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Emissions Scenarios

COORDINATORS
D. Tirpak (U.S.A.)
P. Vellinga (Netherlands)

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EMISSIONS SCENARIOS

Executive Summary

TASK A

The Response Strategies Working Group (RSWG) of the Intergovernmental Panel on Climate Change (IPCC) formed an expert group to develop scenarios of future emissions of greenhouse gases. These scenarios are to serve as initial reference and guidance for the work of the subgroups of RSWG and as a first basis for analyses by the Science Working Group and the Impacts Working Group.

The scenarios depict five different ways that future emissions of greenhouse gases might evolve over the next century and serve to illustrate the types of changes that would be needed to stabilize emissions while continuing to allow growth and improvement in the standard of living. There are limitations regarding our ability to estimate future rates of population growth, economic growth, and technological innovation and these lend uncertainty to projections of greenhouse gases over long time horizons. Based on this analysis, carbon dioxide (CO_2) emissions and atmospheric concentrations in the years 2025 and 2075 could take the values in Executive Summary Table 2.1.

Executive Summary Table 2.2 contains the future emissions of other greenhouse gases for the five scenarios. Executive Summary Figure 2.1 shows the impact of these emissions on atmospheric concentrations of CO_2 and on the greenhouse effect in total. The impacts range from rapid increases in atmospheric concentrations of greenhouse gases throughout the next century in one scenario to declines in the rate of growth in atmospheric concentrations eventually leading to stabilization by early next century in another scenario. Significant policy changes would be required to achieve the latter scenario, although the specific costs of such policies have not been estimated as part of this analysis.

The first of the scenarios, called the *2030 High Emissions Scenario*, depicts a world in which few or no steps are taken to reduce emissions in response to concerns about greenhouse warming. Continued population and economic growth produces increases in the use of energy and in the rate of clearing of tropical forests. The Montreal Protocol comes

EXECUTIVE SUMMARY TABLE 2.1: **Annual CO_2 Emissions and Atmospheric Concentrations**

Scenario	2025 Emissions (Pg C)	2025 Conc. (ppm)	2075 Emissions (Pg C)	2075 Conc. (ppm)
2030 High Emissions	11.5	437	18.7	679
2060 Low Emissions	6.4	398	8.8	492
Control Policies	6.3	398	5.1	469
Accelerated Policies	5.1	393	3.0	413
Alternative Accelerated Policies	3.8	381	3.5	407

EXECUTIVE SUMMARY TABLE 2.2: Greenhouse Gas Emissions

	2030 High Emissions Scenario					
	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C)	6.0	7.7	11.5	15.2	18.7	22.4
N_2O (Teragrams N)	12.5	14.2	16.4	17.3	17.3	17.6
CH_4 (Teragrams)	540.5	613.9	760.8	899.1	992.0	1062.9
CFC-11 (Gigagrams)	278.3	305.1	244.7	251.5	253.0	253.0
CFC-12 (Gigagrams)	361.9	376.0	302.7	314.1	316.1	316.1
HCFC-22 (Gigagrams)	96.9	522.9	1340.4	2681.3	2961.0	2961.0

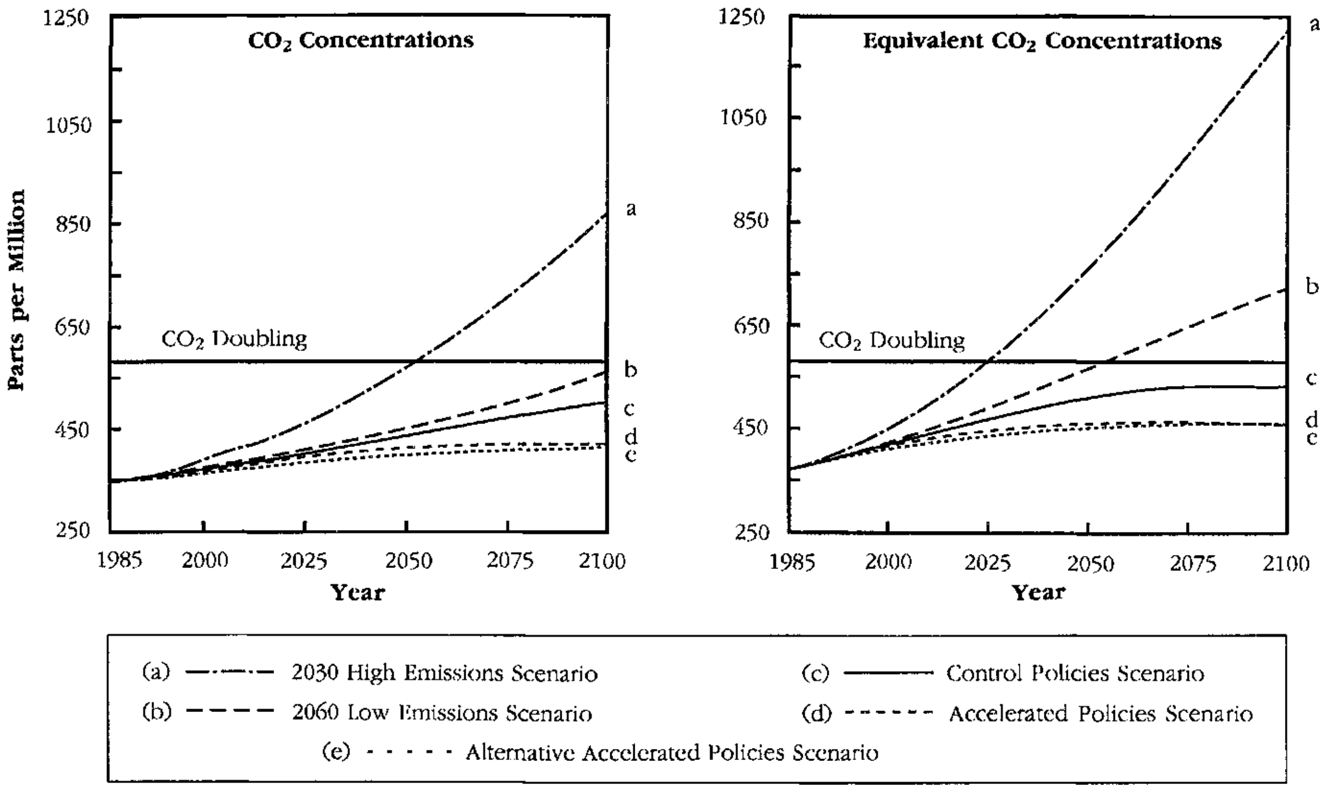
	2060 Low Emissions Scenario					
	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C)	5.9	5.5	6.4	7.5	8.8	10.3
N_2O (Teragrams N)	12.5	13.1	13.9	14.1	14.3	14.6
CH_4 (Teragrams)	540.5	576.8	665.4	723.8	732.4	735.6
CFC-11 (Gigagrams)	278.3	302.1	226.7	223.2	223.2	223.2
CFC-12 (Gigagrams)	361.9	372.2	279.1	277.9	277.9	277.9
HCFC-22 (Gigagrams)	96.9	525.7	1357.2	2707.2	2988.1	2988.1

	Control Policies Scenario					
	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C)	5.9	5.6	6.3	7.1	5.1	3.5
N_2O (Teragrams N)	12.5	12.9	13.2	13.0	12.5	12.2
CH_4 (Teragrams)	540.5	557.9	607.7	621.6	562.0	504.9
CFC-11 (Gigagrams)	278.3	197.1	10.6	0.0	0.0	0.0
CFC-12 (Gigagrams)	361.9	262.2	10.2	0.0	0.0	0.0
HCFC-22 (Gigagrams)	96.9	638.5	1571.9	2927.6	3208.5	3208.5

	Accelerated Policies Scenario					
	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C)	6.0	5.6	5.1	2.9	3.0	2.7
N_2O (Teragrams N)	12.5	12.9	13.1	12.7	12.5	12.3
CH_4 (Teragrams)	540.7	565.8	583.5	553.0	530.1	502.1
CFC-11 (Gigagrams)	278.3	197.1	10.6	0.0	0.0	0.0
CFC-12 (Gigagrams)	361.9	262.2	10.2	0.0	0.0	0.0
HCFC-22 (Gigagrams)	96.9	638.5	1571.9	2927.6	3208.5	3208.5

	Alternative Accelerated Policies Scenario					
	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C)	6.0	4.6	3.8	3.7	3.5	2.6

EXECUTIVE SUMMARY FIGURE 2.1: CO_2 and Equivalent CO_2 Concentrations



into effect but without strengthening and with less than 100 percent compliance. Fossil fuels continue to dominate energy supply, with coal taking a much larger share of energy supply in the future. Emissions of greenhouse gases such as CO_2, CH_4, and N_2O increase continuously throughout the next century with emissions of CO_2 doubling within forty years. Emissions of many of the chlorofluorocarbons stabilize and decline due to compliance to the Montreal Protocol but emissions of substitutes such as HCFC-22 increase. These increases in emissions yield increases in atmospheric concentrations of greenhouse gases with an equivalent greenhouse effect of a doubling of CO_2 concentrations from pre-industrial levels by 2030 and continued increase throughout the rest of the century.

The second of the scenarios, called the *2060 Low Emissions Scenario*, portrays a world in which a number of environmental and economic concerns result in steps to reduce the growth of greenhouse gas emissions. In this scenario, energy efficiency improves more rapidly due to such factors as efficiency standards and technology transfer. Emission controls are adopted globally, reducing emissions of CO and NO_x. The share of primary energy provided by natural gas increases. Full compliance to the Montreal Protocol is realized. Tropical deforestation is halted and a global reforestation effort begins. These steps reduce growth in emissions by 50 to 75 percent and significantly slow down the growth in atmospheric concentrations of greenhouse gases. CO_2 emissions do not double until 2100, but the equivalent greenhouse effect of a doubling of CO_2 concentrations over pre-industrial levels is achieved by 2060 and continues to grow, albeit at a slower rate than in the first scenario.

The third of the scenarios, called the *Control Policies Scenario*, reflects a future where concern over global climate change and other environmental issues, such as stratospheric ozone depletion, motivate steps over and above those taken in the 2060 Low Emissions Scenario. Technological development, commercialization, and government efforts result in rapid penetrations of renewable energy sources in the last half of the next century. The Montreal Protocol is strengthened to include a full phase-out of CFCs and freezes on methylchloroform and carbon tetrachloride. Agricultural policies yield reduction in emissions of greenhouse gases from enteric fermentation in domestic animals, from rice paddies, and from fertilizer. As a result, emissions of CO_2, N_2O, and CH_4 grow slowly through the middle of the next century, then start to decline. Emissions of CO and NO_x decline sharply along with emissions of CFCs. These emission trends yield increases in atmospheric concentrations of greenhouse gases equivalent to slightly less than a doubling of CO_2 from pre-industrial levels by 2090 with concentrations stable after 2090.

The fourth and fifth scenarios, called the *Accelerated Policies Scenarios*, are similar to the Control Policies Scenario but feature much more rapid development and penetration of renewable energy sources encouraged in part by global adoption of carbon fees. Biomass energy represents 10 to 25 percent of primary energy supply by 2025, depending on economic growth assumptions. The results of these two scenarios differ only in emissions of CO_2 and primarily in the short run. In the first of these scenarios, carbon emissions from energy continue to increase through 2000 while total emissions of carbon decline, due to sequestering of carbon through reforestation. After 2000, carbon emissions from all sources decline through the end of the century to levels less than half those in 1985. In the alternative scenario, CO_2 emissions start declining immediately but reach the same levels by the end of the next century. These emission scenarios yield very similar atmospheric concentrations of greenhouse gases. In both scenarios, atmospheric concentrations of greenhouse gases continue to increase but stabilize by the middle of the next century at levels 25 percent greater than current levels but well below an equivalent doubling of CO_2 over pre-industrial levels.

In summary, the 2030 High Emissions and 2060 Low Emissions scenarios may be viewed as two different paths that global greenhouse gas emissions could follow over the next several decades. The latter case assumes sizeable improvements in energy efficiency, which may only be possible with government action. The Control Policies and Accelerated Policies scenarios require deliberate actions by governments (e.g., phasing out of CFCs, increasing fossil energy prices or using other measures to ensure penetration by renewables). In general, these scenarios do not achieve the goals of the Toronto Conference "The Changing Atmosphere—1988," which is a 20 percent reduction in CO_2 emissions by early in the next century. This goal is achieved in the Alternative Accelerated Policy scenario submitted by the Netherlands. The economic implications of all of the scenarios have not been analyzed.

2.1 INTRODUCTION

At its first meeting in Washington, D.C., in January 1989, Working Group III, or the Response Strategies Working Group (RSWG), decided to develop three global emission scenarios that would serve as (1) an initial reference and guidance for the work of the subgroups of the RSWG (Industry and Energy, Forestry and Agriculture, etc.), and (2) a first basis for the work of Working Group I (the Science Working Group) and Working Group II (the Impacts Working Group).

An expert group developed these three scenarios and a draft report and presented them to the RSWG in May 1989. Later, at the general IPCC meeting in June 1989 in Nairobi, the group decided to add a fourth scenario that would lead to stabilization of greenhouse gas concentrations at CO_2 equivalent levels well below the CO_2 doubling level. In addition, Working Group I requested some changes in the initial three scenarios and the expert group decided to provide an alternative fourth scenario that was quite similar to the newly adopted fourth scenario, but which featured lower estimates of carbon dioxide emissions during the next few decades.

This report and the accompanying Appendix represent the outcome of two experts meetings, one held at the National Institute for Public Health and Environmental Protection (RIVM) in Bilthoven, the Netherlands, on April 7–8, 1989, and a subsequent meeting held in Washington, D.C., in December 1989. The experts meeting in April was attended by representatives from the U.S. Environmental Protection Agency (U.S. EPA), the U.S. Department of Energy, the Netherlands' Ministry of Housing, Physical Planning and Environment and its research institute RIVM, the Netherlands' Ministry of Economic Affairs, and United Kingdom observers from Working Group I.

2.2 DEFINITION OF SCENARIOS AND METHODOLOGY

2.2.1 Definition and Use of Scenarios

The scenarios presented in this report represent very different possible futures. RSWG has constructed these scenarios through a process of identifying and estimating natural and anthropogenic sources of emissions, identifying the key factors that are likely to influence future emissions from these sources, making different sets of assumptions about how these factors may change in the future, and then estimating the impact of these combined changes on emissions. The resulting scenarios meet the needs of Working Group I by providing emissions estimates that behave according to specifications, consistent with a world that is evolving in a specified and reasonable manner.

The expert group used two alternative models to construct these scenarios: the Atmospheric Stabilization Framework (ASF) developed by the U.S. EPA, and the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE) developed by RIVM. These models provide both a structure for understanding how different economic and physical factors influence emissions of greenhouse gases, as well as a means of applying different estimates of how these factors may change and calculating the effect that changes will have on future emissions.

2.2.2 SPECIFICATIONS OF SCENARIOS

The scenarios of future greenhouse gas emissions represent vastly different views of the future and a wide range of changes in atmospheric concentrations of greenhouse gases. One scenario depicts a continued rapid buildup in atmospheric concentrations of greenhouse gases through the end of the next century, while another scenario represents a world where concentrations quickly stabilize.

To account for the wide range of impacts on greenhouse warming from the different greenhouse gases the expert group used the concept of *equivalent CO_2 concentration* to define the scenarios. Equivalent CO_2 concentration, or the concentration equivalent to a specified atmospheric concentration of CO_2, is defined as the concentration of CO_2 that, by itself, would produce the increase in direct radiative forcing produced by all of the greenhouse gases. Equivalent CO_2 concentration is derived by first estimating the increase, over pre-industrial levels, in direct radiative forcing from all of the greenhouse gases and then calculating the concentration of CO_2 that would produce the same increase, assuming atmospheric concentrations of all other greenhouse gases stayed at pre-industrial levels.

The equivalent CO_2 concentration is greater than the atmospheric concentration of CO_2 as long as the concentrations of other gases such as methane (CH_4) and nitrous oxide (N_2O) are equal to or greater than pre-industrial levels. For example, assume that atmospheric concentrations of the most important greenhouse gases were as follows: CO_2—444 parts per million (ppm), N_2O—341 parts per billion (ppb), CH_4—2510 ppb, CFC-11—537 parts per trillion (ppt), CFC-12—1077 ppt, and HCFC-22—558 ppt. Direct radiative forcing from all of the greenhouse gases then would be about 4.0 watts/meter^2 above pre-industrial levels, which is less than the 4.3 watts/meter^2 that would be produced by a doubling of CO_2. The equivalent CO_2 concentration would be 550 ppm, which represents slightly less than a doubling of CO_2 over pre-industrial levels.

The four emission scenarios are as follows:

1) *2030 High Emissions:* Equivalent CO_2 concentrations reach a value double that of pre-industrial atmospheric concentrations of CO_2 by 2030.
2) *2060 Low Emissions:* Equivalent CO_2 concentrations reach a value double that of pre-industrial atmospheric concentrations of CO_2 by 2060.
3) *Control Policies:* Equivalent CO_2 concentrations reach a value double that of pre-industrial atmospheric concentrations of CO_2 by 2090 and stabilize thereafter.
4) *Accelerated Policies:* Equivalent CO_2 concentrations stabilize at a level less than a doubling of pre-industrial atmospheric concentrations of CO_2.

No specifications were made as to the relative contribution of different greenhouse gases to the equivalent CO_2 concentrations or, in the first two scenarios, to the pattern of concentrations after they doubled. The expert group also developed an *Alternative Accelerated Policies Scenario*. While the fourth scenario assumes that economic, political, and technological constraints would prevent any significant reduction in emissions in the short run, the alternative fourth scenario assumes a political climate that stresses the urgency of rapidly slowing down the rate of climate change, and assumes earlier reductions in CO_2 emissions.

2.2.3 METHODOLOGY

The methodology used to create the four emission scenarios incorporated two broad steps. First, the group designed and developed two *detailed scenarios* of future greenhouse gas emissions for each of the four requested emission scenarios, with the main difference between the two scenarios being the rate of economic growth. Each of the eight detailed scenarios represented a much different view of how the world might evolve and produce levels of greenhouse gases that meet the scenario specifications. The second step involved combining, for each of the four requested emission scenarios, the two detailed (lower economic growth and higher economic growth) scenarios to create an *average* scenario. For the alternative fourth scenario (Alternative Accelerated Policies) the detailed scenario assumed that immediate action would be taken to stabilize concentrations. Selected results from the eight detailed scenarios, the four average scenarios, and the Alternative Accelerated Policies Scenario are presented in this report.

The design and development of the *detailed* emission scenarios consisted of four steps as follows:

1) Identify emission sources and estimate current (1985) emissions from these sources.
2) Identify alternative assumptions for key parameters that influence greenhouse gas emissions (e.g., economic growth and energy efficiency).
3) For each detailed scenario, combine assumptions for different parameters and implement the greenhouse models (ASF and/or IMAGE) using these assumptions.
4) Validate that the models produce results that meet the scenario specifications for each set of assumptions.

For the eight detailed scenarios, the ASF was used to combine the input assumptions and produce estimates of future emissions. The atmospheric and ocean models incorporated within the ASF were used to estimate future atmospheric concentrations of the greenhouse gases and the equivalent CO_2 concentrations in order to validate that the assumptions provided results consistent with the scenario specifications. The Dutch then reviewed the emission estimates and used IMAGE to further validate that the emission estimates provided the specified results.

2.3 ASSUMPTIONS

To develop scenarios of *future* emissions, certain assumptions must first be made about *current* sources of emissions; then additional assumptions must be made concerning the path of economic and technical change as well as the behavior of other factors that could influence greenhouse gas emissions in the future. The analytical frameworks described above (ASF and IMAGE) serve primarily to organize these assumptions and account for their consequences.

2.3.1 Current Emission Sources

A great deal of uncertainty surrounds the estimates of many of the greenhouse gas emissions. This uncertainty reflects a number of factors, such as poor or inconsistent measurements of emissions, as well as a lack of information on activities that cause emissions, such as the area of tropical forest cleared and the amount of biomass burned as a result of the clearing. The level of uncertainty varies considerably by gas and by emission source. Emissions of CO_2 from the combustion of fossil fuels are estimated within an error of plus or minus 10 percent (Marland and Rotty, 1984), while high and low estimates of emissions of N_2O from fertilizer (including leaching) can vary by a factor of 4 (Bolle et al., 1986).

Estimates of current emissions of CO_2 from fossil fuel combustion and cement production are from Marland et al. (1988), and emissions of CO_2 from tropical deforestation are from Houghton (1988). For 1985, these sources estimate emissions of 5.2 petagrams of carbon (Pg C) from fossil fuel combustion, 0.1 Pg C from cement manufacturing, and 0.7 Pg C from tropical deforestation.

The estimates of current emissions for CO, CH_4, and NO_x reflect the recommendations of Working Group I made in October 1989. Two emission sources for CO have been excluded: oxidation of man-made hydrocarbons and oxidation of natural hydrocarbons, since these two sources are estimated endogenously in the atmospheric model within the ASF. Also, changes in anthropogenic emissions of non-methane hydrocarbons are not estimated. Similarly, NO_x from stratospheric subsidence is excluded. Table 2.1 shows the emission assumptions for CO, Table 2.2, the assumptions for CH_4 (from Cicerone and Oremland, 1988), Table 2.3, the assumptions for NO_x, and Table 2.4, the assumptions for N_2O. The estimates of N_2O emissions reflect the need to balance recent data on emis-

TABLE 2.1: Current Annual CO Emissions

SOURCE	Tg CO	Tg C
Fossil Fuels + Industry	440	189
Oxidation of Man-Made Hydrocarbons*	100	43
Oxidation of Natural Hydrocarbons*	110	47
Wood Fuel	110	47
Biomass Burning	550	236
Oceans	40	17
Vegetation Emissions	130	56
Total	1480	634
Total (Excluding Hydrocarbons)	1270	544

* Not included in ASF

TABLE 2.2: Current Annual CH_4 Emissions

SOURCE	Tg CH_4
Enteric Fermentation	80
Wetlands	115
Rice Paddies	110
Biomass Burning	55
Termites	40
Landfills	40
Oceans	10
Freshwaters	5
Methane Hydrate Destabilization	5
Coal Mining	35
Gas Drilling, Venting, and Transmission	45
Total	540

Source: Cicerone and Oremland, 1988

TABLE 2.3: Current Annual NO_x Emissions

SOURCE	Tg N
Fossil Fuel Combustion	21
Biomass Burning	6
Soil Emission	12
Lightning	8
Stratospheric Subsidence*	1
Total	48

* Not included in ASF

sions of N_2O from stationary sources with estimates of the atmospheric life of N_2O and current growth rates in atmospheric concentrations. Using 0.25 percent as the estimated annual rate of growth in atmospheric concentrations of N_2O and an atmospheric life of 160 years yields 12.5 teragrams of nitrogen (Tg N) as the estimate of N_2O emissions in 1985. Of this total, an estimated 8.0 Tg N is from natural sources, for example, from nitrification and denitrification in soils and from oceans and fresh waters. Other emission sources include 1.0 Tg N from combustion of fossil fuels and 1.6 Tg N from fertilizer, which includes the leaching of fertilizer through the groundwater.

2.3.2 DEMOGRAPHIC, ECONOMIC, AND TECHNOLOGICAL CHANGE

Key factors expected to influence future changes in emissions of greenhouse gases include population growth, economic growth, the costs of technology used to convert energy from one form to another, end-use efficiency, deforestation rates, CFC emissions, and agricultural emissions. The expert group made different assumptions about how these factors may change in the future, then combined these different assumptions to construct the detailed emission scenarios.

The combinations of assumptions used to construct the scenarios are displayed in Table 2.5 and

TABLE 2.4: Current Annual N_2O Emissions

SOURCE	Tg N
Fossil Fuel Combustion	1.0
Fertilizer (Including Leaching)	1.6
Gain of Cultivated Land	0.4
Natural Emissions from Soils	6.0
Emissions from Oceans and Freshwater	2.0
Tropical Deforestation	0.5
Savanna Burning and Wildfires	0.3
Fuelwood and Industrial Biomass	0.2
Burning of Agricultural Wastes	0.4
Total	12.5

TABLE 2.5: Scenario Assumptions

	2030 High Emissions		2060 Low Emissions		Control Policies		Accelerated Policies	
	Higher Growth	Lower Growth	Higher Growth	Lower Growth	Higher Growth	Lower Growth	Higher Growth	Lower Growth
Population[a]	World Bank	World Bank	World Bank	World Bank	World Bank	World Bank	World Bank	World Bank
GNP[b]	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower
Energy Supply[c]	Carbon-intensive	Carbon-intensive	Gas-intensive	Gas-intensive	Non-Fossil-intensive	Non-Fossil-intensive	Early Non-Fossil-intensive	Early Non-Fossil-intensive
Energy Demand[d]	Moderate Efficiency	Moderate Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency	High Efficiency
Control Technology[e]	Modest Controls	Modest Controls	Stringent Controls	Stringent Controls	Stringent Controls	Stringent Controls	Stringent Controls	Stringent Controls
CFCs[f]	Protocol/Low Compliance	Protocol/Low Compliance	Protocol/Full Compliance	Protocol/Full Compliance	Phase Out	Phase Out	Phase Out	Phase Out
Deforestation[g]	Moderate	Rapid	Reforest	Reforest	Reforest	Reforest	Reforest	Reforest
Agriculture[h]	Current Factors	Current Factors	Current Factors	Current Factors	Declining Factors	Declining Factors	Declining Factors	Declining Factors

[a] Population estimates, taken from the World Bank (Zachariah and Vu, 1988) were not varied between scenarios. Global population reaches 9.5 billion in 2050 and 10.4 billion in 2100. In developing countries, population growth rates decline markedly after 2000, achieving a net reproduction rate of unity in every country by 2040.

[b] GNP growth rates were based on estimates from the World Bank (1987). For the Higher Growth cases, the average annual rate of GNP growth for the world decreases from 3.6 percent per year for the period 1985–2000, to about 3.3 percent per year for the period 2000–2025, to about 2.6 percent per year for the period 2025–2100. For the Lower Growth cases, the average annual rate of GNP growth for the world decreases from about 2.2 percent per year for the period 1985–2000, to about 2.1 percent per year for the period 2000–2025, to about 1.3 percent per year for the period 2025–2100.

[c] For the Carbon-intensive cases, energy supply is dominated by fossil fuel technologies. For the Gas-intensive cases, fossil fuels continue to play a major role, but the natural gas share of the energy supply market is increased. For the Non-Fossil-intensive cases, non-fossil technologies become economic in the latter part of the next century and supply most primary energy needs after 2075. For the Early Non-Fossil cases, non-fossil technologies play a much larger role starting in the early part of the next century.

[d] In the Moderate Efficiency cases, the annual rate of improvement in energy intensity (or primary energy use per dollar of GNP) decreases from an initial value between 1.0 and 1.5 percent to an average value of 0.7 to 1.2 percent for the years 2075 to 2100. The average annual rate of improvement in energy intensity for the years 1985 to 2100 ranges between 0.8 and 1.3 percent. In the High Efficiency cases, the annual rate of improvement in energy intensity decreases from an initial value between 1.5 and 2.5 percent to an average value of 1.1 to 1.8 percent for the years 2075 to 2100. The average annual rate of improvement in energy intensity for the years 1985 to 2100 ranges between 1.2 and 1.9 percent.

[e] In the Modest Controls cases, current emission control technologies are assumed. In the Stringent Controls cases, the following controls are assumed: more stringent NO_X and CO controls on mobile and stationary sources, including all gas vehicles using three-way catalysts (in OECD countries by 2000 and in the rest of the world by 2025); from 2000 to 2025 conventional coal burners used for electricity generation are retrofit with low NO_X burners, with 85 percent retrofit in the developed countries and 40 percent in developing countries; starting in 2000 all new combustors used for electricity generation and all new industrial boilers require selective catalytic reduction in the developed countries and low NO_X burners in the developing countries, and after 2025 all new combustors of these types require selective catalytic reduction; other new industrial non-boiler combustors such as kilns and dryers require low NO_X burners after 2000.

[f] In the Protocol/Low Compliance cases, the Montreal Protocol is assumed to come into force and apply through 2100, with 100 percent participation by the United States and developed countries and 85 percent participation by developing countries. The assumptions are the same in the Protocol/Full Compliance case except that all countries participate. In the Phase-Out cases, CFCs are completely phased out by 2000 and production of CCl_4 and CH_3CCl_3 are frozen with 100 percent participation.

[g] Tropical deforestation increases gradually in the Moderate case, from 11 million ha/yr in 1985 to 15 million ha/yr by about 2100. Tropical deforestation increases exponentially in the Rapid case, reaching 34 million ha/yr in about 2050, with almost complete tropical forest deforestation by about 2075. In the Reforest cases, deforestation stops by 2025, and about 1,000 million ha are reforested by 2100.

[h] Levels of activity for the major agricultural activities were not varied between scenarios, since population levels were not varied. Emission factors, however, were changed between scenarios. Current estimates of average emission factors were used in the Current Factors cases, while reduced factors (assuming technological and management improvements) were used in the Declining Factors cases.

explained briefly below. As described earlier, two detailed scenarios were developed for each of the four requested emission scenarios, with the assumptions on the future rate of economic growth being the main difference between the two detailed scenarios. In Table 2.5 "Higher Growth" refers to higher economic growth detailed scenario and "Lower Growth" refers to lower economic growth detailed scenario. Additional information on the assumptions and results of these scenarios are included in the Appendix.

2.3.2.1 *Population*

The population estimates, taken from the World Bank (Zachariah and Vu, 1988), project a global population of 9.5 billion by 2050 and 10.4 billion by 2100. Regional population growth assumptions are shown in Figure 2.1. The bulk of the increase during the first half of the next century occurs in the developing countries, while population in the developed countries remains fairly stable during the entire period.

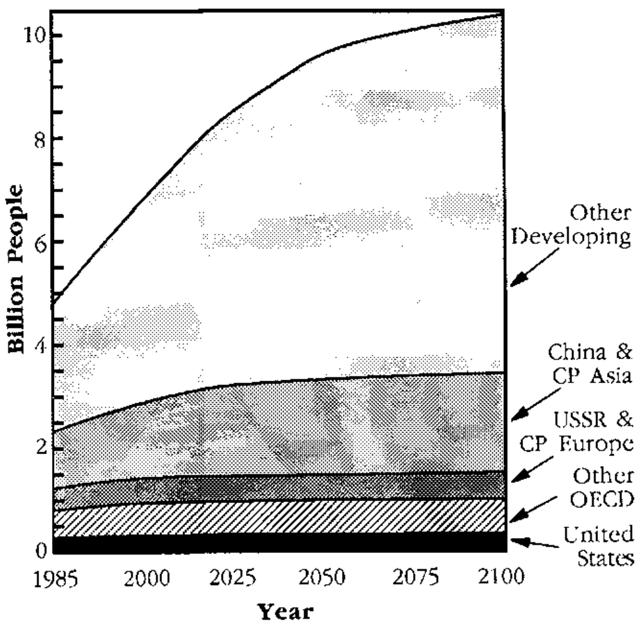
2.3.2.2 *Economic Growth*

Economic growth rates (Table 2.6) were derived from estimates from the World Bank (1987); adjustments to these estimates are described in the Appendix. The overall rate of economic development is one of the most important determinants of future greenhouse gas emissions. Robust economic growth is certainly the goal of most governments, and other things being equal, higher levels of economic activity would be associated with greater greenhouse gas emissions. In the scenarios defined here, for example, some regions reach a per capita income level of $5,000 (typical of Western Europe during the 1970s) by 2020 under the Higher Growth assumptions, but not until 2075 under the Lower Growth assumptions. For other regions, per capita income levels remain below $5,000 throughout the

TABLE 2.6: **Economic Growth Rate Assumptions (Annual Percentage Growth)**

	HIGHER GROWTH				
	1985–2000	2000–2025	2025–2050	2050–2075	2075–2100
Region					
United States	3.0	2.5	2.0	1.5	1.0
Western Europe and Canada	3.0	2.5	2.0	1.5	1.0
Japan, Australia, New Zealand	3.5	2.5	2.0	1.5	1.0
USSR and Eastern Europe	4.6	4.1	3.1	2.6	2.1
Centrally Planned Asia	5.5	5.0	4.5	4.0	3.5
Middle East	4.1	4.6	3.6	3.1	2.6
Africa	4.5	4.0	3.5	3.0	2.5
Latin America	4.7	4.2	3.7	3.2	2.7
Rest of South and East Asia	5.3	4.8	4.3	3.8	3.3
	LOWER GROWTH				
	1985–2000	2000–2025	2025–2050	2050–2075	2075–2100
Region					
United States	2.0	1.5	1.0	1.0	1.0
Western Europe and Canada	2.0	1.5	1.0	1.0	1.0
Japan, Australia, New Zealand	2.5	1.5	1.0	1.0	1.0
USSR and Eastern Europe	2.6	2.1	1.6	1.6	1.6
Centrally Planned Asia	3.5	3.0	2.5	2.5	2.5
Middle East	3.3	2.8	2.1	2.1	2.1
Africa	3.0	2.6	2.1	2.1	2.1
Latin America	2.7	2.2	1.7	1.7	1.7
Rest of South and East Asia	3.3	2.8	2.3	2.3	2.3

FIGURE 2.1: **Global Population Levels by Region, 1985–2100**



period under the Lower Growth assumptions. Scenarios of sustainable development in which all developing countries achieve a higher income level by the middle of the next century could be explored in future analyses.

2.3.2.3 *Energy Supply*

Four alternative assumptions on energy supply provide for a wide range of possible futures. The first set of assumptions, labeled Carbon-intensive, represents a pessimistic view of future non-fossil developments, where the cost of non-fossil energy supply technologies remains high compared to fossil supplies, and/or the technical potential for these energy sources remains low. Fossil energy resources, primarily coal, are adequate to satisfy demand for energy, and synthetic fuels from coal become competitive early in the twenty-first century. Under these assumptions, costs of commercial solar electricity remain at current levels of around $0.11/kwh (1988 U.S. dollars), use of nuclear energy is limited because of concerns over safety, and energy from commercial biomass remains low because of a combination of high development costs, lack of infrastructure, and competition with other uses for the land.

The Gas-intensive assumptions are similar to the Carbon-intensive assumptions except that increased use of natural gas is encouraged in order to meet a number of environmental goals, including reducing CO_2 emissions. Carbon fees of 20 to 25 percent of delivered prices help reduce demand for oil and coal and help provide price subsidies for natural gas of up to 15 percent. Research and development help accelerate reductions in gas exploration and production costs on the order of 0.5 percent annually.

The third set of assumptions, labeled Non-Fossil-intensive, represents a world where technological developments result in competitive and abundant non-fossil energy sources, but not until late in the next century. Costs of commercial solar electricity fall to $0.06/kwh (1988 U.S. dollars) after 2050. Similarly, costs of nuclear energy fall to $0.055/kwh, and political and technological constraints inhibiting its use are relaxed. Finally, costs of producing large quantities of biomass energy are significantly reduced.

The fourth set, labeled Early Non-Fossil-intensive, is similar to the previous set of assumptions but with several key differences. Here, constraints that impede the penetration and use of non-fossil supplies are relaxed, and cost reductions are achieved, *early* in the twenty-first century, so that non-fossil energy sources can make a significant impact by 2025. Fees based on the carbon content of fossil fuels, set at a rate equivalent to $50/ton on coal (1988 U.S. dollars), are phased in on a global scale by 2025.

The use of the assumptions for the different emission scenarios is straightforward. The Carbon-intensive energy supply assumptions are used to construct the 2030 High Emissions scenarios. The Gas-intensive assumptions are used for the 2060 Low Emissions scenarios. The Non-Fossil-intensive assumptions are used with the Control Policies scenarios, and the Early Non-Fossil-intensive assumptions are used in the Accelerated Policies scenarios.

2.3.2.4 *Energy Demand*

Two alternative assumptions are made concerning future demand for energy under each set of economic growth assumptions. These alternatives reflect both the variance in historical trends as well as a wide range of views as to what is possible in the future. The first set of these assumptions, labeled Moderate Efficiency, yields annual improvements in energy intensity (measured as primary energy use per dollar GNP) of around 0.9 percent under the lower economic growth assumptions and 1.3 percent under the higher economic growth assumptions. The High Efficiency assumptions yield annual improvements in energy intensity of around 1.2 percent under lower economic growth and 1.8 percent under the higher economic growth (with annual improvements from 1985 to 2025 averaging 2.3 percent).

2.3.2.5 *CFCs and Halons*

Three sets of assumptions are made concerning future emissions of perhalogenated hydrocarbons and hydrohalocarbons (including CFCs). The first of the assumptions, labeled Protocol/Low Compliance, represents a very pessimistic view of efforts to further control emissions of CFCs. They include no strengthening of the Montreal Protocol and only 85 percent participation by developing countries. The second set of assumptions, labeled Protocol/Full Compliance, still represents a pessimistic view, in that there is no strengthening of the Montreal Protocol, but all countries participate and there is 100 percent compliance to the existing terms. The third set of assumptions (Phase Out) represents an optimistic view of efforts to strengthen the Montreal Protocol; these assumptions include a complete phase-out of CFCs by the year 2000 and limits on emissions of carbon tetrachloride and methylchloroform, as well as 100 percent participation in the strengthened agreement. In all of the above sets of assumptions, the substitution of HCFCs (HCFC-22 is used as proxy) for controlled gases occurs at a rate of .35 to 1.

The use of these assumptions to construct the emission scenarios is also straightforward. For the 2030 High Emissions scenarios, the Protocol/Low Compliance assumptions are used. The Protocol/Full Compliance assumptions are used with the 2060 Low Emissions scenarios. And the Phase Out assumptions are used with both the Control Policies and Accelerated Policies scenarios.

2.3.2.6 *Deforestation*

Three alternate sets of assumptions concerning rates of deforestation and reforestation provide a wide range of futures, from a continued increase in rates of deforestation to rapid cessation of deforestation and vigorous reforestation efforts. All three deforestation scenarios assume low initial biomass and 1985 emissions of CO_2 from tropical deforestation at around 0.7 Pg C.

In the first set of assumptions, labeled Rapid Deforestation, tropical deforestation increases exponentially, reaching 34 million hectares (ha) per year by 2050, leading to complete global deforestation by 2075. No efforts are made to establish tree plantations or to reforest areas.

In the second set of assumptions, labeled Moderate Deforestation, tropical deforestation increases gradually, reaching 15 million ha per year by about 2100, compared with 11 million ha/yr in 1985. The rate of establishment of tree plantations is assumed to be zero and no reforestation occurs.

In the third set of assumptions, labeled Reforestation, tropical deforestation stops by 2025, while about 1,000 million ha is reforested by 2100. Only land that once supported forests and is not intensively cultivated is assumed to be available for reforestation. Of the reforested land, 380 million ha are assumed to be in plantations; the rest absorbs carbon at a slower rate but eventually reaches a much higher level of biomass.

The Rapid Deforestation assumptions were used for the 2030 High Emissions/Lower Growth scenario. The Moderate Deforestation assumptions were used for the 2030 High Emissions/Higher Growth scenario. The Reforestation assumptions were used for all other scenarios.

2.3.2.7 *Agriculture*

The assumptions affecting emissions from agriculture fall into two groups: (1) those that have an impact on consumption and production of agricultural products and (2) those that might change the emissions attributed to a given level of agricultural activity (emission coefficients). Since population growth was the same in all scenarios, future activity levels for the major agricultural variables affecting trace gas emissions (e.g., land use for rice production, meat consumption, dairy consumption, fertilizer use, etc.) did not vary among scenarios.

Two separate sets of assumptions are made concerning future emissions from these activities. The first set, labeled Current Factors, assumes that emissions coefficients from agricultural activities remain constant over time. As examples, the percent of N applied as fertilizer that evolves as N_2O would remain constant in the future, and CH_4 emissions from a single hectare of land cultivated for rice production would also remain constant. The second set of assumptions (Declining Factors) has the emission coefficients declining 0.5 percent annually as a result of efforts to control emissions, for example, by changing types of fertilizer and methods of application, by altering rice cultivation practices and rice cultivars, and by adopting meat and dairy production techniques such as methane-inhibiting ionophores. Examples of Current Factor coefficients, used in the 2030 High Emissions and 2060 Low Emissions scenarios, are shown in Table 2.7. Declining Factors were used in all other Scenarios.

TABLE 2.7: Emission Coefficients for the Agricultural Sector

	N_2O from Fertilizer	
Fertilizer Type	% Evolved Directly	% Evolved from Leaching
Ammonium Nitrate and Ammonium Salts	0.1	2.0
Nitrate	0.05	2.0
Urea	0.5	2.0
Other Nitrogenous and Other Complex	1.0	2.0
Anhydrous Ammonia	0.5	2.0
	Methane from Agricultural Activities	
Rice Production	75 grams CH_4/meter²/harvest	
Enteric Fermentation	(Kilograms CH_4/Head)*	
Cattle	41	
Sheep	6	
Dairy Cows	64	
Pigs	15	

* Global Averages

2.4 RESULTS

Combining the diverse sets of assumptions described in the previous section in the modeling frameworks provides a wide range of different views of how the world could evolve. As described earlier, two alternative detailed scenarios provide results that are consistent with each of the four requested scenarios of greenhouse gas concentration buildup. The detailed scenarios were also combined to create an Average Scenario for each requested emission profile. An additional scenario provides an alternative view of how stabilization of greenhouse gas concentrations can be achieved. Table 2.8 shows the expected emissions of each gas from each source for each of the four average (2030 High Emissions, 2060 Low Emissions, Control Policies, Accelerated Policies) scenarios and the Alternative Accelerated Policies Scenario.

Both the ASF and IMAGE were used to estimate changes in atmospheric concentrations of the greenhouse gases in order to confirm that they met the specifications of the four emission scenarios. The results of the ASF and IMAGE were within 5 percent, with variations due primarily to the use of different approaches to estimate atmospheric concentrations of the greenhouse gases and a different conceptual approach to the modeling of land-use changes. Figure 2.2 displays CO_2 concentrations and equivalent CO_2 concentrations estimated by the Atmospheric Stabilization Framework for the four averaged scenarios and the Alternative Accelerated Policies Scenario along with the level of atmospheric CO_2 concentrations representing a doubling of preindustrial concentrations. These divergent outcomes are described in more detail below for the energy, forestry, and agricultural sectors.

2.4.1 Energy Sector

The two most important determinants of greenhouse gas emissions are the level of energy demand and the combination of sources that are used to supply that energy. The basic differences between the scenarios in global primary energy supplies are illustrated in Figures 2.3 and 2.4. The regional differences in primary energy consumption are illustrated in Figures 2.5 and 2.6.

TABLE 2.8: **Greenhouse Gas Emissions: 2030 High Emissions (Average) Scenario**

Gas/Source	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C/Yr)						
Commercial Energy	5.1	6.5	9.9	13.5	17.7	21.7
Tropical Deforestation	0.7	1.0	1.4	1.4	0.7	0.4
Cement	0.1	0.2	0.2	0.3	0.3	0.3
Total	6.0	7.7	11.5	15.2	18.7	22.4
N_2O (Teragrams N/Yr)						
Commercial Energy	1.1	1.4	2.1	2.8	3.5	4.1
Fertilizer	1.5	2.5	3.5	3.7	3.9	3.9
Gain of Cultivated Land	0.4	0.6	0.8	0.8	0.4	0.2
Natural Land Emissions	6.0	6.0	6.0	6.0	6.0	6.0
Oceans/Freshwater	2.0	2.0	2.0	2.0	2.0	2.0
Biomass Burning	1.4	1.8	2.0	2.0	1.5	1.3
Total	12.5	14.2	16.4	17.3	17.3	17.6
CH_4 (Teragrams CH_4/Yr)						
Commercial Energy	2.0	2.3	3.2	4.1	4.9	6.3
Fuel Production	80.0	98.1	158.7	212.5	268.9	326.9
Enteric Fermentation	74.5	94.5	124.6	156.0	163.6	166.9
Rice	110.0	125.7	148.7	167.9	168.8	157.1
Oceans/Freshwater	15.0	15.0	15.0	15.0	15.0	15.0
Landfills	40.0	50.1	71.1	103.5	149.2	179.6
Wetlands	115.0	115.0	115.0	115.0	115.0	115.0
Biomass Burning	55.1	64.4	75.6	76.1	57.7	47.2
Wild Ruminants and Termites	44.0	44.0	44.0	44.0	44.0	44.0
Methane Hydrate	5.0	5.0	5.0	5.0	5.0	5.0
Total	540.5	613.9	760.8	899.1	992.0	1062.9
NO_X (Teragrams N/Yr)						
Commercial Energy	23.2	28.2	39.1	51.4	63.2	75.4
Biomass Burning	6.1	7.0	8.3	8.3	6.4	5.2
Natural Land	12.0	12.0	12.0	12.0	12.0	12.0
Lightning	9.0	9.0	9.0	9.0	9.0	9.0
Total	50.2	56.2	68.3	80.7	90.5	101.5
CO (Teragrams C/Yr)						
Commercial Energy	182.2	198.3	289.0	386.8	468.8	627.8
Tropical Deforestation	135.0	189.6	255.2	255.2	135.0	72.1
Oceans	17.0	17.0	17.0	17.0	17.0	17.0
Agricultural Burning	146.0	153.7	162.8	165.7	160.7	153.0
Wood Use	47.0	47.0	47.1	47.3	47.6	48.0
Wildfires	10.0	10.0	10.0	10.0	10.0	10.0
Total	537.2	615.6	781.2	881.9	839.1	927.9
CFCs (Gigagrams/Yr)						
CFC-11	278.3	305.1	244.7	251.5	253.0	253.0
CFC-12	361.9	376.0	302.7	314.1	316.1	316.1
HCFC-22	96.9	522.9	1340.4	2681.3	2961.0	2961.0
Halon-1211	1.4	8.8	18.6	18.9	19.1	19.1
Halon-1301	2.1	5.1	7.4	7.5	7.7	7.8

Note: Totals reflect rounding.

TABLE 2.8 *(continued)*: **Greenhouse Gas Emissions: 2060 Low Emissions (Average) Scenario**

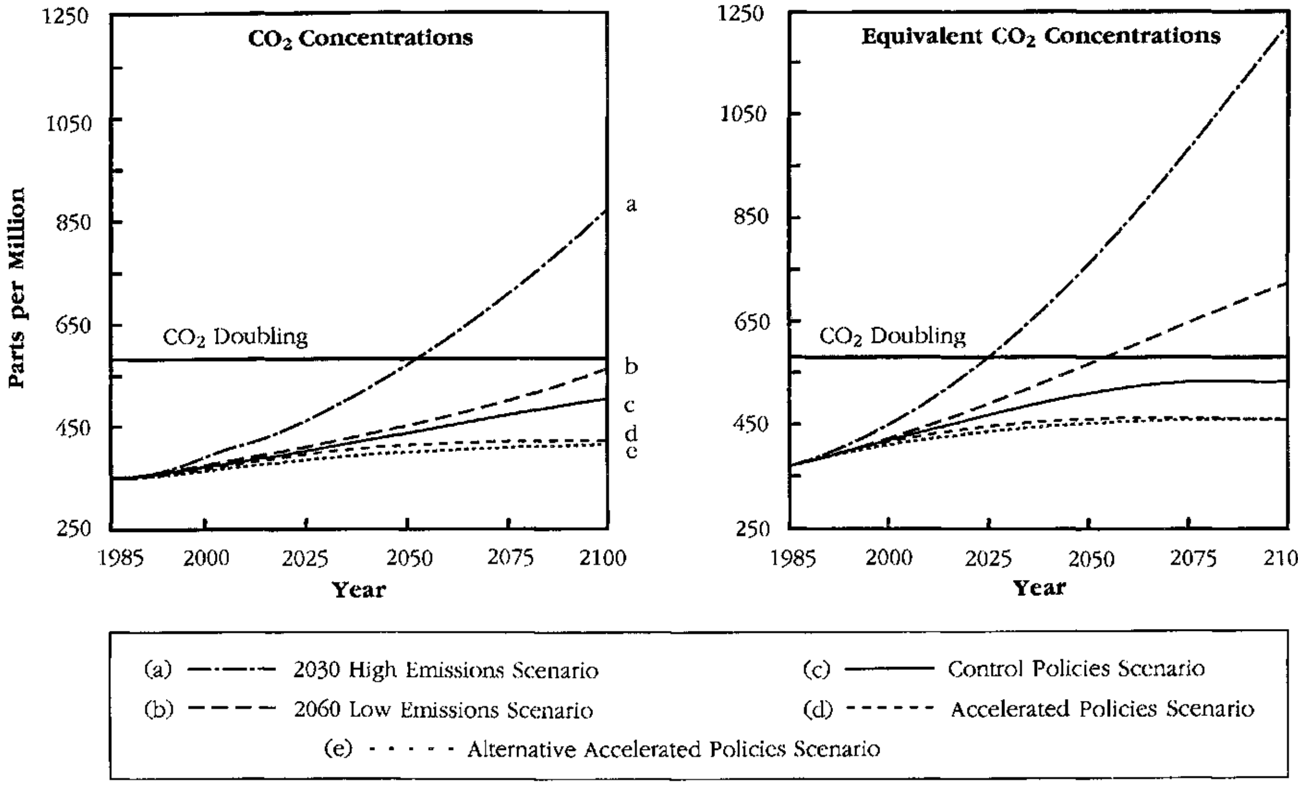
Gas/Source	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C/Yr)						
Commercial Energy	5.1	5.6	6.6	7.6	8.7	10.3
Tropical Deforestation	0.7	−0.2	−0.5	−0.3	−0.2	−0.2
Cement	0.1	0.2	0.2	0.2	0.2	0.2
Total	5.9	5.5	6.4	7.5	8.8	10.3
N_2O (Teragrams N/Yr)						
Commercial Energy	1.1	1.2	1.3	1.4	1.5	1.8
Fertilizer	1.5	2.5	3.5	3.7	3.9	3.9
Gain of Cultivated Land	0.4	0.2	0.0	0.0	0.0	0.0
Natural Land Emissions	6.0	6.0	6.0	6.0	6.0	6.0
Oceans/Freshwater	2.0	2.0	2.0	2.0	2.0	2.0
Biomass Burning	1.1	1.2	1.0	1.0	1.0	0.9
Total	12.5	13.1	13.9	14.1	14.3	14.6
CH_4 (Teragrams CH_4/Yr)						
Commercial Energy	2.0	2.1	1.8	1.7	1.8	2.1
Fuel Production	80.0	88.8	118.2	132.2	136.6	151.5
Enteric Fermentation	74.5	94.5	124.6	156.0	163.6	166.9
Rice	110.0	125.7	148.7	167.9	168.8	157.1
Oceans/Freshwater	15.0	15.0	15.0	15.0	15.0	15.0
Landfills	40.0	43.0	55.4	50.0	47.1	45.6
Wetlands	115.0	115.0	115.0	115.0	115.0	115.0
Biomass Burning	55.1	43.9	38.0	37.0	35.5	33.4
Wild Ruminants and Termites	44.0	44.0	44.0	44.0	44.0	44.0
Methane Hydrate	5.0	5.0	5.0	5.0	5.0	5.0
Total	540.5	576.8	665.4	723.8	732.4	735.6
NO_X (Teragrams N/Yr)						
Commercial Energy	23.2	24.4	21.0	16.2	16.5	19.2
Biomass Burning	6.1	4.8	4.2	4.0	3.9	3.7
Natural Land	12.0	12.0	12.0	12.0	12.0	12.0
Lightning	9.0	9.0	9.0	9.0	9.0	9.0
Total	50.2	50.2	46.1	41.2	41.4	43.8
CO (Teragrams C/Yr)						
Commercial Energy	182.2	149.2	99.2	54.2	57.7	71.3
Tropical Deforestation	135.0	53.6	7.4	1.8	1.8	0.0
Oceans	17.0	17.0	17.0	17.0	17.0	17.0
Agricultural Burning	146.0	153.7	162.8	165.7	160.7	153.0
Wood Use	47.0	44.1	39.7	35.8	32.5	29.6
Wildfires	10.0	10.0	10.0	10.0	10.0	10.0
Total	537.2	427.6	336.1	284.6	279.8	280.9
CFCs (Gigagrams/Yr)						
CFC-11	278.3	302.1	226.7	223.2	223.2	223.2
CFC-12	361.9	372.2	279.1	277.9	277.9	277.9
HCFC-22	96.9	525.7	1357.2	2707.2	2988.1	2988.1
Halon-1211	1.4	8.8	18.2	17.8	17.5	17.5
Halon-1301	2.1	5.1	7.3	7.2	7.3	7.3

TABLE 2.8 (*continued*):	Greenhouse Gas Emissions: Control Policies (Average) Scenario					
Gas/Source	**1985**	**2000**	**2025**	**2050**	**2075**	**2100**
CO_2 (Petagrams C/Yr)						
Commercial Energy	5.1	5.6	6.5	7.2	5.0	3.5
Tropical Deforestation	0.7	−0.2	−0.5	−0.3	−0.2	−0.2
Cement	0.1	0.2	0.2	0.2	0.2	0.2
Total	5.9	5.6	6.3	7.1	5.1	3.5
N_2O (Teragrams N/Yr)						
Commercial Energy	1.1	1.2	1.3	1.4	1.1	1.1
Fertilizer	1.5	2.3	2.8	2.6	2.4	2.2
Gain of Cultivated Land	0.4	0.2	0.0	0.0	0.0	0.0
Natural Land Emissions	6.0	6.0	6.0	6.0	6.0	6.0
Oceans/Freshwater	2.0	2.0	2.0	2.0	2.0	2.0
Biomass Burning	1.4	1.2	1.0	1.0	1.0	0.9
Total	12.5	12.9	13.2	13.0	12.5	12.2
CH_4 (Teragrams CH_4/Yr)						
Commercial Energy	2.0	2.0	1.7	1.7	1.5	1.7
Fuel Production	80.0	85.2	108.3	117.4	83.6	59.0
Enteric Fermentation	74.5	88.3	103.7	115.3	107.8	98.0
Rice	110.0	116.6	121.6	121.2	107.5	88.3
Oceans/Freshwater	15.0	15.0	15.0	15.0	15.0	15.0
Landfills	40.0	43.0	55.4	50.0	47.1	45.6
Wetlands	115.0	115.0	115.0	115.0	115.0	115.0
Biomass Burning	55.1	43.9	38.0	37.0	35.5	33.4
Wild Ruminants and Termites	44.0	44.0	44.0	44.0	44.0	44.0
Methane Hydrate	5.0	5.0	5.0	5.0	5.0	5.0
Total	540.5	557.9	607.7	621.6	562.0	504.9
NO_X (Teragrams N/Yr)						
Commercial Energy	23.2	24.5	21.2	16.9	14.4	14.7
Biomass Burning	6.1	4.8	4.2	4.0	3.9	3.7
Natural Land	12.0	12.0	12.0	12.0	12.0	12.0
Lightning	9.0	9.0	9.0	9.0	9.0	9.0
Total	50.2	50.3	46.4	41.9	39.3	39.4
CO (Teragrams C/Yr)						
Commercial Energy	182.2	149.0	99.3	55.0	52.2	60.6
Tropical Deforestation	135.0	53.6	7.4	1.8	1.8	0.0
Oceans	17.0	17.0	17.0	17.0	17.0	17.0
Agricultural Burning	146.0	153.7	162.8	165.7	160.7	153.0
Wood Use	47.0	44.1	39.7	35.8	32.5	29.6
Wildfires	10.0	10.0	10.0	10.0	10.0	10.0
Total	537.2	427.4	336.1	285.4	274.3	270.2
CFCs (Gigagrams/Yr)						
CFC-11	278.3	197.1	10.6	0.0	0.0	0.0
CFC-12	361.9	262.2	10.2	0.0	0.0	0.0
HCFC-22	96.9	638.5	1571.9	2927.6	3208.5	3208.5
Halon-1211	1.4	7.7	3.0	0.0	0.0	0.0
Halon-1301	2.1	4.1	1.8	0.0	0.0	0.0

TABLE 2.8 (*continued*): **Greenhouse Gas Emissions: Accelerated Policies (Average) and Alternative Accelerated Policies Scenario**

Gas/Source	1985	2000	2025	2050	2075	2100
CO_2 (Petagrams C/Yr)						
Accelerated Policies						
Commercial Energy	5.1	5.7	5.4	3.0	2.9	2.7
Tropical Deforestation	0.7	−0.2	−0.5	−0.3	−0.2	−0.2
Cement	0.1	0.2	0.2	0.2	0.2	0.2
Total	6.0	5.6	5.1	2.9	3.0	2.7
Alternative Accelerated Policies						
Commercial Energy	5.1	4.7	4.1	3.8	3.4	2.6
Tropical Deforestation	0.7	−0.2	−0.5	−0.3	−0.2	−0.2
Cement	0.1	0.2	0.2	0.2	0.2	0.2
Total	6.0	4.6	3.8	3.7	3.5	2.6
N_2O (Teragrams N/Yr)						
Commercial Energy	1.0	1.2	1.2	1.0	1.0	1.1
Fertilizer	1.6	2.3	2.8	2.6	2.4	2.2
Gain of Cultivated Land	0.4	0.2	0.0	0.0	0.0	0.0
Natural Land Emissions	6.0	6.0	6.0	6.0	6.0	6.0
Oceans/Freshwater	2.0	2.0	2.0	2.0	2.0	2.0
Biomass Burning	1.1	1.2	1.0	1.0	1.0	0.9
Total	12.5	12.9	13.1	12.7	12.5	12.3
CH_4 (Teragrams CH_4/Yr)						
Commercial Energy	2.0	1.9	1.9	1.6	1.7	1.9
Fuel Production	80.0	93.3	84.0	48.7	50.3	52.4
Enteric Fermentation	75.2	88.3	103.7	115.3	107.8	98.0
Rice	109.4	116.6	121.6	121.2	107.9	91.2
Oceans/Freshwater	15.0	15.0	15.0	15.0	15.0	15.0
Landfills	40.0	43.0	55.4	50.0	47.1	45.6
Wetlands	115.0	115.0	115.0	115.0	115.0	115.0
Biomass Burning	55.1	43.8	37.9	37.2	36.3	34.0
Wild Ruminants and Termites	44.0	44.0	44.0	44.0	44.0	44.0
Methane Hydrate	5.0	5.0	5.0	5.0	5.0	5.0
Total	540.7	565.8	583.5	553.0	530.1	502.1
NO_X (Teragrams N/Yr)						
Commercial Energy	24.2	24.7	24.7	18.7	18.0	18.8
Biomass Burning	6.1	4.8	4.2	4.1	3.9	3.8
Natural Land	12.0	12.0	12.0	12.0	12.0	12.0
Lightning	9.0	9.0	9.0	9.0	9.0	9.0
Total	51.2	50.5	49.9	43.8	42.9	43.5
CO (Teragrams C/Yr)						
Commercial Energy	185.8	133.3	104.2	55.4	58.4	68.0
Tropical Deforestation	135.0	53.6	7.4	1.8	1.8	0.0
Oceans	17.0	17.0	17.0	17.0	17.0	17.0
Agricultural Burning	146.0	153.1	162.6	166.9	165.3	156.4
Wood Use	47.0	44.1	39.7	35.8	32.5	29.6
Wildfires	10.0	10.0	10.0	10.0	10.0	10.0
Total	540.8	411.1	340.8	287.0	285.0	281.0
CFCs (Gigagrams/Yr)						
CFC-11	278.3	197.1	10.6	0.0	0.0	0.0
CFC-12	361.9	262.2	10.2	0.0	0.0	0.0
HCFC-22	96.9	638.5	1571.9	2927.6	3208.5	3208.5
Halon-1211	1.4	7.7	3.0	0.0	0.0	0.0
Halon-1301	2.1	4.1	1.8	0.0	0.0	0.0

FIGURE 2.2: CO_2 and Equivalent CO_2 Concentrations: Average



2.4.1.1 *2030 High Emissions Scenarios*

In the 2030 High Emissions scenarios, fossil fuel consumption increases rapidly through the entire time horizon (1985 to 2100). With higher economic growth, primary energy supply increases from a 1985 level of 290 EJ to 660 EJ in 2025 (an annual growth rate of 2.1 percent) and reaches 1680 EJ in 2100 (an annual growth rate of 1.3 percent). Oil and natural gas supplies increase through 2025, then start to decline because of resource constraints. Coal becomes the dominant fuel; its share of primary energy supply rises from below 30 percent in 1985 to over 65 percent by the end of the time period. By 2100, half of all coal mined is used in synthetic fuel production. With lower economic growth, primary energy demand and supply increase at about half the rate seen with higher economic growth. Primary energy supply increases to 470 EJ by 2025 and to 730 EJ by 2100, with average annual rates of growth of 1.2 percent and 0.6 percent, respectively. Oil and natural gas supply follows a pattern similar to that described above, and the share of primary energy supplied by coal increases to 55 percent in 2100.

Regional energy consumption patterns also differ between the two 2030 High Emissions detailed scenarios. Under the Higher Growth assumptions, all regions show an increase in primary energy consumption, but the increase in developing countries far exceeds that in the developed countries.

This result reflects the higher rates of economic growth assumed in developing countries as well as assumptions concerning energy use during this rapid development. The share of primary energy consumed in the developing countries increases from 22 percent in 1985 to over 60 percent in 2100. A similar pattern of regional growth is seen in the Lower Growth scenario, but the portion of energy consumed in the developing countries increases to only 45 percent in 2100.

2.4.1.2 *2060 Low Emissions Scenarios*

Reflecting the assumptions made concerning greater improvements in energy efficiency, the 2060 Low Emissions scenarios display smaller increases in primary energy supply and fossil fuel use than seen in the 2030 High Emissions scenarios. In addition, natural gas plays a larger role through 2025, but that role is reduced thereafter because of resource constraints. Primary energy supply reaches only 450 EJ in 2025 and 850 EJ in 2100 under the Higher Growth assumptions and 374 EJ in 2025 and 430 EJ in 2100 under the Lower Growth assumptions. The share of primary energy supply provided by natural gas grows from 19 percent in 1985 to 23 percent in 2100 under the Higher Growth assumptions and to 25 percent under the Lower Growth assumptions. The role of coal continues to expand; coal's share of primary energy increases from 28 percent in 1985 to 54 percent by 2100 (Higher Growth assumptions) and to 41 percent by 2100 (Lower Growth assumptions).

The regional patterns are similar to those shown in the scenarios that assume less efficiency improvement. The share of global primary energy consumed in the developing world increases from 22 percent in 1985 to over 50 percent by 2100 under the Higher Growth assumptions and to 45 percent by 2100 under the Lower Growth assumptions. Again, these results reflect higher rate of economic growth assumed for developing countries.

2.4.1.3 *Control Policies Scenarios*

The estimates of energy supply for the Control Policies scenarios are similar to those found in the 2060 Low Emissions scenarios, except that non-fossil energy supplies start to play a larger role after 2025, providing over 79 percent of primary energy by 2100 under Higher Growth assumptions and over 62 percent of primary energy by 2100 under Lower Growth assumptions. Most of the increase in non-fossil energy supplies occurs after 2050, since these supplies are not assumed to become competitive and widely available until the middle to end of the next century.

2.4.1.4 *Accelerated Policies Scenarios*

The Accelerated Policies scenarios provide a much different picture of future energy supply and demand. Non-fossil energy supplies, especially commercial biomass energy, play a much larger role and make an impact much earlier. Energy consumption in the scenarios is similar to the energy consumption in the Control Policies scenarios, except that in the Higher Growth scenario, energy use is slightly higher at mid-century because of the increased availability of biomass supplies and their lower costs. The share of primary energy provided by non-fossil sources increases from 13 percent in 1985 to 49 percent in 2025 to 78 percent by 2100 with high economic growth and to 33 percent in 2025 and 80 percent in 2100 with low economic growth.

Figure 2.7 shows the CO_2 emissions from fossil fuels under all of the scenarios. CO_2 emissions, which were 5.2 Pg C in 1985, reach levels in 2100 ranging from 30.8 Pg C in the 2030 High Emissions/Higher Growth scenario to 1.9 Pg C in the Accelerated Policies/Lower Growth scenario. Emissions of CO_2 from combustion of fossil fuels in the Alternative Accelerated Policies scenario decline immediately and continue to decline through 2100. This result differs from the other Stabilization scenarios (Higher Growth, Lower Growth, and Average), in which global emissions of CO_2 from fossil fuels grow through the year 2000 and then start to decline.

2.4.2 Forestry Sector

As shown in Figure 2.8, net emissions of CO_2 from tropical deforestation and reforestation varied considerably between the 2030 High Emissions scenario and all other scenarios.

2.4.2.1 *2030 High Emissions Scenarios*

In the 2030 High Emissions/Lower Growth scenario, future CO_2 emissions closely follow the rapidly increasing rate of land clearing assumed in the scenario. Emissions peak at over 2 Pg C/yr around the year 2050, with a total flux from the biosphere to the atmosphere of about 140 Pg C between 1985 and 2100.

In the 2030 High Emissions/Higher Growth scenario, emissions of CO_2 grow at a slower rate because a slower rate of land clearing is assumed. CO_2 emissions are spread out over a longer period, reaching a peak of slightly over 1 Pg C near the end of the century, with total flux of carbon over the time period at 120 Pg C.

FIGURE 2.3: Global Primary Energy Supply by Type: Lower Growth

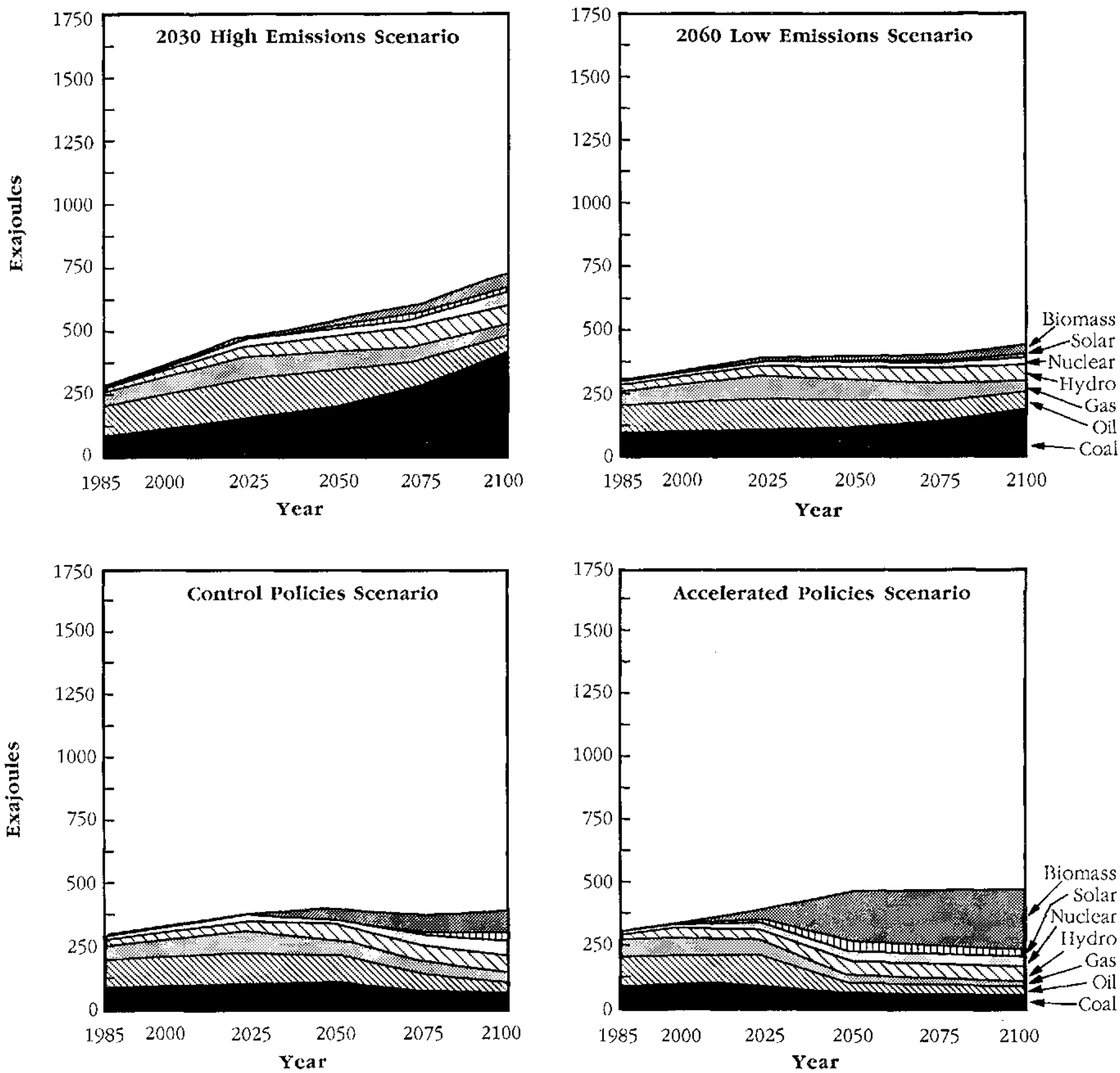


FIGURE 2.4: Global Primary Energy Supply by Type: Higher Growth

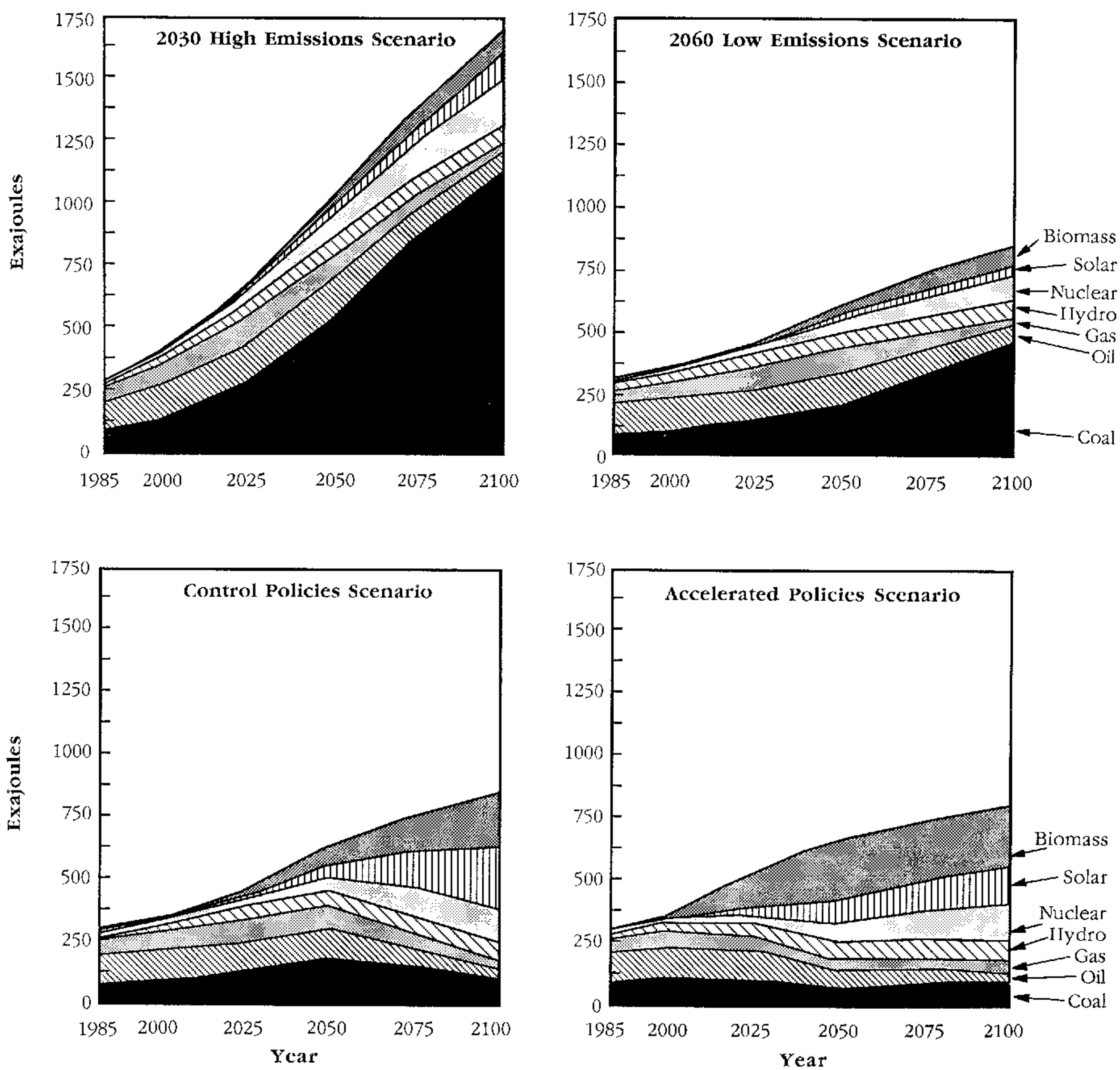


FIGURE 2.5: Primary Energy Consumption by Region: Lower Growth

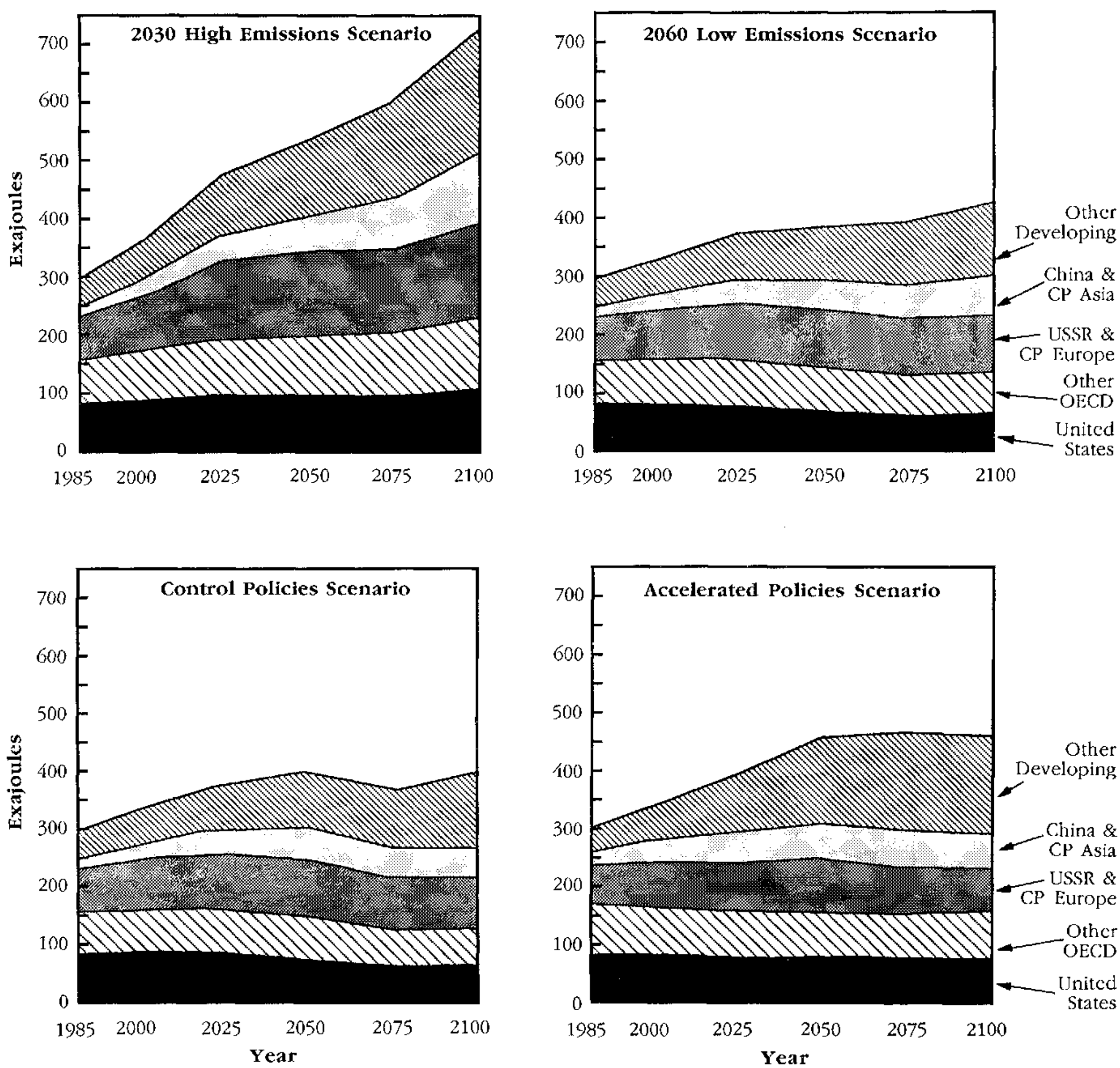


FIGURE 2.6: **Primary Energy Consumption by Region: Higher Growth**

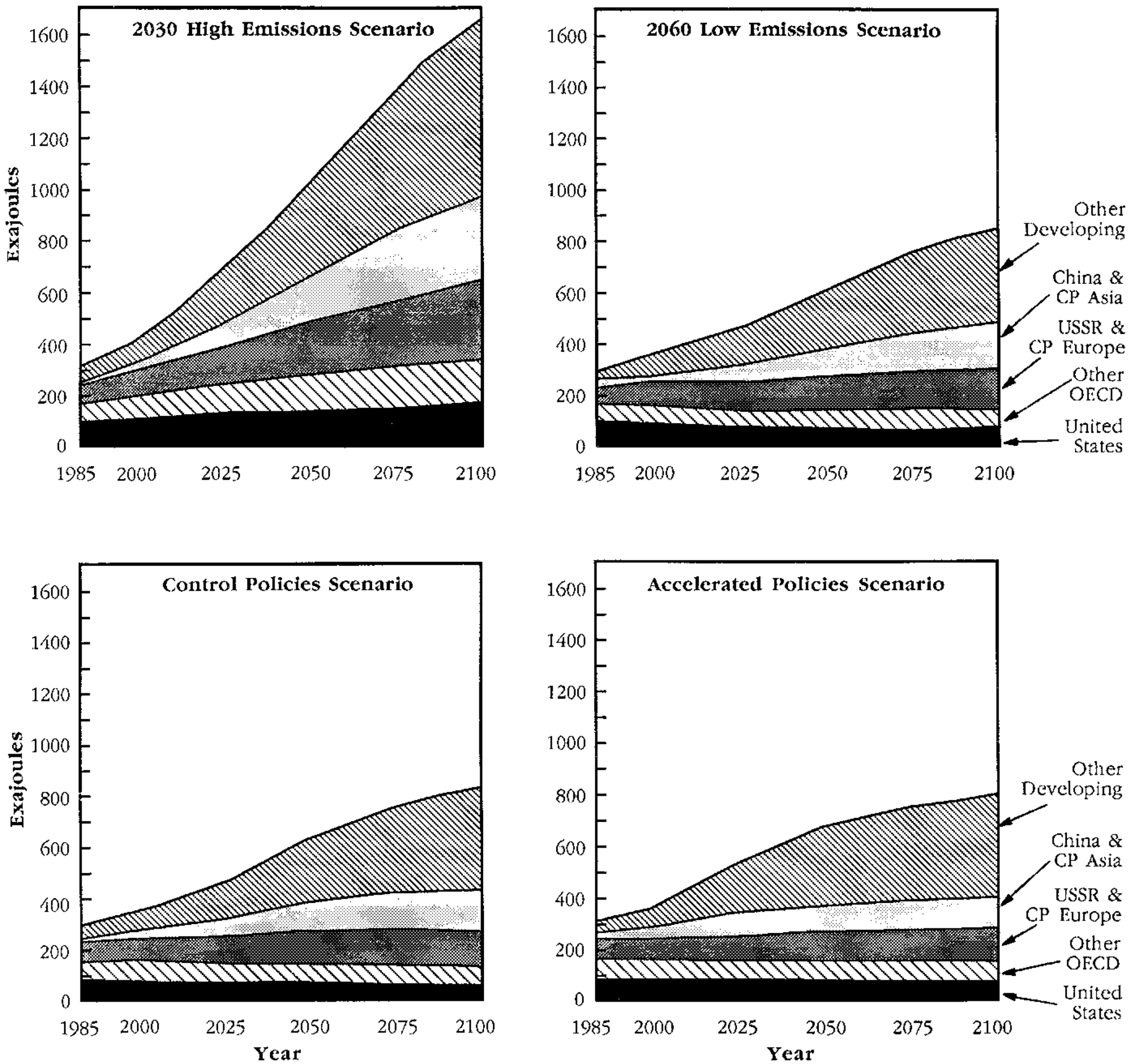


FIGURE 2.7: CO_2 Emissions from Fossil Fuels

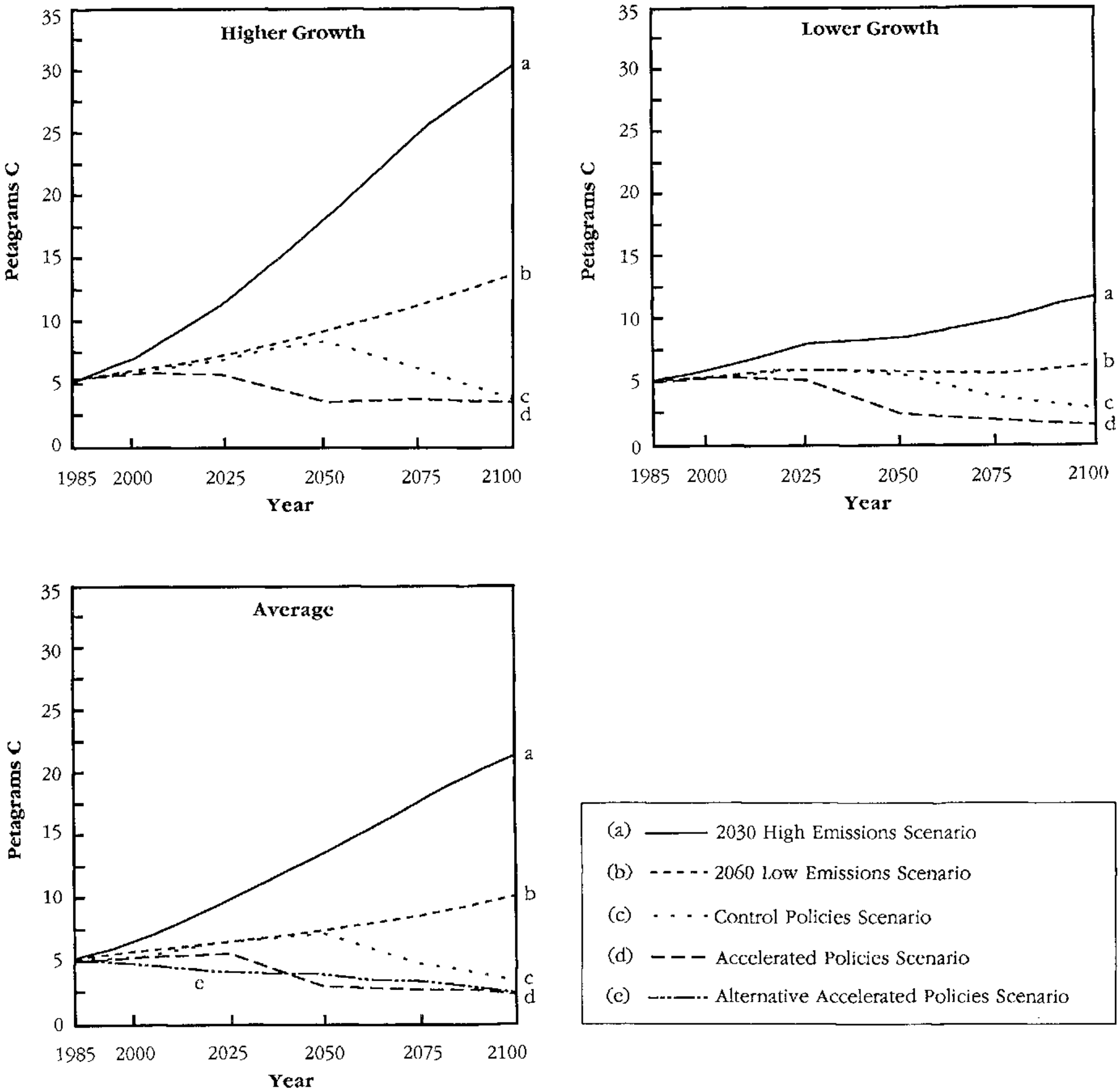
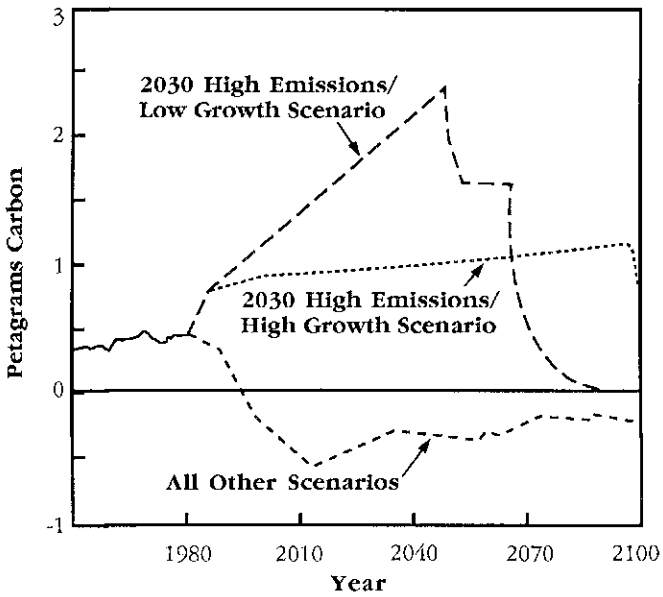


FIGURE 2.8: **Net CO_2 Emissions from Deforestation (Petagrams Carbon)**



2.4.2.2 *2060 Low Emissions, Control Policies, and Accelerated Policies Scenarios*

All of the other scenarios use the Reforestation assumptions, which yield a total release of carbon from deforestation of 10 Pg C, but a total accumulation of carbon from reforestation of 35 Pg C between 1985 and 2100. Therefore, net accumulation over the period is 25 Pg C, with annual accumulation peaking at about 0.7 Pg C before 2025.

Because of differences in modeling approaches and in input assumptions it is difficult to compare the results of the ASF to the results from IMAGE from land-use change. The results from IMAGE are more pessimistic and tend to yield greater net emissions of CO_2.

2.4.3 Agricultural Sector

The land area used for rice production increases by nearly 45 percent between 1985 and 2100. As a result of increased population and income, demand for animal protein rises: between 1985 and 2100, dairy production increases by 135 percent and meat production increases by about 120 percent. Satisfying the demands of increasing populations with a finite amount of land requires more intensive cultivation, increasing fertilizer use by 160 percent.

2.4.3.1 *2030 High Emissions and 2060 Low Emissions Scenarios*

Emissions of CH_4 and N_2O in the 2030 High Emissions and 2060 Low Emissions scenarios increase proportionately with agricultural activities. CH_4 from rice production increases 45 percent, and from enteric fermentation, 125 percent. N_2O from fertilizer use increases 155 percent by 2100.

2.4.3.2 *Control Policies and Accelerated Policies Scenarios*

By 2100, emissions of CH_4 and N_2O are roughly 45 percent lower in the Control Policies and Accelerated Policies scenarios owing to the assumed decline in emission coefficients.

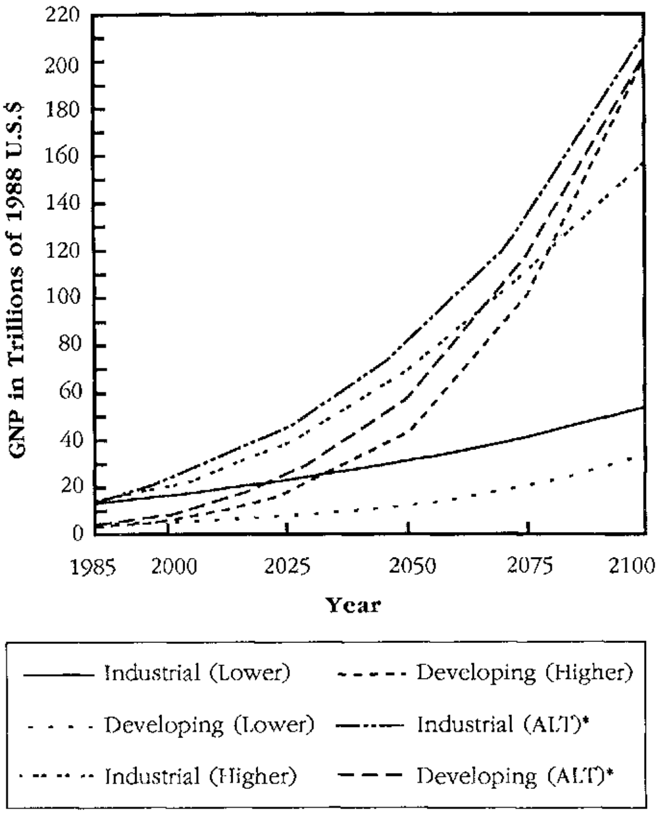
2.5 SENSITIVITY ANALYSIS

2.5.1 Economic Goals and Emissions

At the May meeting of RSWG in Geneva, the Japanese delegation suggested that the implications of different CO_2 pathways be shown by estimating and graphing three parameters for each scenario: GNP, Energy/GNP, CO_2/Energy. These values for all nine scenarios are presented in Figures 2.9, 2.10, and 2.11; Figure 2.9 shows global GNP, Figure 2.10, energy/GNP, and Figure 2.11, CO_2/unit energy. Although the scenarios are believed to be technically feasible, the economic implications of these changes should be explored in the national analyses being performed by participating countries in RSWG. Also, it should be noted that the assumed levels of long run economic growth may not represent accurate measures of human welfare, especially in the developed countries.

The scenarios illustrate the possible potential growth in emissions from developing countries and highlight the importance of addressing the causes for this growth in global strategies to limit emis-

FIGURE 2.9: **Alternative GNP Paths for Industrialized and Developing Nations (Trillions U.S.$)**



* Path labeled "ALT" represents the Alternative Accelerated Policies Scenario.

sions. The higher rates of economic growth assumed for the developing countries account for much of the emission growth, and efforts to limit emissions and maintain economic growth could require both technology transfer and financial assistance from developed countries.

2.5.2 THERE ARE MANY WAYS TO GET THERE

The alternative societal, economic, policy, and technological paths incorporated in the scenarios do not cover the infinite variety of ways the future may unfold. At every step in the development of scenarios, trade-offs had to be made. It is possible to construct emission scenarios that would result in similar equivalent CO_2 concentrations assuming either high or low rates of economic growth, a high percentage of CO_2 emissions, or a high percentage of emissions of other greenhouse gases, that energy intensity reductions (due to technological change) increase end-use energy efficiency, that non-fossil energy supplies (e.g., renewable or nuclear) are substituted for fossil fuels, and that lifestyle changes alter the composition of final demand. Alternative scenarios could have been constructed with greater emphasis on the role of such factors as the amounts and modes of travel, the size of buildings, and the composition of industrial and agricultural output, for example.

While the assumed rate of economic growth is one of the most powerful determinants of the rate of greenhouse gas emissions, it is by no means the only determinant. Other important factors can potentially offset the association between higher economic growth and higher rates of greenhouse gas emissions. For example, a higher rate of economic growth makes it possible for capital stocks (e.g., power plants, factories, housing) to be refurbished or replaced more quickly, and makes the accelerated penetration of advanced technologies possible. Similarly, under slow economic growth an increase in deforestation may be more likely because of a lack of other economic opportunities. The alternative scenarios were constructed with these factors in mind.

Other greenhouse gas emissions could prove more important than indicated in the scenarios here. For example, higher anthropogenic emissions rates for CO and N_2O, still within the bounds of current scientific understanding, could have been assumed. Similarly, less optimistic assumptions about the ability to reduce emissions of CO, CH_4, and NO_x would have resulted in higher emissions of these gases, which would require greater reductions of greenhouse gases emissions from other sources in order to meet an equivalent CO_2 concentration target.

Less optimistic assumptions about the feasibility and impact of reforestation policies could also increase the need to reduce emissions of greenhouse gases from other sources in order to maintain equivalent CO_2 concentrations below stated goals. Similarly, if the competition for land—for agricultural use, biomass production, reforestation, and forest conservation—were to drive up costs faster than assumed in these scenarios, biomass production would decline and CO_2 emissions would be higher. This would require stronger emission reduction efforts in other areas, for example, in increased energy efficiency.

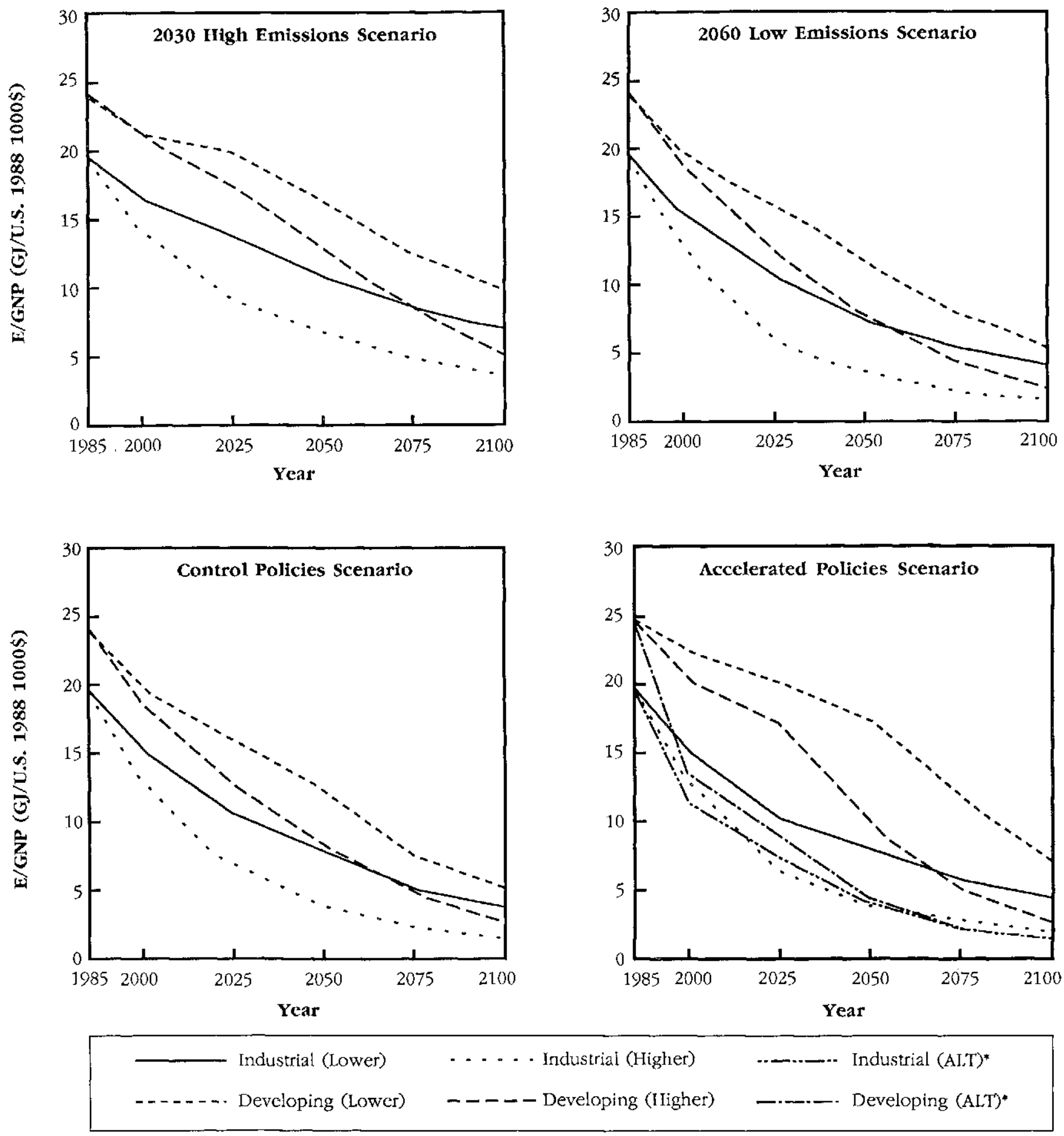
2.5.3 Reference to Other Studies and Proposals

The expert group responded only to the criteria established by Working Group I and RSWG to construct the reference scenarios. Other studies have suggested alternatives. Conclusions reached by the Bellagio Workshop (Jaeger, 1988) suggested that an ecological goal of a 0.1 degree C temperature increase per decade might be desirable. The Bruntland Commission emphasized the need for sustainable development and mentioned the desirability of a 50 percent reduction in primary energy consumption in industrialized countries by 2030, and the Toronto Conference, "The Changing Atmosphere—1988," suggested additional short-term emission reduction goals. The expert group did not attempt to analyze these alternatives. It should be noted that for the Accelerated Policies scenarios, primary energy use in industrialized countries stays relatively flat through 2025, as do global CO_2 emissions from the commercial energy sector. In the future it may be desirable to compare the results of these global analyses with results from studies using national models that can evaluate future emissions scenarios in greater detail.

2.5.4 Time Profile of Emissions

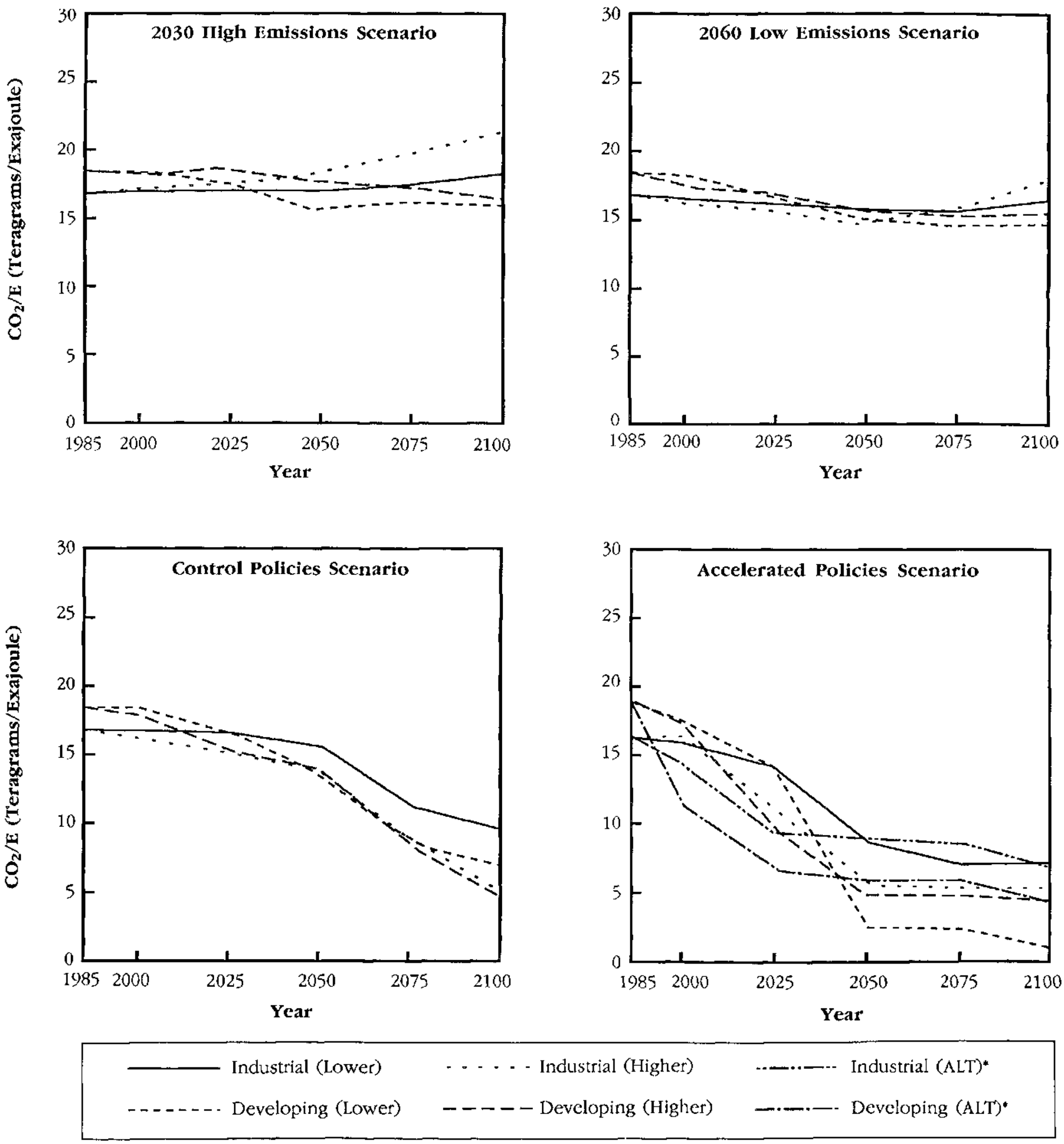
The expert group recognized that emissions and concentrations in the future are not only a function of factors such as economic growth and technological change, but also of when measures to reduce emissions are adopted. To explore this issue, a preliminary sensitivity analysis was undertaken using IMAGE. In this analysis stable atmospheric concentrations equivalent to a doubling of CO_2 by the year 2090 were used as a target. The simulations utilized the emissions estimates from the 2030 High Emissions (Average) scenario, but modified the emissions at different points in time (2000, 2010, 2020, and 2030) in order to achieve the goal of keeping greenhouse gas concentrations from doubling. In all cases, CO_2 emissions have to decline in order to achieve stable concentrations at the $2xCO_2$-equivalent level in 2090, but Figures 2.12 and 2.13 clearly show that emissions would have to be curtailed sharply if the emissions reduction measures are delayed until a later date. For example, if emissions reduction measures are begun in 2000, a gradual 17 percent reduction in CO_2 emissions (from 2000 levels) is sufficient to meet the targeted concentrations. If measures are not implemented until 2020, however, the model calculates that a reduction of 60 percent (from 2020 levels) is necessary to achieve the targets.

FIGURE 2.10: **Alternative Energy Intensities for Industrialized and Developing Nations**



* Path labeled "ALT" represents the Alternative Policies Scenario.

FIGURE 2.11: **Alternative Carbon Intensities for Industrialized and Developing Nations**



* Path labeled "ALT" represents the Alternative Accelerated Policies Scenario.

FIGURE 2.12: CO_2 Emissions for Delayed Response Analysis

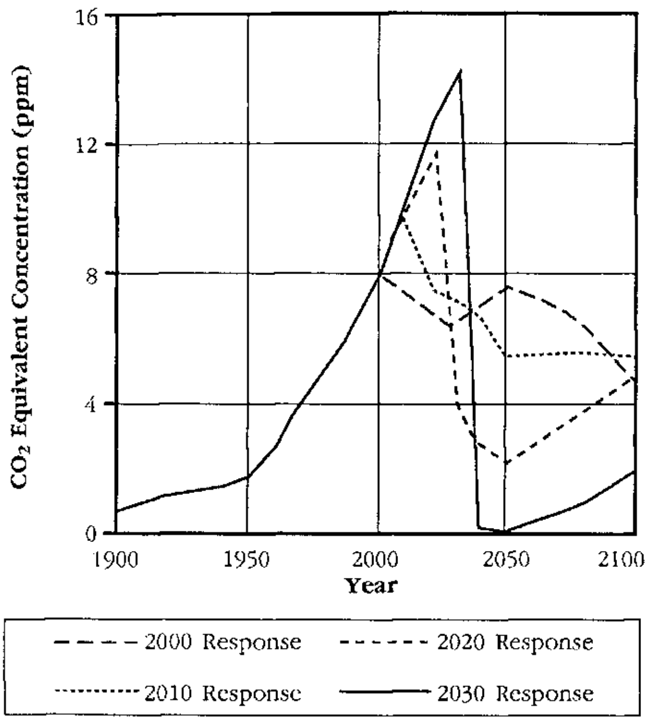
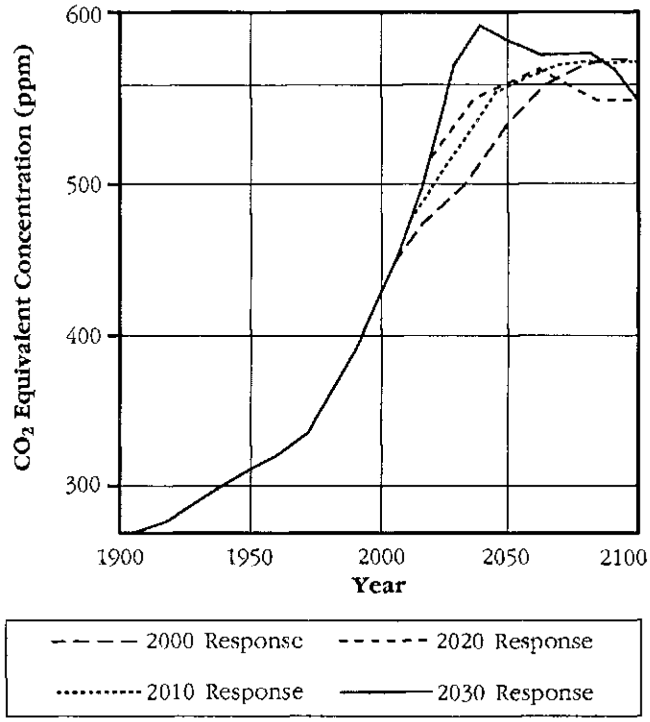


FIGURE 2.13: CO_2 Equivalent Concentrations for Delayed Response Analysis



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