee for A Framework Convention on Climate Change (1992), op. cit.
- <sup>6</sup> Manne, A., Mendelsohn, R. and Richels, R. (1995). "MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies." *Energy Policy*, 23 (1).
- <sup>7</sup> Manne, A. and Richels, R. (1995). "The Greenhouse Debate: Economic Efficiency, Burden Sharing and Hedging Strategies." *The Energy Journal*, 16 (4).
- <sup>8</sup> Manne, A. and Schratzenholzer, L. (1996). "International Energy Workshop." International Institute for Applied Systems Analysis, Laxenburg, Austria, January.
- <sup>9</sup> IPCC (1992). *Climate Change 1992*, Cambridge University Press.
- <sup>10</sup> IPCC (1994). *Climate Change 1994*, op. cit.
- <sup>11</sup> Wigley, T., Richels, R. and Edmonds, J. (1996). "Economic and Environmental Choices in the Stabilization of Atmospheric CO<sub>2</sub> Concentrations," *Nature*, Vol. 379, 18 January.
- <sup>12</sup> IPCC (1996). *Climate Change 1995*, Cambridge University Press.
- <sup>13</sup> Nordhaus, W. (1979). *The Efficient Use of Energy Resources*. Yale University Press, New Haven.
- <sup>14</sup> Manne, A. and Richels, R. (1995), op. cit.
- <sup>15</sup> Richels, R. and Edmonds, J. (1995). "The Economics of Stabilizing Atmospheric CO<sub>2</sub> Concentrations." *Energy Policy*, 23 (4/5).
- <sup>16</sup> Kosobud, R., Daly, T., South, D. and Quinn, K. (1994). "Tradable Cumulative CO<sub>2</sub> Permits and Global Warming Control," *The Energy Journal*, 15 (2).
- <sup>17</sup> IPCC (1996). *Climate Change 1995*.
- <sup>18</sup> Manne, A. and Richels, R. (1996). "The Berlin Mandate: The Cost of Meeting Post-2000 Targets and Timetables." *Energy Policy*, 24 (3).
- <sup>19</sup> Richels, R., Edmonds, J., Gruenspecht, H. and Wigley, T. (1996). "The Berlin Mandate: The Design of Cost Effective Mitigation Strategies." EMF-14, Working Paper 3, Stanford University, Stanford, CA.
- <sup>20</sup> IPCC (1996). *Climate Change 1995*, op. cit.
- <sup>21</sup> IPCC (1996). *Climate Change 1995*, op. cit.
- <sup>22</sup> Energy Modeling Forum (1993). "Reducing Global Carbon Emissions: Costs and Policy Options." EMF-12, Stanford University, Stanford, CA.

## A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies

By WILLIAM D. NORDHAUS AND ZILI YANG\*

*Most analyses treat global warming as a single-agent problem. The present study presents the Regional Integrated model of Climate and the Economy (RICE) model. By disaggregating into countries, the model analyzes different national strategies in climate-change policy: pure market solutions, efficient cooperative outcomes, and noncooperative equilibria. This study finds that cooperative policies show much higher levels of emissions reductions than do noncooperative strategies; that there are substantial differences in the levels of controls in both the cooperative and the noncooperative policies among different countries; and that high-income countries may be the major losers from cooperation. (JEL H41, Q4, Q2, Q20)*

Although the issue of greenhouse warming was first seriously studied a century ago, it has over the last decade emerged as the central international environmental question. Most nations have adopted the Framework Convention on Climate Change negotiated at the 1992 Rio Earth Summit. Under the Convention, nations agreed to take steps to limit carbon dioxide (CO<sub>2</sub>) and other greenhouse gas (GHG) emissions before they reach "dangerous" levels. Having increased its CO<sub>2</sub> emissions at an average growth rate of almost 2 percent annually for about a century, the United States has committed itself to capping its emissions at 1990 levels, and many other high-income countries have made similar or even more ambitious proposals (for a review of commitments, see Daniel M. Bodansky [1995] or International Energy Agency (IEA) [1994]).

The climate-change issue is so controversial primarily because the stakes are so high. If un-

checked, recent surveys indicate that over the next century the globally averaged surface temperature will rise around 3°C (degrees Celsius), which would produce climates that are unprecedented during the entire span of human civilization. While warming may seem benign, it has major and unpredictable impacts on weather patterns, ocean currents, sea-level rise, river run-offs, storm and monsoonal tracks, desertification, and other geophysical phenomena. Many scientists and ecologists view these changes and uncertainties with alarm.

The other half of the calculus is the cost of slowing climate change. Even the most draconian policies (such as a virtual phaseout of fossil fuels) would only slow and not stop climate change, and significant steps to slow the rate of increase of climate change would cost hundreds of billions of dollars annually using today's energy technologies. Given the many economic issues facing humanity, it would require an unusually dire risk and uncommonly statesmanlike behavior for nations to divert 1 or 2 percent of their national incomes today to reduce conjectural risks that will not occur until well into the next millennium.

In addition to the grave risks and huge costs, the issue of greenhouse warming is difficult because the problem is so complex. It involves a series of poorly understood systems, including the carbon cycle, climate reactions, geophysical, ecological, and biological impacts of

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climate changes, economic impacts, along with potential adaptations and new technologies, with all of these stretching over a period of a century or more. Social and natural scientists have made impressive advances in understanding each of these systems over the last quarter century, and numerous efforts are underway today to link together the different components into an *integrated assessment* of climate change policies. One of the earliest integrated models was the DICE model, which is a globally aggregated model integrating a general-equilibrium model of the global economy with a climate system including emissions, concentrations, climate change, impacts, and optimal policy (see Nordhaus, 1992, 1994). Other recent integrated models of climate change include Alan S. Manne and Richard Richels (1992), Stephen C. Peck and Thomas J. Teisberg (1992), and Zili Yang (1993).

Globally aggregated models have the shortcoming of losing many of the interesting and important details of different regions. Perhaps the central shortcoming, however, is that global models ignore the fact that policy decisions to reduce GHG emissions are taken primarily at the national level. It is single nations, not the United Nations, that determine energy and environmental policy, so any grand design to slow global warming must be translated into national measures. The purpose of the present study is to improve the realism of integrated assessments by lodging policy making at the more appropriate national level. This involves introducing a number of regions of the world and considering different degrees of cooperation among nations.

The present paper reports on the results of the current version of the RICE model.<sup>1</sup> It outlines briefly the philosophy, sketches the modeling structure, and describes the major results.

<sup>1</sup> An experimental version of the RICE model with illustrative data was presented at the MIT Conference on the Environment (see Nordhaus, 1990). The current version (called RICE-6.3.2 for purposes of documentation) incorporates a number of changes, primarily a revision of the treatment of non-CO<sub>2</sub> greenhouse gases and improved estimates of the economic and emissions data. A major cause of the long gestation period of this research has been the difficulty in finding a satisfactory algorithm for solving the intertemporal general equilibrium (see below).

## I. Description of the RICE Model

### A. Overview

This section begins with a succinct description of the RICE model; the equations of the model are provided in Appendix A.<sup>2</sup> The *RICE model*, or *Regional Integrated model of Climate and the Economy*, is a regional, dynamic, general-equilibrium model of the economy which integrates economic activity with the sources, emissions, and consequences of greenhouse-gas emissions and climate change. Most existing models of global climate change take the vantage point of the Global Commoner engaged in determining how nations *should* design sensible strategies to cope with future climate change. The RICE model takes a positive point of view by asking how nations *would in practice* choose climate-change policies in light of economic trade-offs and national self-interests. Put differently, global optimization models ask how nations would choose the optimal (or Pareto-efficient) path for reductions of GHGs. The RICE model allows us to calculate not only the efficient path (which we designate the cooperative approach)<sup>3</sup> but also to compare that path with noncooperative approaches.

In the RICE model, the world is divided into a number of regions. Each is endowed with an initial capital stock, population, and technology. Population and technology grow exogenously, while capital accumulation is determined by optimizing the flow of consumption over time. Output is produced by a Cobb-Douglas production function in capital, labor, and technology. In the long run, capital is fully mobile so that the real return on capital

<sup>2</sup> The structural equations of the RICE model are generally the same as those of the aggregated DICE model. For a detailed discussion of the derivation of the equations, see Nordhaus (1994). The GAMS program for the RICE model is available from the authors upon request.

<sup>3</sup> This study identifies the cooperative solution as the one that generates an efficient level and distribution of emissions. The solutions that might emerge from international negotiations are a further issue that is not addressed in this study. Issues concerning possible bargaining outcomes are discussed below in Section II.C. "Welfare Effects by Region."

is equalized across regions. The preference function of each region is a utility function which is the sum of discounted utilities of per capita consumption times population, where the pure rate of social time preference (the discount rate on utility) is 3 percent per year in each region. The utility function is logarithmic in per capita consumption.

The major contribution of the integrated approaches like the RICE model is to integrate the climate-related sectors with the economic model. This part of the model contains a number of geophysical relationships that link together the different forces affecting climate change, generate the greenhouse-gas emissions, and measure the impacts of climate change. RICE includes region-specific emissions equations, a global concentrations equation, a global climate-change equation, and regional climate-damage relationships. Endogenous emissions are limited to CO<sub>2</sub>, while other greenhouse gases are treated as exogenous. Uncontrolled emissions are a slowly declining fraction of gross output—a relationship which is consistent with the observed “decarbonization” in most countries over this century that is also predicted by more detailed energy models. CO<sub>2</sub> emissions can be controlled by increasing the prices of factors or outputs that are CO<sub>2</sub> intensive, and we represent the CO<sub>2</sub>-reduction cost schedule parametrically by drawing upon a number of studies of the cost of CO<sub>2</sub> reductions. Climate change is represented by the realized global mean surface temperature, which uses relations based on current climate models. The economic impacts of climate change are assumed to be increasing along with the realized temperature increase. The impacts of climate change are estimated from a number of different studies, but it must be recognized that this is the most uncertain part of the model.

The major economic choices faced by nations (or the concert of nations) in this approach are (a) to consume goods and services, (b) to invest in productive capital, and (c) to slow climate change through reducing CO<sub>2</sub> emissions. The new element introduced in the RICE model and not present in other models of global warming is the possibility of different strategies undertaken by nations. We distinguish three distinct approaches:

- *Market policies.* The market approach is one in which there are no controls on the emissions of greenhouse gases. This has been the approach followed by virtually all nations up to now.
- *Cooperative policies.* The second approach is the ideal one in which global environmental concerns are treated cooperatively through the efficient actions of all nations. In this approach, nations agree to reduce CO<sub>2</sub> emissions in a globally efficient way. This solution is efficient but requires an unrealistically high degree of cooperation.
- *Noncooperative policies.* In the third approach, individual nations undertake policies that are in their national self-interests and ignore the spillovers of their actions on other nations. In the noncooperative approach, to the extent that nations are small and the externality is truly global, efforts to reduce CO<sub>2</sub> emissions will be much smaller than in the global cooperative solution. This solution is inefficient but realistic.

#### B. Basic Structure

We outline here the major features and innovations of the RICE model; the equations of the model are contained in Appendix A.

The RICE model divides the global economy into 10 different regions. The first five are 1) the United States, 2) Japan, 3) China, 4) the European Union, 5) and the former Soviet Union (FSU). Each is treated as a single decision maker. The last five regions have different numbers of countries, and each is treated as multiple decision makers. These five regions are 6) India, 7) Brazil and Indonesia, 8) 11 large countries, 9) 38 medium-sized countries, and 10) 137 small countries. (Basic data on the major regions are contained in Appendix B.) To reduce the severe computational complexity of the solution, we sometimes aggregate regions 6 through 10 into one region as the “rest of the world” or “ROW.”

The goal in creating the different regions is to structure the problem so that the noncooperative equilibrium is equivalent to the full but enormous game with about 200 countries. This is done by allocating the smaller countries to groups so that within each group the national benefits from slowing climate change are

roughly equal. We then mimic the free-riding temptations of global public goods by dividing the benefit function for each region by the number of countries (that is, decision-making units) within that region.

An example will clarify the way regions are used. Region 9 contains 38 countries—including Bulgaria and Hungary, which are countries with roughly similar populations and economies. We assume that all the countries in region 9 are similar in terms of their sizes, mitigation cost functions, and damage functions. Hence, for region 9 the (slightly simplified) net benefit function to be maximized in the noncooperative case is  $N(E_9) = B(E_9)/38 - C(E_9)$ , where  $N(E_9)$  is the net benefits of emissions for region 9,  $E_9$  is emissions in region 9,  $B(E_9)$  is the benefit of emissions, 38 is the number of equal-sized decision makers in region 9, and  $C(E_9)$  is the cost function. Therefore, when the representative country in region 9 maximizes its net economic welfare in the noncooperative case, not only will it ignore the benefits accruing outside region 9, but it will also internalize only  $1/38$  of the benefits of the region. This procedure includes in a computationally feasible manner all the different countries while ensuring that the incentives for free-riding are maintained.

A major difficulty in constructing the RICE model has been to estimate the regional parameters of the different functions.<sup>4</sup> Gross domestic products, populations, CO<sub>2</sub> emissions, and capital stocks are taken from a variety of international sources. Future population growth estimates are taken from the United Nations projections. The major uncertainty in the economic projections is long-run levels of per capita output in the different regions. These projections are based on the assumption of *partial convergence of per capita incomes*. That is, we assume that the relative differences in regions' per capita incomes decline over time but do not disappear. The extent of convergence is a controversial issue, but to the extent that differences in per capita incomes are primarily based on differences in the extent of adoption of available technologies, produc-

<sup>4</sup> A detailed list of sources and data are available from the authors.

TABLE 1—FUTURE LEVELS OF INCOMES, DIFFERENT REGIONS

Region	Ratio of region's per capita income to that of the United States (US <sub>1990</sub> = 1)		
	1990	2100	2200
1) United States	1.00	3.11	4.69
2) Japan	1.09	4.07	4.83
3) China	0.02	0.47	1.55
4) European Union	0.85	2.89	4.27
5) Former Soviet Union	0.14	0.87	2.02
6) Rest of the world	0.07	0.84	1.69

Note: These values are the values of per capita GDP generated by the market solution for the RICE model. The GDPs are calculated using market exchange rates.

tivity differences should largely disappear over the long run.

The assumed ratios of long-run levels of per capita GDPs to that of the United States are given in Table 1, showing the observed values for 1990 along with projections for 2100 and 2200. While highly conjectural, these estimates are consistent with recent trends in country GDP growth. One interesting feature of this approach is that it gives considerably higher estimates of output and emissions than do the conventional global models, such as those used by governments in the Intergovernmental Panel on Climate Change (IPCC). For the modeling, each region's income growth is generated through Hicks-neutral technological change, which starts at approximately the observed rates for 1960–1990. After 1990, growth rates are assumed to decline exponentially in a manner leading to the asymptotic productivity ratios shown in Table 1.

CO<sub>2</sub> emissions are separated into industrial emissions (largely from fossil fuels) and those from land-use changes and are calibrated to 1990 levels. The ratio of CO<sub>2</sub> emissions to output is assumed initially to decline at different rates, with each region's decline rate decreasing along with the overall rate of technological change by region. Here again, asymptotic CO<sub>2</sub>-output ratios are assumed to converge considerably but not completely in the future.

The costs of reducing emissions by region are estimated separately on the basis of the existing studies of the cost of reduction of CO<sub>2</sub>

emissions. In United States other regions have parameter functional forms estimated on the basis of undertaken by the Forum.

Estimates of damages are calculated at stage. There are estimated impacts on the market sectors reliable studies for developing countries in different damage functions for each parameter and that the parameters as in the United States. Impacts are calculated by different sectors and so on) in aggregating the estimates. (T Nordhaus [1995] argue do not consider a major estimate Fankhauser [1995] in Nordhaus [1995] sized that the across country conjectural. Table assumptions for

<sup>5</sup> See Andrew Darius W. Gaskin. The functional form of the model was estimated in nine factors: United States and where  $i$  is region  $i$  emissions,  $b_{1,i}$  and  $b_{2,i}$  control rate or framework path,  $Y_i(t)$  is the time period exponents ( $b_2$ ) are the intercepts ( $b_{1,i}$ , the different countries above.

emissions. Most studies are based on the United States and Europe, and estimates for other regions have low levels of reliability. We have parametrized the cost function using the functional form from earlier studies but have estimated the *intercepts* of the cost functions on the basis of the international comparisons undertaken by the OECD and by Energy Modeling Forum 13.<sup>5</sup>

Estimates of the economic impacts or damages from climate change are sparse at this stage. There are numerous studies of the estimated impact of climate change on the marketed sectors for the United States, but few reliable studies for the nonmarket sectors or for developing countries. To estimate the impacts in different regions, we assume that the damage function from climate change is identical for each industry across different regions, and that the cost functions have the same parameters as those estimated for the United States. Impacts in different regions are calculated by taking the estimated shares of different sectors (agriculture, coastal activities, and so on) in national output and then aggregating those up to obtain overall national estimates. (This approach is described in Nordhaus [1994].) The results in the aggregate do not differ markedly from the other major estimates (see particularly Samuel Fankhauser [1993] and the survey of experts in Nordhaus [1994]), but it must be emphasized that the distribution of climate impacts across countries is at this stage highly conjectural. Table 2 shows the major inputs assumptions for the different regions.

<sup>5</sup> See Andrew Dean and Peter Hoeller (1992) and Darius W. Gaskins and John P. Weyant (1993). The functional form of the mitigation-cost function in the DICE model was estimated from studies of the cost of CO<sub>2</sub> reduction in nine families of models primarily based on the United States and takes the form  $C_i(t) = b_{1,i} \mu_i(t) b_2 Y_i(t)$ , where  $i$  is region  $i$ ,  $C_i(t)$  = the cost of reducing CO<sub>2</sub> emissions,  $b_{1,i}$  and  $b_2$  are parameters,  $\mu_i(t)$  is the emission-control rate or fractional reduction in emissions from the market path,  $Y_i(t)$  is region  $i$ 's gross regional product, and  $t$  is the time period. The RICE model assumes that the exponents ( $b_2$ ) are the same across countries and calibrates the intercepts ( $b_{1,i}$ ) to estimates of the cost functions from the different countries or regional models mentioned above.

The climate-change policies are characterized by "control rates" and "carbon taxes." Control rates are simply the percentage reductions in CO<sub>2</sub> emissions relative to a baseline or uncontrolled path. Carbon taxes represent the marginal cost of reducing CO<sub>2</sub> emissions. A carbon tax would equal the price of a carbon-emissions permit if there were tradable permits, and the prices of such permits in different countries would obviously be equalized (at market exchange rates) if permits were freely tradable. In the market solution, carbon taxes are zero. In the cooperative solution, emissions are curtailed in a cost-effective manner. The model does not deal explicitly with mechanisms by which winners might compensate losers, although we discuss some of the issues below.

### C. Algorithm to Calculate General Equilibrium

The RICE model presents a radically different philosophy for estimating strategies to cope with global warming from global-optimization models used in many integrated assessments. The baseline calculation is calibrated to a market equilibrium of the world economy with all the differences in populations, technologies, and incomes—the world is taken as it is for the purpose of the baseline calibration. We then calculate different strategies for global warming conditional on the existing distribution of capital, labor, and technology. The strategies include doing nothing (the market solution), finding an efficient solution given the existing distribution of income (the cooperative solution), and finding the solution in which nations select policies to maximize national preferences alone (the non-cooperative or nationalistic equilibrium). This public-choice approach is in sharp contrast to many of the debates on climate change today; in these, the distributional issues of who shall pay to slow climate change rise to the top of the agenda.

We now describe the algorithm for finding the cooperative solution in the RICE model. The technique we employ originates with T. Negishi (1960), was discussed briefly in Nordhaus (1990) in the context of global warming, and has been used in similar models

TABLE 2—MAJOR INPUT PARAMETERS FOR THE RICE MODEL

Region	Cost intercept <sup>a</sup>	Climate damage intercept <sup>b</sup>	CO <sub>2</sub> emissions, 1990		Population 2100 <sup>c</sup>	Per capita output (2100) <sup>f</sup>	CO <sub>2</sub> ratio, 2100 <sup>g</sup>
			Land-use <sup>e</sup>	Industrial <sup>d</sup>			
United States	0.07	0.01102	0.010	1.360	0.294	68.8	0.1190
Japan	0.05	0.01174	0.000	0.292	0.125	89.1	0.0630
China	0.15	0.01523	0.136	0.669	1.656	9.9	0.5120
European Union	0.05	0.01174	0.100	0.872	0.427	63.0	0.0740
Former Soviet Union	0.15	0.00857	0.000	1.066	0.366	18.9	0.3220
Rest of world	0.10	0.02093	1.730	1.700	6.738	18.1	1.1850

<sup>a</sup> The intercept of cost function equals the fraction of annual output required to reduce net CO<sub>2</sub> emissions to 0.

<sup>b</sup> The intercept of climate-damage function equals the reduction in annual net output from an increase of 2.5°C in global mean temperature.

<sup>c</sup> Emissions are measured in billions of tons carbon per year. Land-use emissions are primarily from deforestation.

<sup>d</sup> Emissions are measured in billions of tons carbon per year. Industrial uses primarily from burning fossil fuels.

<sup>e</sup> Population is in billions of people.

<sup>f</sup> Gross domestic product (GDP) is measured at 1990 market exchange rates in thousands of 1990 U.S. dollars.

<sup>g</sup> The ratio is of industrial CO<sub>2</sub> emissions to GDP (tons of carbon per \$1000 of output in 1990 U.S. dollars).

by Manne and Thomas Rutherford (see, particularly, 1994). The theoretical basis for the algorithm is a theorem of Negishi which relies on the second theorem of welfare economics. Negishi suggested and proved that under certain conditions a competitive equilibrium can be found by maximizing a social welfare function of  $N$  agents in which the welfare weight of each of the agents is adjusted to satisfy the agent's budget constraint. We will call this equilibrium the *Negishi solution*.

What are the appropriate welfare weights? In our calibration, we adopt the realistic approach by taking the welfare weights that reflect the actual economic outcome across regions. We do this not as a brief for the existing international distribution of resources and income but because it is the starting point for analyzing potential improvements in economic welfare that would arise from policies that are imposed on the actual world economy. Hence, the weights are ones such that the excess demands in all markets are zero at the given welfare weights and prices.<sup>6</sup> More precisely, the algorithmic procedure is the following. We first solve the RICE model by

<sup>6</sup> A brief but illuminating discussion of the Negishi approach is in contained in Andreu Mas-Colell et al. (1995 pp. 630–31).

optimizing a global social welfare function of the form:

$$(1) \quad W = \sum_{i=1}^N \phi^i U^i [c^i(1), c^i(2), \dots, c^i(t), \dots, c^i(T)]$$

where  $W$  is the value of the global social welfare function and  $\phi^i$  are the welfare or Negishi weights for country  $i$ ,  $i = 1, \dots, N$ . The  $U^i$  are the preference functions for the different countries, and the  $c^i(t)$  are the consumption bundles of the countries.

The relevant excess demand is found in the intertemporal budget constraint of each region. To find the competitive equilibrium, we add a constraint to the problem that requires each region to satisfy its intertemporal budget constraint, which is represented by terminal net foreign assets,  $NFA^i(T)$ ,  $T$  being the last period:

$$(2) \quad NFA^i(T) = 0, \quad i = 1, \dots, N.$$

Next, define  $\psi^i(T)$  as the dual variable of  $NFA^i(T)$ , which in economic terms is the marginal utility of consumption or income in the last period. Given condition (2),  $\psi^i(T)$  is a function of the welfare weights and we can write these functions as  $\psi^i(T) = G^i(\phi^1, \phi^2, \dots, \phi^N)$ ,  $i = 1, \dots, N$ . Without condition (2),

an arbitrar would gen which impl live within variables a welfare-we are equal : straits is t Hence, t the welfare variables  $\psi$  of consum

$$(3) \quad \psi^i(T)$$

Combinin; each of the isified and change in the Negisl timized or generated equi-libriu dowments equilibriu solution.'

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<sup>7</sup> The di flows is no the same is employed.

an arbitrary set of social welfare weights would generate a set of nonzero  $NFA^i(T)$ , which implies that at least one region does not live within its budget. However, when the dual variables are equalized across all countries, the welfare-weighted marginal utilities of income are equal and the intertemporal budget constraints is therefore satisfied.

Hence, the algorithm works by searching for the welfare weights, as a function of the dual variables  $\psi^i(T)$ , so that the marginal utilities of consumption are equalized:

$$(3) \quad \psi^i(T) = G(\phi^1, \phi^2, \dots, \phi^N) = \psi^*,$$

for all  $i = 1, \dots, N$ .

Combining (1), (2), and (3), we know that each of the country budget constraints is satisfied and that no region can gain from a change in the resulting allocation. Hence, by the Negishi theorem, we know that this optimized outcome using the welfare weights generated in (3) represents a competitive equilibrium consistent with the initial endowments, technology, and preferences. The equilibrium thus found is the "pure Negishi solution."

Unsatisfactory aspects of the solution led to the following refinements of the pure Negishi solution. The major problem with the pure Negishi solution was that it generated extremely large capital flows among regions (this is a common feature in intertemporally optimized models).<sup>7</sup> Because these are unrealistic, we took one further step which was to impose certain flow and stock constraints on debt and current accounts to ensure that net foreign investment does not exceed certain limits. These limitations limited the export-GDP ratio to 1, limited the ratio of net foreign assets to output to 0.1, and limited the current account deficit to GDP ratio to 0.1 (see Appendix A for details). These constraints were based on observed limitations, but they made

virtually no difference for the results of the analysis below.

Given these constraints on international capital flows, our algorithm will not produce the necessary complete price equalization for carbon-trading permits, which are assumed to be fully tradable and reach price. To ensure price equalization for carbon-emission rights, we adjust the Negishi weights across regions for every period. We call this new algorithm the *time-dependent Negishi solution*. It differs from the pure Negishi solution because it incorporates the constraints on capital flows so that the regional budget constraints are binding for every period. As a result, carbon-emissions permits have equal prices in all regions in each time period (at market exchange rates). Under this revised algorithm, we seek the *time-dependent Negishi weights*,  $\phi^i(t)$ . To find these, we first solve the model with an arbitrary set of welfare weights while continuing to impose (2). Following the Negishi theorem, we then reset the welfare weights for all countries and time periods according to the following formula:

$$(4) \quad \phi^i(t) = \frac{1}{\sum_{i=1}^n \frac{1}{\psi^i(t)}}.$$

This equation sets the welfare weights equal to the inverse of the marginal utilities of consumption. The search algorithm based on (4) very quickly converges to a solution that satisfies (2) and (3). We have conducted a number of experiments and have found no indication of multiple equilibria.

What is the underlying economic rationale for this algorithm? The solution represents a competitive equilibrium under the assumption that the preferences or technological constraints limit the international flows of capital. For example, there may be strong home-country preferences in portfolios because of limitations of the marketability of human capital. The limitation of this approach is that to the extent that the constraints on capital flows have nonmarket-clearing elements due to rationing, the excess demands will not be zero and we may depart from the market

<sup>7</sup> The difficulty raised by unrealistically high capital flows is not related to the use of the Negishi technique; the same issue would occur if fixed-point methods were employed.

equilibrium (which would in any case be difficult to compute).

Once we have obtained a competitive equilibrium, we then perturb various elements, such as the climate parameters or the cost functions, and resolve the maximization in (1). We do this holding the welfare weights constant across runs. This resolves the index number problem of changing prices by calculating the welfare changes at the market welfare weights.<sup>8</sup>

#### D. Finding the Noncooperative Equilibrium

The algorithm just described provides the solutions for both the market and the cooperative equilibrium. A different approach is necessary to find the noncooperative equilibrium. The noncooperative or nationalistic equilibrium exists as the equilibrium of the strategies of the different countries. We hence need an assumption about strategies and a method of finding the equilibrium.

As for strategies, we assume that each nation determines its policies by maximizing its domestic intertemporal utility function assuming that other nations' strategies are unaffected by its policies. The noncooperative strategies are hence dynamic, full-information, Nash strategies, and we are seeking the Nash equilibrium. Technically, our solution is a Nash equilibrium in a finite game with perfect information, and it is therefore time consistent. Such games have pure strategy Nash equilibria which can be calculated through backward induction, which is essentially what our algorithm does (for a discussion, see Mas-Colell et al. [1995 Chapter 9]).

More precisely, we assume that each nation sets its own control rate over time [ $\mu^i = \{\mu^i(1), \mu^i(2), \mu^i(3), \dots, \mu^i(t), \dots, \mu^i(T)\}$ ;  $i = 1, \dots, N$ ] so as to maximize its national objective function taking the control rates of the other regions  $\{\mu^1, \dots, \mu^{i-1}, \mu^{i+1}, \dots, \mu^N\}$  as given. Beginning with an initial set of control rates, we iterate through the different

regions by optimizing for each region holding the control rates and resulting emissions, concentrations, and impacts in other regions from the previous iteration fixed. We continue to cycle through this sequence until the set of control rates are unchanged given the set of noncooperative strategies of other countries, which is then the Nash equilibrium. The outcome matches well the theoretical predictions and is in our simulations invariant to initial conditions, which suggests that the Nash equilibrium is unique.

How reasonable is this solution concept? While the pure Nash equilibrium is a sensible assumption for small countries like Chad, whose global warming policies will hardly make the front pages, it may lack realism for large or influential countries. Large countries like China and influential countries like the United States would probably want to take into account the effect of their policies on other countries' policies. The ambivalent policy on global warming by the United States over the last decade has undoubtedly strengthened the hand of those in other countries who want to do little. An alternative approach would be for countries to posit conjectural variations or reactions of other countries to their policies. For example, the United States might assume that Japan or Europe would be a follower in terms of carbon-tax policies or tradable emissions policies. Another possibility would be to model coalitions of different countries. We have not explored these alternative solution strategies in the present paper. Once we admit nonzero conjectural variations, we are in a deep thicket and the possibilities become unlimited. Future research will examine the possibility of coalitions of countries.

#### E. The Economic and Environmental Impact of Alternative Strategies

Using the algorithms just described, we will analyze the three different strategies as described in Table 3: market, cooperative, and noncooperative. In addition, for reference we sometimes compare the results of the RICE model to those of its parent, the DICE model, which is essentially a one-region efficient or cooperative solution.

<sup>8</sup> The RICE model runs on the GAMS software (see Anthony Brooke et al., 1988). The full model including searching for welfare weights takes approximately 6 hours on a 486-66 processor.

TABLE 3—ALTERNATIVE SOLUTION CONCEPTS FOR THE RICE MODEL

1. *Market RICE*: This strategy assumes that there is no correction for the climate-change externality and that there is therefore no abatement of CO<sub>2</sub> emissions.
2. *Cooperative RICE*: In this strategy, countries undertake policies that reduce greenhouse-gas emissions efficiently. The reduction of CO<sub>2</sub> emissions is efficient across countries and across time.
3. *Noncooperative RICE*: This strategic concept assumes that each country sets its CO<sub>2</sub> emissions controls to maximize its own economic welfare assuming that other countries' control strategies are invariant to a country's policies.

## II. Results

We now report the results of the policies and strategies described above. As in all modeling efforts of this kind, they should be interpreted with caution as this study is the first empirical application of noncooperative game theory to global environmental policy. On the other hand, the major results concerning the level of stringency of climate-change policies have been relatively stable over a wide variety of models and alternative specifications of the RICE model, so we have considerable confidence in these estimates (conditional, of course, on the assumptions underlying the major components, such as those concerning the long-run growth projections, the costs and damages, and the discount rate).

### A. Output, Emissions, and Climate Change

The projections for the major economic and environmental variables are shown as Figures 1 through 4. One important outcome of this study is that the RICE model has substantially higher projected world output and emissions by the end of the next century than do many other integrated assessments, such as the earlier DICE model.<sup>9</sup> Projections for

regional outputs are shown in Figure 1; these indicate that the projected relative sizes of the Chinese and ROW economies grow sharply over the next century. The output growth in the RICE model is significantly larger than that in many projections prepared by international study groups, most of which envision a stability of current relative income differentials rather than the projected partial convergence in the RICE model. Note as well that we use market exchange rates because we will want to find the equilibrium in which the prices of internationally-traded carbon-emissions permits are equalized.

Emissions are also considerably higher in RICE than in the many other projections. For example, CO<sub>2</sub> emissions in the RICE model reach 38 billion tons of carbon by the year 2100 in the market or uncontrolled run. This compares with an estimated 21 billion tons in the DICE model and a range of 5 to 35 billion tons in the IPCC projections (see T. M. L. Wigley [1994] for a description). CO<sub>2</sub> emissions grow substantially faster in the RICE model partially because of the projected rapid growth in output and partially because of the rising output share of regions with high emission-output ratios.

Figure 2 shows the resulting CO<sub>2</sub> emissions under the different solution concepts and also compares estimates from this study with the earlier DICE model. Model estimates (not shown) indicate that the share of CO<sub>2</sub> emissions will rise sharply in China, region S1 (India), region S3 (middle-sized developing countries like Thailand), and region S4 (smaller developing countries). These four regions accounted for about one third of CO<sub>2</sub> emissions in 1990 but are projected in the market runs of the RICE model to comprise three quarters of emissions by 2100.

CO<sub>2</sub> concentrations are shown in Figure 3. Given the higher emissions rates in the RICE model, its concentrations rise more rapidly than in the DICE model. It is useful to examine the date of doubling of CO<sub>2</sub> concentrations relative

<sup>9</sup> This statement is based on a comparison of the results in the RICE model with the projections of the Intergov-

ernmental Panel on Climate Change (IPCC) (1990), the results in Nordhaus (1994), and preliminary results of the survey of models by the Energy Modeling Forum 14 directed by John Weyant, Energy Modeling Forum (EMF) (1995).

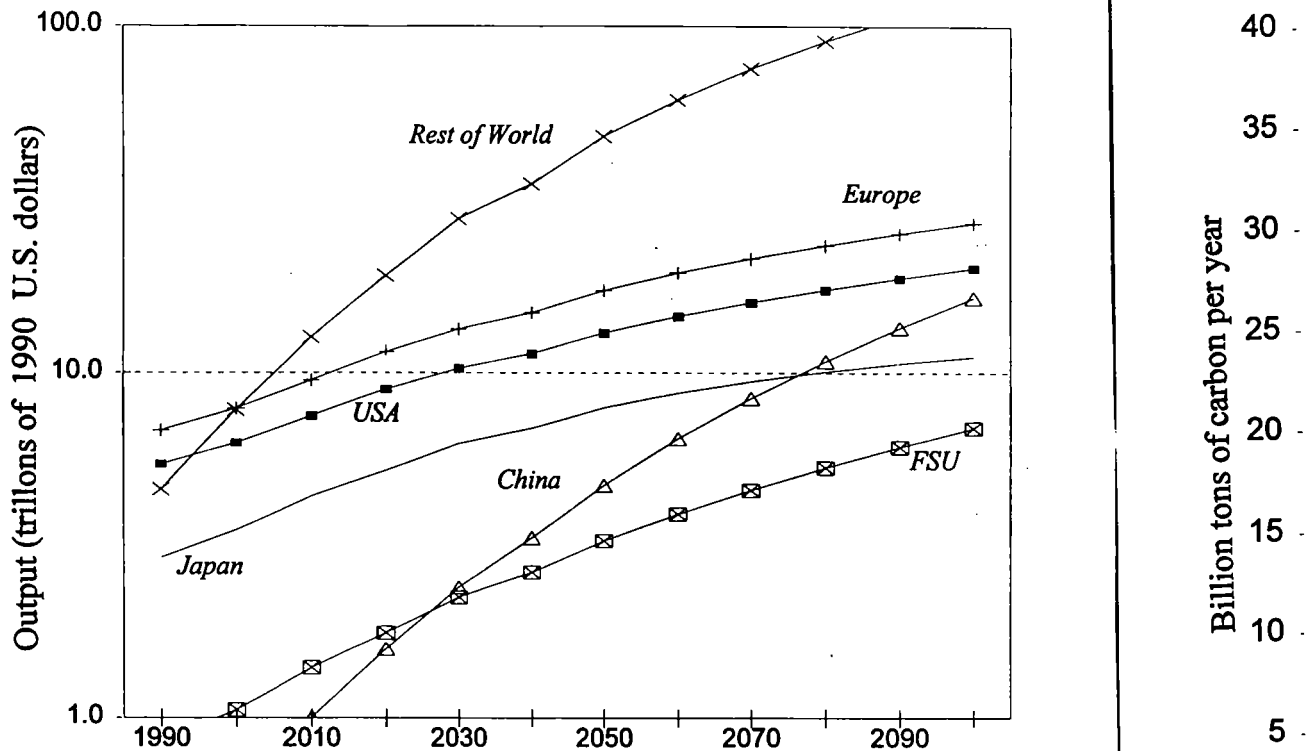


FIGURE 1. REGIONAL OUTPUTS: COOPERATIVE SCENARIO

to preindustrial concentrations; that benchmark is taken to be 1,200 billion tons of atmospheric CO<sub>2</sub> concentrations (or 565 parts per million of CO<sub>2</sub>). The doubling date is 2100 in the (cooperative) DICE model, 2070 in the cooperative RICE model, and 2065 in both the market and the noncooperative model. The doubling time for the CO<sub>2</sub> equivalent of all greenhouse gases is slightly earlier than those for CO<sub>2</sub> alone.

The projected increase in global mean temperature over the 1990–2100 period is shown in Figure 4.<sup>10</sup> The estimated temperature increase from the mid-nineteenth century to 2100 is estimated to be 3.06°C in the market run. The cooperative strategy lowers global temperature by 0.22°C in 2100, whereas the noncooperative

<sup>10</sup> The climate model used in the RICE model is a calibrated version of the two-equation Schneider-Thompson model with an equilibrium temperature sensitivity coefficient of 3°C for a doubling of CO<sub>2</sub> concentrations. The derivation of the climate model is discussed in Nordhaus (1994).

strategies reduce warming by considerably less (a reduction of 0.086°C in 2100), both compared to the market strategy. One reason that the difference in the temperature increase between the cooperative and the market runs is so small is because of the long time lag between changes in emissions and temperature increases (the difference between the runs grows over time as the lags in the emissions-concentrations-temperature relationship plays out).<sup>11</sup> Additionally, the difference is small because of the nonlinear relationship between CO<sub>2</sub> concentrations and temperature.<sup>12</sup> But the major rea-

<sup>11</sup> The projected temperature difference between the cooperative and market runs is 0.41°C in 2200 whereas that between the noncooperative and market runs is only 0.12°C in 2200.

<sup>12</sup> More recent estimates of global warming show considerably less near-term warming than earlier estimates (compare the current RICE with the 1992 DICE model). Recent evidence suggests that the cooling effects of sulfates derived primarily from fossil-fuel emissions will lower global mean temperature increases until the end of the next century.

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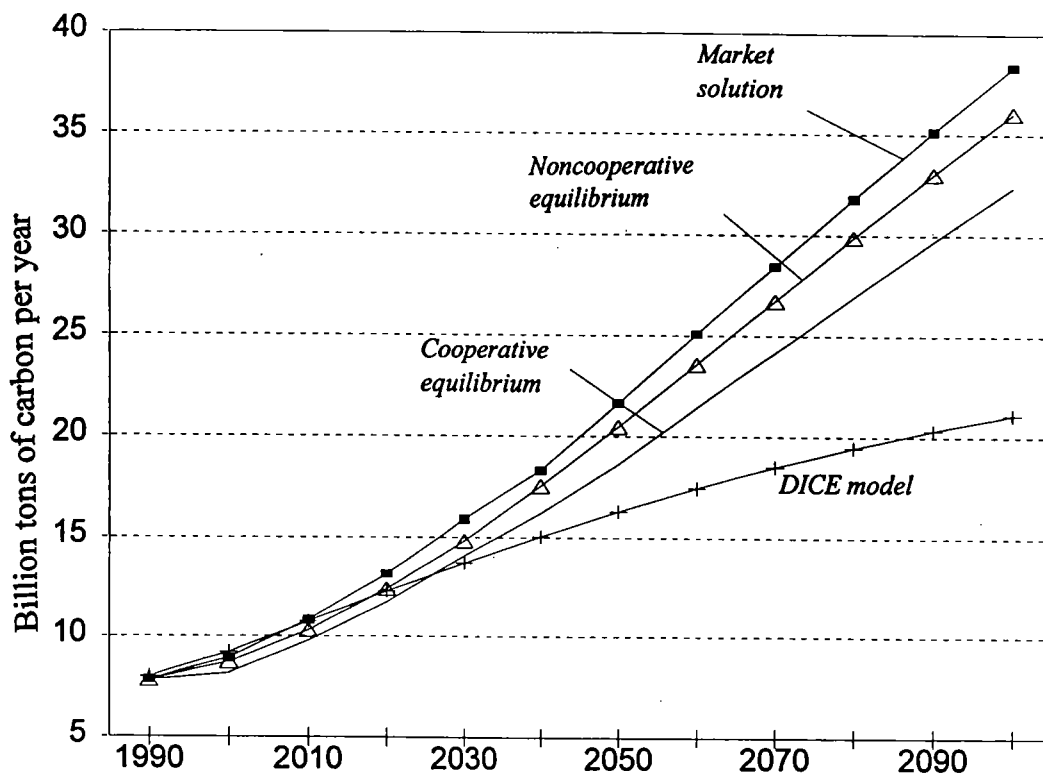


FIGURE 2. CO<sub>2</sub> EMISSIONS: DIFFERENT APPROACHES

son for the small decrease in temperature between the market and cooperative runs is that the high cost of control means that the economically efficient strategy is for only a small reduction in CO<sub>2</sub> emissions.

**B. Policy Variables**

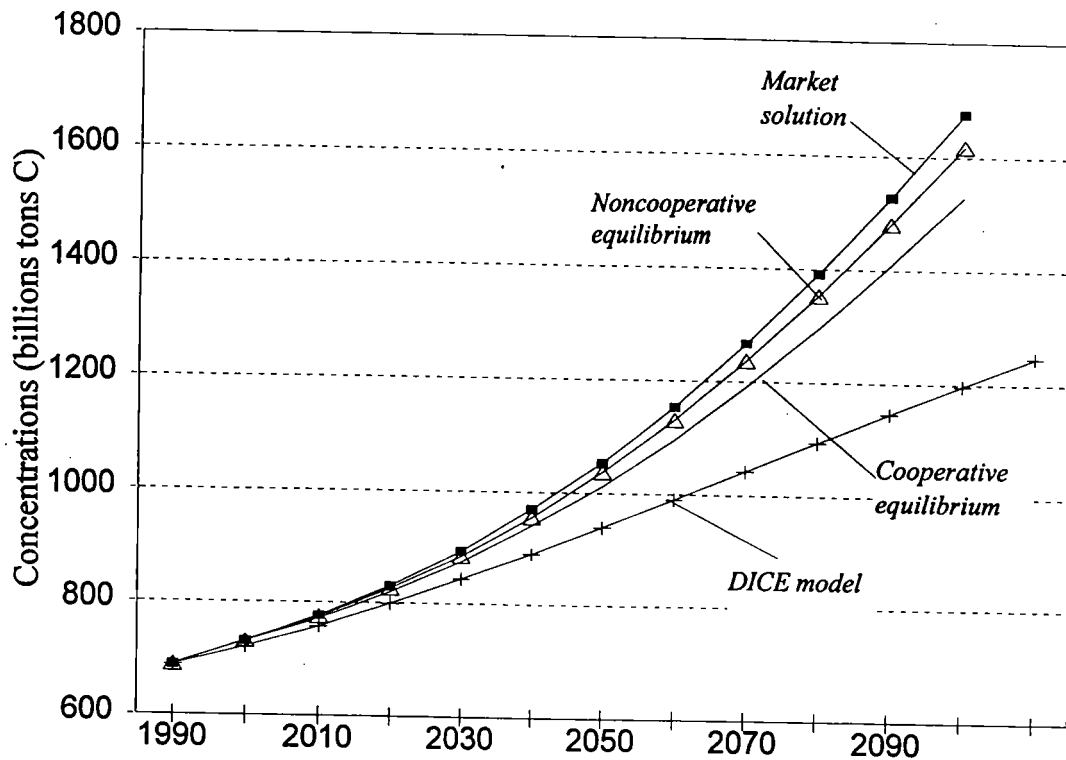
We next examine the policy variables for the different degrees of cooperation among nations (market, noncooperative, and cooperative). The results are shown in terms of both the control rates for CO<sub>2</sub> emissions and the carbon taxes. Carbon taxes should be interpreted as the marginal cost of control of CO<sub>2</sub> whether these are efficiently implemented through taxes, regulations, or tradable permits.

The major results are shown in Figures 5 through 9. The central finding of this study is that the noncooperative policies produce significantly lower control rates and carbon taxes than does global cooperation. The reason is

straightforward: when countries free-ride on the climate-change policies of other countries, then they cut back their own efforts substantially. Begin with the emissions control rates, shown in Figure 5. The global average rate of control of CO<sub>2</sub> is around 10 percent in the cooperative solution. This varies by region, with relatively high controls in China and the former Soviet Union; for these regions, we estimate the marginal costs of control to be relatively low. For the efficient case, the lowest control rates are in Japan and the European Union, which are already relatively energy efficient and where the marginal costs of controls are consequently relatively high. According to the data used in the RICE model, the efficient control rates for 2000 range from 17 percent in China to about 7 percent in Japan. The United States is in the middle of the pack, with an efficient control rate of slightly below 9 percent. The control rates rise over time as the marginal damages from CO<sub>2</sub> emissions rise. (Note that

considerably less, both come from the reason that the increase between market runs is so small. The lag between market and cooperative increases grows over time as concentrations rise (but).<sup>11</sup> Additionally, because of the increase in CO<sub>2</sub> concentrations, the major rea-

between the cooperative runs that between 1.12°C in 2200. The findings show that earlier estimates (the DICE model) are likely to overestimate the effects of emissions until the end of

FIGURE 3. CO<sub>2</sub> CONCENTRATIONS

these relative control rates would be roughly proportional to those shown here if the overall level of controls were raised or lowered.)

One immediate conclusion that comes from this result is that current approaches to combating global warming make no sense from the point of view of pure economic efficiency. The current Framework Convention calls for major emissions reductions in the OECD region with no immediate reductions in the developing countries—this being exactly the opposite of the efficient solution. The only potential rationale for the Framework Convention is that it puts a very high weight on equity (by relieving poor countries of obligations to reduce emissions) and rules out the possibility of side payments (say through allocation of emissions permits).

The control rates in the noncooperative solution are markedly lower (not shown but available from the authors). There are two major findings here. First, the aggregate global emissions control rate for the noncooperative equilibrium is in 2000 only 2.3 percent as compared

with the average of 9.7 percent in the cooperative case. The reason for the lower control rate is completely intuitive: it results from the free-riding wherein each nation ignores the impacts of its CO<sub>2</sub> emissions on the welfare of other nations (as well, of course, as assuming that other nations' efforts are unaffected by its own self-interested behavior). The size of the free-riding effect is the major new result here.

The second interesting conclusion in the noncooperative approach is the distribution of control rates. This model predicts that the largest (albeit small) efforts will be taken by the largest regions—particularly by the United States and the European Union. This prediction seems quite on the mark. It also correctly suggests that developing countries, particularly small and poor countries such as Benin and Kyrgyzstan, will not be in the forefront of global-warming politics.

Figures 6 through 7 show the results for estimated carbon taxes. Looking first at Figure 6, we can compare the aggregate carbon taxes

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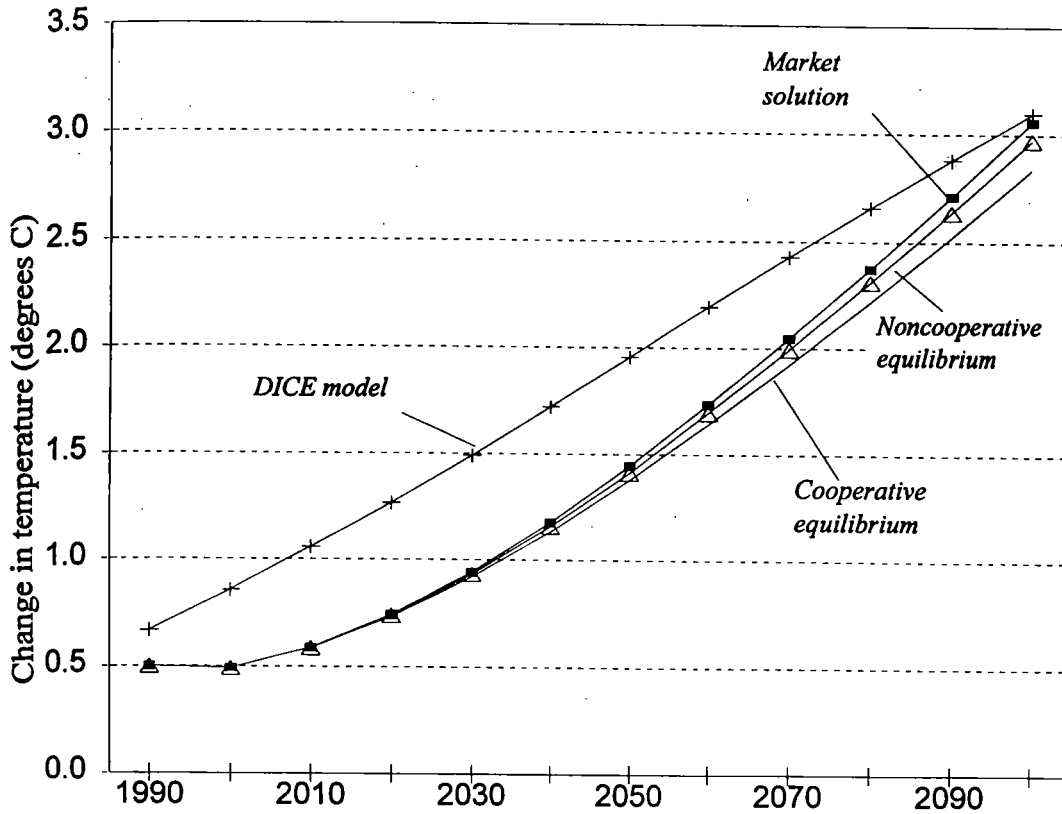


FIGURE 4. TEMPERATURE CHANGE

under different strategies. Note that the cooperative RICE model looks quite similar to the older DICE model (which also found the global optimum). The carbon tax starts slightly higher and grows more rapidly because of the steeper trajectory for emissions. The first-period carbon tax in the cooperative case is \$6.19 per ton carbon in 2000 versus \$5.94 in the DICE model. (Here and throughout, all dollar figures refer to prices in 1990 U.S. dollars at 1990 market exchange rates.)

The cooperative tax rates are significantly higher than the noncooperative or nationalistic policies for all regions and periods. The weighted average carbon tax for the noncooperative policy is 24 cents per ton carbon for the noncooperation equilibrium in 2000. The distribution of carbon taxes for the noncooperative policy is shown in Figure 7. For the noncooperative strategies, large countries tend

to have significantly more (but not very) stringent controls as compared to small countries. The noncooperative carbon taxes are highest in the European Union (\$0.86 per ton in 2000) and the United States (\$0.65 per ton in 2000). The difference reflects the slightly larger output in the European Union. For smaller countries, the tax rates are much smaller: 10 cents per ton in India, and only 1 cent per ton in the S4 group of countries.

It seems appropriate to conclude that *outside the United States, Europe, and Japan, the rational noncooperative strategy would be simply to ignore global warming at the present time*. Even by the end of the 21st century, no country acting in a noncooperative framework would have carbon taxes above \$2 per ton C. If we define the "cooperation ratio" as the ratio of the noncooperative carbon tax to the cooperative carbon tax, we can calculate that

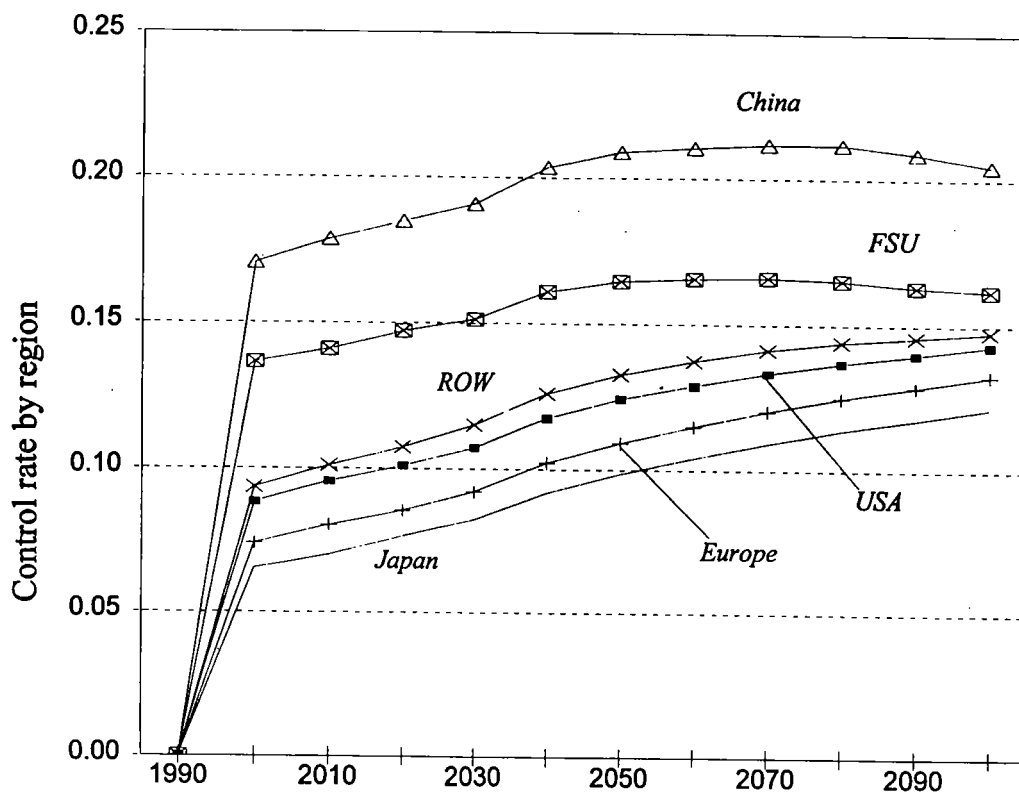


FIGURE 5. CO<sub>2</sub> CONTROL RATES:  
COOPERATIVE SCENARIO

this ratio ranges from essentially zero in the smallest countries to between 10 and 15 percent for the United States and Europe.

What happens to the cooperation ratio over time? According to our calculations, the degree of cooperation is expected to fall in the noncooperative solution. Cooperation in the Nash equilibrium decreases as the extent of inequality of country income falls. Hence, the extent of cooperation is calculated to decline slightly over the next four decades as the share of the United States, Japan, and Europe declines and the distribution of economic sizes of nations becomes more equal. *Greater equality leads to smaller incentives to be a good global citizen.*

For small countries (with GDPs of under \$20 billion) the noncooperative optimal control rates and carbon taxes are minuscule, \$0.01 per ton carbon versus \$5.98 in the global cooperative case. While the taxes in the noncooperative strategies are significantly lower

than those in the global cooperative strategies, some have expressed surprise that they are not even lower. The reason is that there are a few countries or regions (notably the United States, China, Japan, and Europe) which are large enough so that it is their own self interest to reduce CO<sub>2</sub> emissions even ignoring the benefits to other countries. Were China to break up, were Europe to make decisions on a national level, or were the Republican Revolution in the United States to devolve environmental decisions to the states, the predicted degree of cooperation would be even lower.

There are a few other intriguing details of the runs worth noting. China is definitely a key player and exhibits a different pattern. Figure 5 shows that China has the highest cooperative control rates of all the regions—this reflecting the relatively high CO<sub>2</sub> emissions per unit output (see Table 2). But countries which are hardly players today (India, China, and the

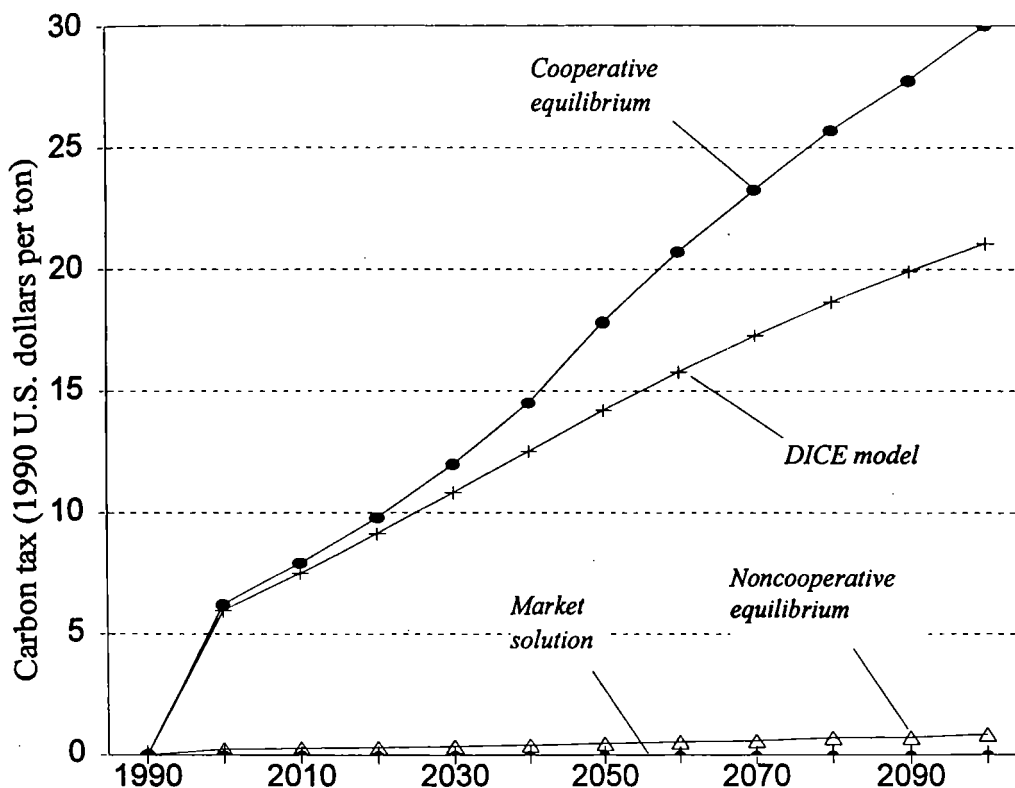


FIGURE 6. AVERAGE CARBON TAXES

smaller developing countries) dominate CO<sub>2</sub> emissions by the middle of the next century and will have to behave cooperatively if the gains from cooperation are to be realized.

### C. Welfare Effects by Region

What are the overall economic effects by region? The gain to cooperation is calculated as the present value of the change in consumption valued using the region-specific discount rates on consumption (not to be confused with the pure rates of social time preference, or discount rates on utility, which are equal across regions). The discount rates in this calculation are region and time specific, and they average about 4½ percent per year (in real terms) over the next century. In these runs, there are no international transfers, which essentially means that each country

is assigned its optimal policy without any side payments from other countries. This is equivalent to each country receiving in the cooperative equilibrium a quota of tradable emissions permits equal to the quantity of its own emissions.

The resulting impacts upon economic welfare are shown in Table 4. Note first that the overall results from the cooperative RICE solution are quite close to those of the original DICE model. The former is about one quarter higher because of the higher growth rates in the RICE model. By contrast, the noncooperative, six-region RICE model shows extremely slim net benefits—only \$43 billion in discounted benefits as opposed to \$344 billion for the cooperative RICE or \$271 for the cooperative DICE model.

Figure 8 shows the gains to different regions for the cooperative and noncooperative cases.

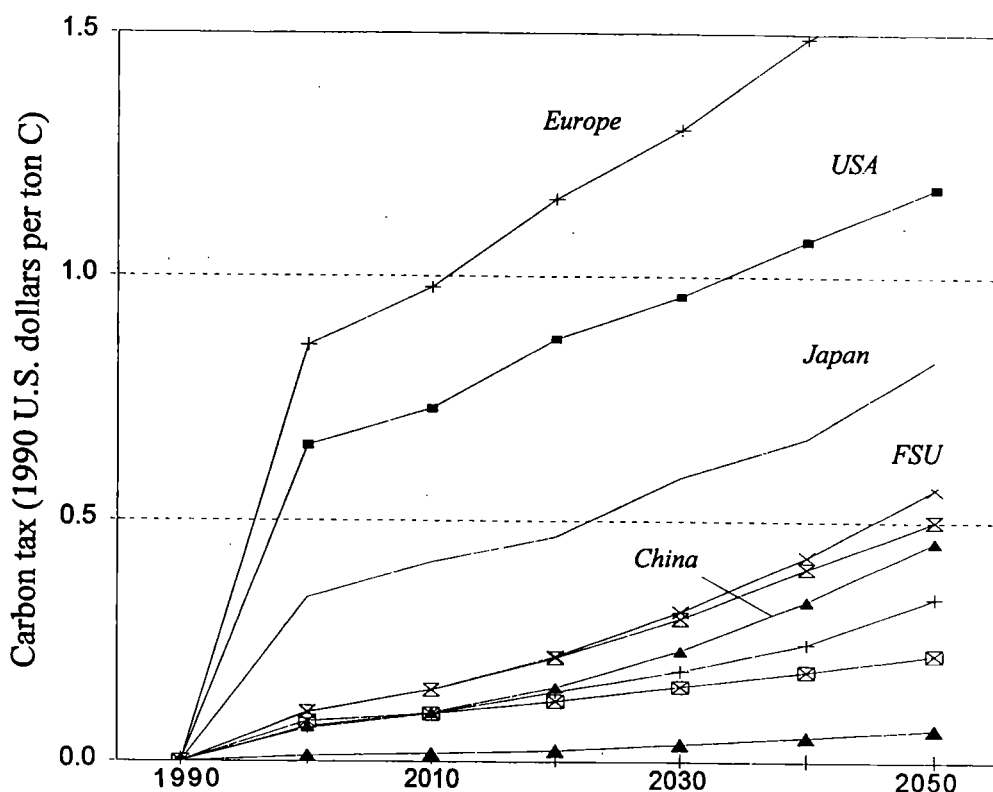


FIGURE 7. NONCOOPERATIVE CARBON TAXES

Table 4 and Figure 8 present a number of surprises in the regional results. The noncooperative solution produces positive net benefits relative to the market solution for all regions. This result is expected because the noncooperative policies improve welfare while the external interactions among countries are ones that are beneficial relative to the market case. The net benefits in the noncooperative case are relatively uniform across the different regions, with most of the positive effects coming from the reductions in damage from climate change.

The major surprise in these results is the lopsided benefits from the cooperative strategy. *The United States actually loses in the cooperative solution relative to the noncooperative equilibrium.* The reason is that, with its relatively large emissions, the United States would be slated to incur major costs today, while its benefits would be relatively small given its declining share of the world economy. Similarly, the former Soviet Union has quite modest net

benefits in the cooperative strategy because it is required to undertake significant mitigation efforts and has few benefits because of its northerly location. By contrast, the ROW region reaps major net benefits from the cooperative solution because the mitigation efforts are undertaken primarily in the high-income countries early in time while the major benefits in terms of damages avoided accrue to the developing countries in several decades.

These results indicate that the cooperative solution—one in which nations are allocated emissions equals to their efficient emissions—might well not emerge as the outcome of a bargaining process in which nations will only sign on to an agreement that improves their economic welfare. Of course, the pattern of net gains can in principle be altered through different schemes for allocating emissions rights to countries (that is, by adding side payments to the program analyzed here); the gains and losses could be made much more equal over

TABLE 4—NET BENEFITS OF DIFFERENT STRATEGIES BY REGION RELATIVE TO THE MARKET EQUILIBRIUM  
(BILLIONS OF 1990 U.S. DOLLARS, DISCOUNTED TO 1990)

Strategy	Net benefits by region						Total
	United States	Japan	China	European Union	Former Soviet Union	Rest of world	
Market	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Noncooperative	2.9	3.6	8.7	7.9	2.7	16.5	42.5
Cooperative	0.8	46.3	39.4	28.5	4.1	224.8	343.8
DICE (cooperative) <sup>a</sup>	na	na	na	na	na	na	271.0

Note: Each entry indicates the net benefits for a region relative to the market or uncontrolled strategy. NA is not available.  
<sup>a</sup> From the aggregate DICE model in Nordhaus (1994).

space and time through different allocations or side payments. Determining possible bargaining outcomes is, however, a difficult empirical issue that is outside the scope of the present paper and is the subject of current research by the authors. What this study examines is the set of national emissions that is consistent with an efficient allocations of emissions over space and time. The interesting new result of this paper is that a scheme with no side payments will reduce the standards of living of all major regions for at least half a century and will reduce the discounted net welfare of the United States when all time periods are considered. Moreover, it is interesting to note that all the emission-rights allocations proposals that are currently under consideration are even more unfavorable to the United States than the one underlying the cooperative equilibrium and are therefore even less likely to be acceptable to high-income countries than the program examined here.

What is the time profile of benefits? Figure 9 shows the time paths of *discounted cumulative consumption* in different regions. More precisely, the numbers are the sum of the consumption differences between the cooperative strategy and the market strategy from the beginning of the period (1990) until the date shown on the horizontal axis. For each region, the consumption figures are discounted back to 1990 and the discount rate is the region-specific and variable discount rate on consumption.

This figure shows the problem of global warming in a nutshell. It indicates how each region would experience the economic impacts of a cooperative strategy relative to the

market solution through different time periods. For example, it shows that the United States would have a cumulative discounted consumption loss from cooperation relative to the market of \$12 billion through 2050. *The calculation indicates that a cooperative global-warming accord would reduce the cumulative discounted consumption of all countries except Japan through 2050.* The ROW region suffers major losses, approaching a total of \$100 billion by mid-century. Moreover, as can be seen by adding the numbers for the different regions together, there is still a negative effect on cumulative global consumption by the middle of the next century.

On a longer time scale (not shown), the ROW breaks even by the end of the next century and is the major beneficiary after that point. The United States and the former Soviet Union experience a reduction in discounted cumulative consumption through the end of the next century. All the curves are heading up at the end of the period, and the discounted cumulative totals over the 250-year estimation period, shown in Table 4, are positive for all regions and quite large for the ROW region.

The estimates of the regional costs and benefits in the RICE model are sensitive to parameters of the mitigation-cost and climate-damage functions, but the major determinant of the patterns is initial emissions and growth of output, which are considerably more secure than the cost and damage estimates. The basic dilemma is clear: the long period between emissions reductions and reduced climate damage means that countries must be extraordinarily farsighted. In addition, the pattern of

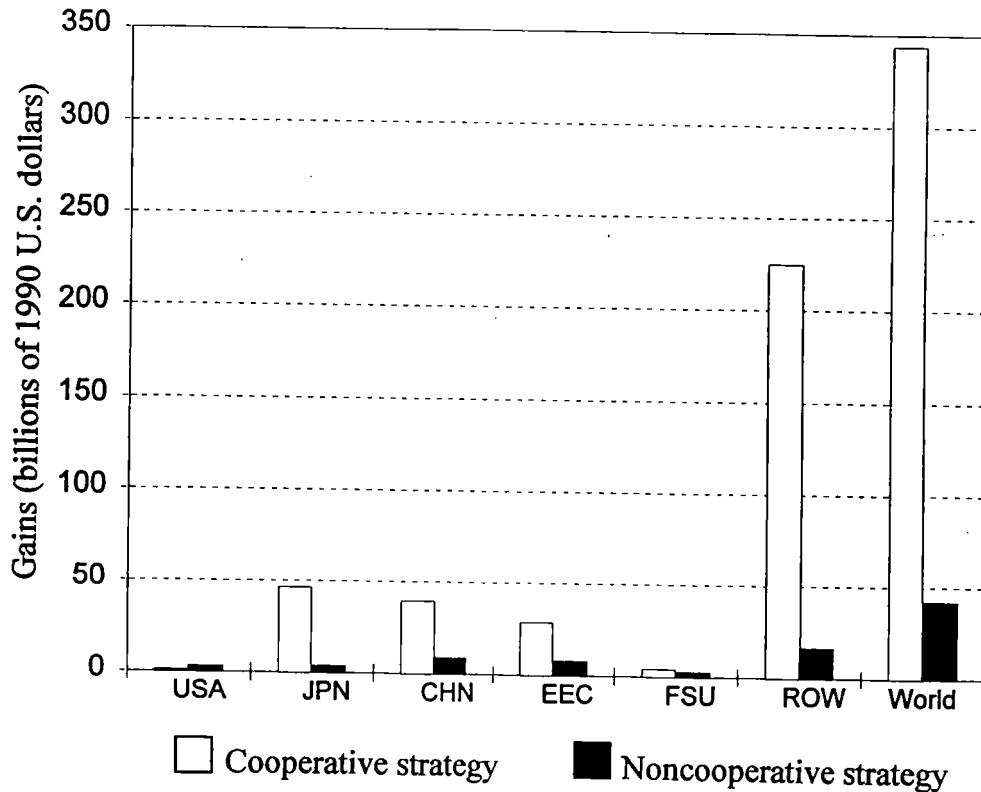


FIGURE 8. GAINS FROM CLIMATE-CHANGE POLICY:  
COOPERATIVE AND NONCOOPERATIVE POLICIES (TOTAL GAINS DISCOUNTED TO 1990)

gains and losses, with the major long-run gains coming to developing countries while the net benefits to the United States and the former Soviet Union are minimal, is a most surprising and troubling finding.

#### D. Sensitivity Analysis

To understand the full range of outcomes and policy responses to the threat of global warming, we must assess the fact that many of the underlying processes are imperfectly understood. Social scientists have developed a variety of tools to incorporate uncertainty into quantitative modeling, and these can help put bounds on potential future outcomes.<sup>13</sup> Although

<sup>13</sup> See M. Granger Morgan and Max Henrion (1990) for a recent survey of tools for the analysis of uncertainty in quantitative risk and policy analysis.

uncertainties are often critical to determining policies, formal techniques for determining the uncertainty of future trajectories or of impacts have been rarely applied to major policy issues.<sup>14</sup>

A full-scale analysis of the uncertainties associated with the RICE model—including uncertainty about model structure as well as about individual parameters—is beyond the scope of the current article. Many of the central uncertainties have been examined in the context of the DICE model (see Nordhaus,

<sup>14</sup> One notable and controversial example of the systematic application of statistical techniques is the Rasmussen report (Nuclear Regulatory Commission, 1975), which estimated the risk of accidents of different levels of severity in commercial nuclear power plants. An exemplary study used probabilistic assessments for ozone depletion (National Academy of Sciences, 1979).

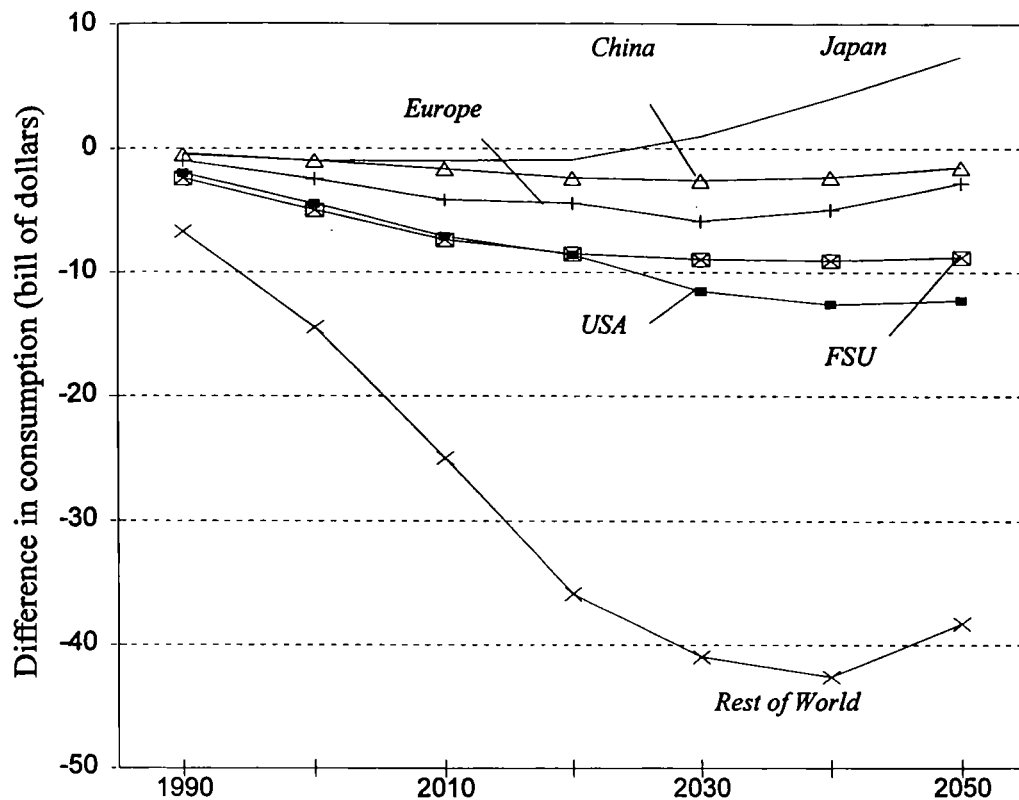


FIGURE 9. CUMULATIVE DISCOUNTED CONSUMPTION: COOPERATIVE VERSUS MARKET STRATEGY (TOTAL GAINS FOR CONSUMPTION THROUGH THE GIVEN DATE, DISCOUNTED BACK TO 1990)

1994 Chapters 6–8), and those results apply equally well to the RICE model. To understand the extent of sensitivity of the model we present here a limited sensitivity analysis with respect to the important parameters of the model. For each of the important parameters of the model (see the description in Appendix A), we have varied the parameter by changing it from the subjective 50th percentile to the subjective 90th percentile.<sup>15</sup> The exact derivation of the uncertainty range was developed

<sup>15</sup> Symbolically, we can represent the RICE model as a mapping,  $Y_t = F(X_{t-1}, \Gamma)$ , where  $Y_t$  is the vector of endogenous and policy variables,  $X_{t-1}$  is a vector of current and lagged exogenous variables, and  $\Gamma$  is the set of uncertain parameters. The base run estimates outcomes for the "best-guess" parameters ( $\Gamma^{50}$ , which represents the 50th percentile of the distribution of the parameters). In

in Nordhaus (1994 Table 6.1), and the reader is referred to that reference for a full discussion.

Figure 10 shows the results of the sensitivity analysis. That figure shows the sensitivity of three important variables in the cooperative equilibrium: the carbon tax in 2000, the efficient reduction of CO<sub>2</sub> emissions in 2000, and the change in global mean temperature in

the sensitivity analyses, we estimate the (subjective) 90th percentile of the distribution,  $\Gamma^{90}$ . Figure 10 shows the ratio of different outcomes for the 90th percentile of a variable to the 50th percentile of that variable; that is,  $\Delta_i = F(X_{t-1}, \Gamma^{90})/F(X_{t-1}, \Gamma^{50})$ , where  $\Delta_i$  is the ratio of outcomes for variables of interest when varying the  $i$ th parameter,  $\Gamma^{90}$  is the vector of  $\Gamma$  with all variables set at their 50th percentile while  $\Gamma^{50}$  is the vector of parameters with all variables but the  $i$ th set at the 50th percentile while the  $i$ th parameter is set at its 90th percentile.

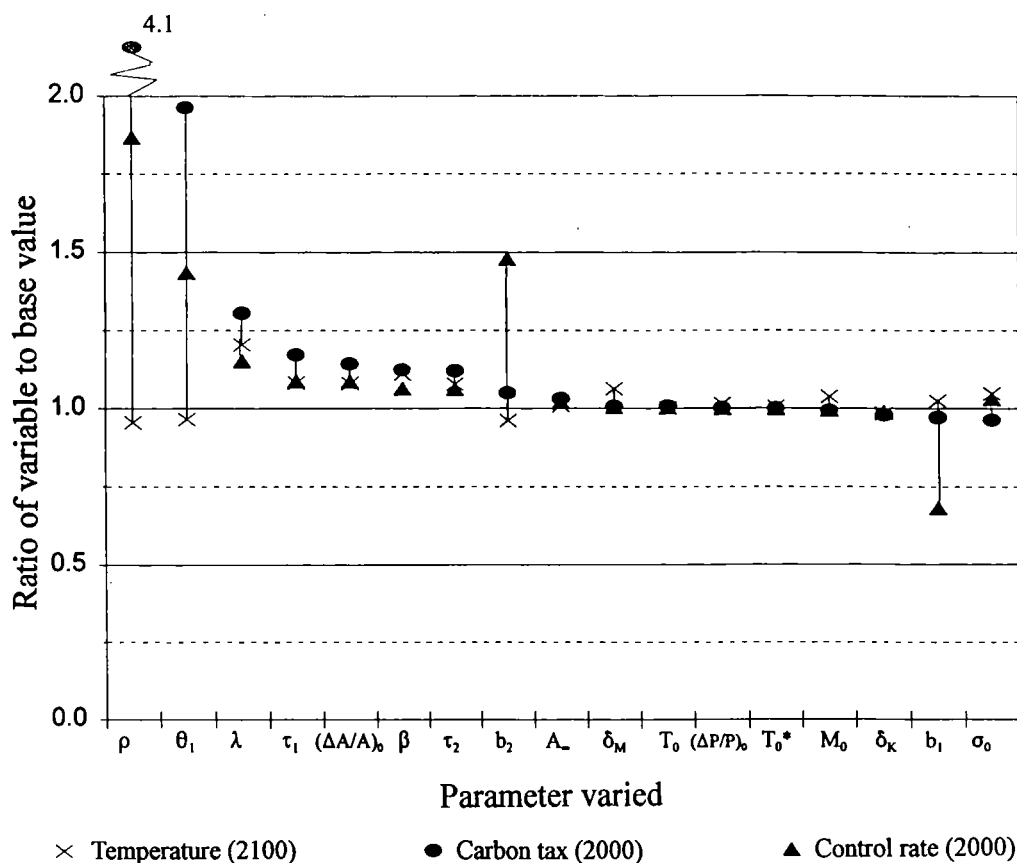


FIGURE 10. SENSITIVITY TESTS FOR PARAMETERS

Note: The variables on the horizontal axis are parameters of the RICE model as defined in Appendix A. The markers indicate the ratio of the outcome variable in the sensitivity case to the outcome for the base case. The sensitivity cases set the values of the variables at the subjective 90th percentile. The outcome variables are the optimal cooperative carbon tax in 2000, the optimal cooperative reduction rate for CO<sub>2</sub> emissions in 2000, and global mean temperature in 2100.

2100. For each of the three variables, we have displayed in Figure 10 the ratio of the value of the variable in the sensitivity run to the value of the variable in the base case.

Figure 10 indicates that the results are extremely sensitive to the pure rate of social time preference. The low rate of time preference (equal to 1 rather than 3 percent per year) increases the carbon tax by a factor of 4 and the control rate by a factor of almost 2. In addition, the damage intercept (which is the fraction of output lost from a doubling of atmospheric CO<sub>2</sub>) leads to a marked increase in both the carbon tax and the control rate. The other

variables are relatively unimportant for the results.<sup>16</sup>

In analyzing model sensitivity, it is easy to become lost in the details. For policy purposes, however, the single most critical question is how an uncertainty affects *current policy*, which is best seen in the effect on the carbon tax. By this standard, the two crucial parameters are the discount rate (which indicates the

<sup>16</sup> These results parallel closely the findings of other studies on the sensitivity of policy to uncertainties about major variables.

relative importance of the future compared to the present) and the damages from climate change (which measure the willingness to pay to prevent or slow climate change). *It is interesting to note that both major uncertainties involve human preferences rather than pure questions of "fact" about the natural sciences.*

### III. Conclusions

To summarize, this paper has presented the RICE model, which is a new dynamic, multi-region, general-equilibrium model of climate and the economy. It differs from earlier work, which focussed on a globally aggregated approach, by introducing production, consumption, emissions, and damages for different regions. This approach compares three different strategies for the control of global warming: a market approach in which no climate change policies are taken, a global cooperative approach in which all countries choose climate-change policies to maximize global incomes, and a noncooperative or nationalistic approach in which each country takes policies to maximize its own national income. These results are tentative and subject to revision. Further work will be necessary to test their robustness against alternative assumptions, to appraise the results for different coalitions, and to compare the results against other models. Subject to these reservations, the following are the major conclusions.

First, the model produces results for the baseline (market or uncontrolled) which differ significantly from other projections.<sup>17</sup> Output and emissions in the RICE model are estimated to grow much more rapidly than in the DICE model or than in many international projections (such as that of the Intergovernmental Panel on Climate Change). The more rapid growth comes largely from a view of the growth process in which there is considerable but incomplete convergence of per capita incomes of countries. The higher projected growth of output, emis-

sions, and CO<sub>2</sub> concentrations as compared with the earlier DICE model is largely offset by revisions in estimated effects of other greenhouse gases. As a result the estimated extent of global warming in the market case by the year 2100—approximately 3°C—differs little between the RICE model and other estimates.

Second, the efficient or cooperative policies in the regional model confirm estimates made in globally aggregated models, such as the DICE model. The best summary variable for efficient controls is the carbon tax, which is calculated to be about \$6 per ton carbon in 2000, a number that is virtually identical to estimates for the efficient policy in the DICE model.<sup>18</sup> The estimated degree of control in the RICE model is, however, estimated to grow somewhat more rapidly than in the DICE and other models, with estimated efficient carbon taxes at the end of the next century near \$27 per ton carbon.

Third, the RICE model provides estimates of the efficient control rates in different regions as well. In the efficient solution, carbon taxes are identical in all regions. The control rates will differ, however, because of different costs of reducing CO<sub>2</sub> emissions. The estimates presented here indicate that the efficient emissions control rates will be highest in China and the former Soviet Union and lowest in Japan and Europe, with the differences being at least a factor of two. These results indicate that there will be substantial inefficiencies in any policy (such as that currently in force under the Framework Convention) that equalizes emissions control rates across countries or does not allow trading of emissions permits.

Fourth, a major contribution of this study is to estimate the difference between the efficient policy and the noncooperative policy. The noncooperative or nationalistic policy is one in which countries maximize their economic welfare taking policies of other countries as given. This implies that small countries, whose climate-change policies have little effect on their own economic

<sup>17</sup> In the discussion that follows, the results for the DICE model refer to DICE-123 as presented in Nordhaus (1994).

<sup>18</sup> All dollar figures refer to prices in 1990 U.S. dollars at 1990 market exchange rates.

welfare, will have little incentive to reduce emissions while the largest countries will have greatly attenuated incentives to engage in costly reductions in CO<sub>2</sub> emissions. The calculations here indicate that the controls in the noncooperative case (as measured by the average rate of carbon tax) will be only  $\frac{1}{25}$  of the level of the cooperative case. That is, while the average carbon tax in 2000 is estimated to be about \$6 per ton carbon in the cooperative case, it is calculated to be about \$0.24 per ton in the noncooperative case. Moreover, the divergence between the cooperative and the noncooperative policies is calculated to increase over time as the inequality of country sizes decreases, and this divergence would increase further if large countries like China, India, Russia, Canada or the United States splinter into smaller countries or decision-making units.

Fifth, these results indicate that the stakes in controlling global warming are modest in the context of overall economic activity over the next century. If our estimates are accurate, they indicate that the losses from global warming will be in the range of 1 to 2 percent of global income over the next century. The net costs (that is, climate-change damages less mitigation costs) can be reduced by perhaps  $\frac{1}{3}$  percent of income by a judicious choice of climate-change policies—although, to be sure, the impact is much greater on our descendants than on ourselves. According to RICE, successful cooperation would lead to net gains, but the failure to cooperate is unlikely to lead to economic disaster over the next century.

Sixth, the pattern of gains and losses from different strategies is quite surprising. All countries gain from the noncooperative approach, although the amount of gain is relatively small. The net gains from cooperation without international transfers are quite unevenly distributed, with the major gains accruing to developing countries with low and rapidly growing emissions. High-income countries have but modest gains to cooperation, but the United States actually loses from cooperating relative to a noncooperative strategy. In addition, the time path of gains and losses indicates that even in the cooperative scenario, all regions except

Japan show reductions in cumulative discounted consumption until after the middle of the next century.

Seventh, the results indicate that there are major gains to taking an efficient cooperative approach to coping with global warming as opposed to the noncooperative approach. We estimate that the net economic gain from an efficient policy has a discounted value of \$344 billion relative to the market scenario, while the noncooperative policy has a gain of only \$43 billion. Hence, there are clear gains to attaining a cooperative policy (assuming, of course, that the policy is itself efficient). The gains from cooperation would be even larger if climate change proved to have catastrophic consequences that are very unevenly felt across nations.

In sum, the results of this new integrated model of climate and the economy emphasizes the implications of the fact that while climate change is a global externality, the decision makers are national and relatively small. These inherent difficulties involved in planning over a horizon of a century or more about so uncertain and complex a phenomenon are compounded by the dispersed nature of the decisions and the strong tendency for free-riding by nonparticipants in any global agreement. Countries may therefore be triply persuaded not to undertake costly efforts today—first because the benefits are so conjectural, secondly because they occur so far in the future, and third because no individual country can have a significant impact upon the pace of global warming. The present study indicates that the third of these, the dispersed nature of the decision making and the consequent diluted incentives to act, is a powerful hindrance to setting efficient climate-change policies.

#### APPENDIX A: EQUATIONS OF THE RICE MODEL

This appendix gives the details of the RICE model. We first list and define the variables and then provide the complete equation listing.

##### 1. Variables

The variables are as follows. In the listing,  $t$  always refers to time ( $t = 1990, 2000, \dots$ ) while  $i$  refers to the region ( $i = 1, \dots, n = \text{USA, Japan, Europe, } \dots$ ). The regional definition is given in Appendix B.

VC  
A,  
P,  
i  
O(  
  
 $\alpha =$   
 $b_{i,t}$   
 $\beta =$   
 $\epsilon$   
 $\gamma =$   
 $\delta_K$   
 $\delta_M$   
 $\tau$   
 $\lambda =$   
 $t$   
 $\rho =$   
 $\sigma_i$   
 $\tau_{i,t}$   
 $f$   
 $F$   
 $t$   
 $\theta_{i,t}$   
  
 $i$   
 $C_i$   
 $c_i$   
CA  
 $D_i$   
 $E_i$   
EX  
 $F_i$   
 $c$   
 $\Omega_i$   
 $a$   
 $K_i$   
IM,  
 $M_i$   
 $i$   
NF  
 $\phi_i$   
 $Q_i$   
 $R_i$   
 $T_i$   
 $l$   
 $T^*$   
 $l$   
 $u_i$   
 $W =$   
 $s$   
 $Y_i$   
 $d$   
  
 $l$   
 $I_i$   
 $\mu_i$

*Exogenous Variables.*

$A_i(t)$  = level of technology  
 $P_i(t)$  = population at time  $t$ , also proportional to labor inputs  
 $O(t)$  = forcings of exogenous greenhouse gases

*Parameters.*

$\alpha$  = elasticity of marginal utility of consumption  
 $b_{1,i}, b_2$  = parameters of emissions-reduction cost function  
 $\beta$  = marginal atmospheric retention ratio of CO<sub>2</sub> emissions  
 $\gamma$  = elasticity of output with respect to capital  
 $\delta_K$  = rate of depreciation of the capital stock  
 $\delta_M$  = rate of transfer of CO<sub>2</sub> from atmosphere to other reservoirs  
 $\lambda$  = feedback parameter in climate model (inverse to temperature-sensitivity coefficient)  
 $\rho$  = pure rate of social time preference  
 $\sigma_i(t)$  = CO<sub>2</sub> emissions/output ratio  
 $\tau_1, \tau_2, \tau_3, \tau_4$  = parameters of climate equation ( $\tau_1$  is a function of the heat capacity of the atmosphere and upper ocean while  $\tau_2$  depends upon the turnover time between the upper ocean and the deep ocean)  
 $\theta_{1,i}, \theta_2$  = parameters of climate damage function

*Endogenous Variables.*

$C_i(t)$  = total consumption  
 $c_i(t)$  = per capita consumption  
 $CA_i(t)$  = current account balance  
 $D_i(t)$  = damage from greenhouse warming  
 $E_i(t)$  = CO<sub>2</sub> emissions  
 $EX_{i,j}(t)$  = exports from region  $i$  to region  $j$   
 $F(t)$  = radiative forcing from all greenhouse gas concentrations  
 $\Omega_i(t)$  = output scaling factor due to emissions controls and to damages from climate change  
 $K_i(t)$  = capital stock  
 $IM_{i,j}(t)$  = imports from region  $i$  to region  $j$   
 $M(t)$  = increase in mass of CO<sub>2</sub> in atmosphere from pre-industrial level  
 $NFA_i(t)$  = net foreign assets of country  $i$   
 $\phi_i$  = welfare weight on country  $i$   
 $Q_i(t)$  = gross domestic or regional product  
 $R(t)$  = net rate of return on capital  
 $T(t)$  = atmospheric temperature relative to preindustrial level  
 $T^*(t)$  = deep ocean temperature relative to preindustrial level  
 $u_i(t) = u_i[c_i(t)]$  = utility of per capita consumption  
 $W$  = social welfare function determined by country consumption levels  
 $Y_i(t)$  = gross national or regional product (net of climate damage and mitigation costs)

*Policy Variables.*

$I_i(t)$  = gross investment  
 $\mu_i(t)$  = rate of emissions reduction

*2. Equations*

$$(A1) \quad \max_{c_i(t)} W = \sum_{t=0}^T \sum_{i=1}^n \frac{\phi_i U^i[c_i(t), P_i(t)]}{(1+\rho)^t}$$

$$= \sum_{t=0}^T \sum_{i=1}^n \frac{\phi_i P_i(t) [c_i(t)^{1-\alpha} - 1]}{(1-\alpha)(1+\rho)^t}$$

subject to

$$(A2) \quad Q_i(t) = A_i(t) K_i(t)^\gamma P_i(t)^{1-\gamma}$$

$$(A3) \quad Y_i(t) = \Omega_i(t) Q_i(t)$$

$$(A4) \quad C_i(t) = Y_i(t) - I_i(t) + \sum_{j \neq i}^n IM_{i,j}(t)$$

$$- \sum_{j \neq i}^n EX_{i,j}(t)$$

$$(A5) \quad c_i(t) = \frac{C_i(t)}{P_i(t)}$$

$$(A6) \quad K_i(t) = (1 - \delta_K) K_i(t-1) + I_i(t)$$

$$(A7) \quad E_i(t) = [1 - \mu_i(t)] \sigma_i(t) Q_i(t).$$

$$0 \leq \mu_i(t) \leq 1.$$

$$(A8) \quad M(t) = \beta \sum_{i=1}^n E_i(t) + (1 - \delta_M) M(t-1)$$

$$(A9) \quad T(t) = T(t-1) + \frac{\tau_1 [F(t) - \lambda T(t-1)] - \tau_2 [T(t-1) - T^*(t-1)]}{\tau_3}$$

$$(A10) \quad T^*(t) = T^*(t-1) + \frac{T(t-1) - T^*(t-1)}{\tau_4}$$

$$(A11) \quad F(t) = \frac{4.1 \log[M(t)/M(0)]}{\log(2)} + O(t)$$

$$(A12) \quad \Omega_i(t) = \frac{1 - b_{1,i} \mu_i(t)^{b_2}}{1 + \theta_{1,i} T(t)^{\theta_2}}, \quad i = 1, 2, \dots, n.$$

$$(A13) \quad R(t) = \frac{\sum_{i=1}^n \gamma Q_i(t)}{\sum_{i=1}^n K_i(t)} - \delta_K$$

$$(A14) \quad NFA_i(t) = NFA_i(t-1) + CA_i(t-1)$$

$$(A15) \quad CA_i(t) = R(t) NFA_i(t) + \sum_{j \neq i}^n IM_{i,j}(t) - \sum_{j \neq i}^n EX_{i,j}(t)$$

$$(A16) \quad -CA_i(t) \leq 0.1 Q_i(t)$$

$$(A17) \quad -NFA_i(t) \leq 0.1 Q_i(t)$$

$$(A18) \quad \sum_{j \neq i}^n EX_{i,j}(t) \leq Q_i(t).$$

## APPENDIX B: REGIONAL GROUPING IN THE RICE MODEL

Country or group	Number of countries	Gross domestic product (millions of 1990 US \$)	Population, 1990 (thousands)	CO <sub>2</sub> emissions, 1990 (millions of tons C)
1) United States	1	5,464,796	250,372	1,370.0
2) Japan	1	2,932,055	123,537	291.5
3) Former Soviet Union	1	855,207	289,324	1,065.7
4) China	1	370,024	1,133,683	805.5
5) Europe	1	6,828,042	366,497	872.3
6) Huge	1	295,760	849,515	215.4
7) Large	2	586,072	327,274	593.0
8) Midsized	11	2,155,910	442,370	789.7
9) Small	38	1,272,414	876,027	1,212.0
10) Tiny	137	318,464	607,503	623.9
Total				
Bottom 5 groups (ROW)		21,078,746	5,266,102	7,839.1
		4,628,621	3,102,689	3,434.0

Selected countries in groups 6 through 10:

Code	Country	Gross domestic product (millions of 1990 US \$)	Population, 1990 (thousands)	CO <sub>2</sub> emissions, 1990 (millions of tons C)
S1	India	295,760		
S2	Brazil	479,214	849,515	215.4
	Indonesia	106,859	149,042	317.1
S3	Canada	566,694	178,232	275.9
	Australia	296,053	26,522	127.6
	Mexico	244,046	17,045	72.1
	Argentina	141,353	81,724	144.1
	Turkey	108,447	32,322	33.1
	South Africa	101,963	56,098	35.3
S4	Venezuela	48,599	37,959	78.0
	Romania	37,625	19,325	43.0
	Nigeria	35,460	23,200	59.4
	Egypt	35,400	96,203	95.9
	Slovenia	17,331	52,426	22.3
S5	Kenya	8,675	2,000	4.8
	Iceland	6,024	24,160	5.0
	Honduras	2,944	255	0.5
	Maldives	174	5,105	12.0
	Anguilla	23	214	0.0*
	Tuvalu	5	7	0.0*
			9	0.0*

\* Less than 50,000 tons per year.

## REFERENCES

- Bodansky, Daniel M. "Emerging Climate Change Regime." *Annual Review of Energy and the Environment*, 1995, 20, forthcoming.
- Brooke, Anthony; Kendrick, David and Meeraus, Alexander. *GAMS: A user's guide*. Redwood City, CA: The Scientific Press, 1988.
- Dean, Andrew and Hoeller, Peter. *Costs of reducing CO<sub>2</sub> emissions: Evidence from six global models*, OCDE/GD(92)140, Organization for Economic Cooperation and Development, Paris, processed 1992.
- EMF, Energy Modeling Forum 14. "Background Papers" and "Tabulations of Model Runs." Unpublished, 1995.
- Fankhauser, Samuel. "The Economic Costs of Global Warming: Some Monetary Estimates," in Y. Kaya, N. Nakicenovic, W. D. Nordhaus, and F. L. Toth, *Costs, impacts, and benefits of CO<sub>2</sub> mitigation*. Laxenburg, Austria: International Institute for Systems Analysis, Laxenburg, Austria, CP-93-2, 1993.

EMBER

CO <sub>2</sub> emissions (millions of tons)
1,370.0
291.7
1,065.7
805.3
872.3
215.4
593.0
789.7
1,212.0
623.9
7,839.1
3,434.0

CO <sub>2</sub> emissions (millions of tons)
215.4
317.1
275.9
127.6
72.1
144.1
33.1
5.3
3.0
43.0
59.4
95.9
22.3
4.8
5.0
0.5
12.0
0.0
0.0
0.0

W. and Weyant, John P. "EMF-12: Comparisons of the Costs of Reducing CO<sub>2</sub> Emissions." *American Economic Review*, May 1993, 83(2), pp. 318-23.

Intergovernmental Panel on Climate Change (IPCC). *Climate change: The IPCC scientific assessment*. J. T. Houghton, G. J. ... and J. J. Ephraums, eds. New York: Cambridge University Press, 1990.

International Energy Agency (IEA). *Climate change policy initiatives: 1994 update, Vol. 1*. Paris: Organization of Economic Cooperation and Development, 1994.

..., Alan S. and Richels, Richard. *Buying greenhouse insurance: The economic costs of CO<sub>2</sub> emission limits*. Cambridge, MA: MIT Press, 1992.

..., Alan S. and Rutherford, Thomas F. "International Trade, Capital Flows and Sectoral Analysis: Formulation and Solution of Intertemporal Equilibrium Models," in W. W. Cooper and A. B. Whinston, eds., *New directions in computational economics*. Dordrecht, Netherlands: Kluwer, 1994, pp. 191-205.

..., Andreu; Whinston, Michael D. and Green, Jerry R. *Microeconomic theory*. New York: Oxford University Press, 1995.

Morgan, M. Granger and Henrion, Max. *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis*. New York: Cambridge University Press, 1990.

National Academy of Sciences. *Stratospheric ozone depletion by halocarbons: Chemistry and transport*. Report of a committee of the National Research Council, National Research Council, Washington, DC, 1979.

Negishi, T. "Welfare Economics and the Existence of an Equilibrium for a Competitive Economy." *Metroeconomica*, 1960, 12, pp. 92-97.

Nordhaus, William D. "An Intertemporal General-Equilibrium Model of Economic Growth and Climate Change," in Wood, David, ed., *Proceedings of a Conference at MIT*, October 1990.

\_\_\_\_\_. "To Slow or Not to Slow: The Economics of the Greenhouse Effect." *Economic Journal*, July 1991, 101(407), pp. 920-37.

\_\_\_\_\_. "An Optimal Transition Path for Slowing Climate Change." *Science*, November 20, 1992, pp. 1315-19.

\_\_\_\_\_. *Managing the global commons: The economics of the greenhouse effect*. Cambridge, MA: MIT Press, 1994.

Nuclear Regulatory Commission. *Reactor safety study: An assessment of accident risks in U.S. Commercial nuclear power plants*, NUREG-75/014 WASH-1400. Washington, DC: 1975.

Peck, Stephen C. and Teisberg, Thomas J. "CETA: A Model for Carbon Emissions Trajectory Assessment." *Energy Journal*, 1992, 13(1), pp. 55-77.

Wigley, T. M. L. "The Contribution from Emissions of Different Gases to the Enhanced Greenhouse Effect," in Ted Hanisch, ed., *Climate change and the agenda for research*. Boulder, CO: Westview Press, 1994, pp. 193-222.

Yang, Zili. "Essays on the International Aspects of Resource and Environmental Economics." Ph.D. dissertation, Yale University, 1993.

eration and De-  
1992.  
"Background  
Model Runs."  
  
conomic Costs  
Monetary Esti-  
enovic, W. D.  
s, impacts, and  
xenburg, Aus-  
Systems Anal-  
3-2, 1993.