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Policy Options For Stabilizing Global Climate

Report To Congress Main Report



POLICY OPTIONS FOR STABILIZING GLOBAL CLIMATE

REPORT TO CONGRESS

Editors: Daniel A. Lashof and Dennis A. Tirpak

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FOREWORD

I am pleased to transmit the attached <u>Policy Options for</u> <u>Stabilizing Global Climate</u>, the second of two reports on global climate change prepared in response to a Congressional request in the Fiscal Year 1987 Continuing Resolution Authority. The first report assessed the potential health and environmental effects of climate change on the U.S. This report examines a range of possible response options and estimates their potential for reducing or limiting emissions of greenhouse gases on a global scale.

The magnitude of the effort required to produce this report was greater than many had anticipated. The lead authors and many other contributors have nevertheless created an impressive and scholarly work that provides a valuable foundation for the additional research and analysis that will be needed for determining future policy actions. I would like to congratulate all those involved.

The report is one of the first to take a comprehensive and global approach, covering all sectors and all greenhouse gases, in the analysis of policy options for reducing greenhouse gases. It carefully describes the types of gases involved, their physical sources, and the level of emissions by source as well as geographic location. Based on a wide range of policy options, from energy efficiency to new methods of rice cultivation, it presents possible future scenarios of greenhouse gas emissions to the year 2100 depending on the level of response as well as many other independent factors.

The results demonstrate that greenhouse gas emissions can be effectively reduced. However, the report acknowledges that the actual size of these reductions will depend upon a great many factors, not the least of which are the accuracy of the data and the inherent limitations of the models employed in the analysis. Economic growth, population growth, and the extent to which countries respond to climate change are among the many other uncertainties.

Another key limitation of the report is that comprehensive estimates of the costs of achieving these reductions are not provided. This was a conscious decision based on the time and resources available for preparing the report, as well as the interest of several groups in undertaking their own cost analyses. Cost assessments have been conducted over the last year, both within EPA and among other agencies. Additional studies are underway that will improve our information on this important topic.

Since the final draft report was released approximately a year ago it has undergone a thorough and rigorous review. Several additional reports on responses to global climate change have also been issued which have provided a further basis for judging the quality and thoroughness of the report. These include reports by the Intergovernmental Panel on Climate Change, the Office of Technology Assessment, the National Research Council, and others. Remarkably, the final report has required only relatively minor improvements to meet the standards set by our reviewers as well as other experts studying the issue.

I believe this is not only due to the excellent effort devoted to the preparation of this report, but it is also a reflection of the broad consensus that exists concerning the nature and potential of the options we have for addressing the problem of global climate change.

Unfortunately, there is no silver bullet among them. Choosing among the wide range of options is thus going to be the toughest challenge we now face.

Terry Davies Assistant Administrator Office of Policy, Planning and Evaluation

This report would not have been possible without the tireless efforts of the primary chapter authors:

Executive Summary

Chapter I. Introduction

Chapter II. Greenhouse Gas Trends

Chapter III. Climate Change Processes

Chapter IV. Human Activities Affecting Trace Gases and Climate

Chapter V. Technical Options for Reducing Greenhouse Gas Emissions

Daniel Lashof Dennis Tirpak

Joel Scheraga Irving Mintzer

Inez Fung Michael Prather

> Daniel Lashof Alan Robock

Barbara Braatz Craig Ebert

Emissions Emissions Barry Solomon (Energy Services and Supply) Craig Ebert (Energy Supply) Joel Scheraga (Energy Supply) Michael Adler (Renewable Energy) Dilip Ahuja (Biomass) John Wells (Haolocarbons) Stephen Seidel (CFCs) Kenneth Andrasko (Forestry) Lauretta Burke (Agriculture)

Chapter VI. Thinking About the Future

Daniel Lashof Leon Schipper Barry Solomon

Chapter VII. Policy Options

Chapter VIII. International Cooperation to Reduce Greenhouse Gas Emissions

Appendix A. Model Descriptions

Appendix B. Implementation of the Scenarios

Appendix C. Sensitivity Analyses

Alan Miller

Alan Miller Jayant Sathaye

William Pepper Parvadha Suntharalingam

Craig Ebert

Craig Ebert Parvadha Suntharalingam Model integration was coordinated by William Pepper and Craig Ebert, with assistance from Rossana Florez. Models and/or analysis were prepared by Irving Mintzer; Jayant Sathaye, Andrea Ketoff, Leon Schipper, and Sharad Lele; Klaus Frohberg and Phil Vande Kamp; Richard Houghton; Berrien Moore, Chris Ringo, and William Emmanuel; Michael Prather; Ivar Isaksen, Terje Berntsen, and Sverre Solberg; and Anne Thompson.

Document integration was coordinated by Craig Ebert and Barbara Braatz. Editorial assistance was proved by Susan MacMillan. Technical, graphics, and typing assistance was provided by Julie Anderson, Patricia Baldridge, Karen Borza, Margo Brown, Donald Devost, Courtney Dinsmore, Katie Donaldson, Michael Green, Amy Kim, Judy Koput, Cheryl LaBrecque, Nathaniel Watkins, Cynthia Whitfield, Donna Whitlock, and Karen Zambri.

Literally hundreds of other people have contributed to this report, including the organizers and attendants at four workshops sponsored by the U.S. Environmental Protection Agency to gather information and ideas, and dozens of formal and informal reviewers. We would like to thank this legion for their interest in this project and apologize for not doing so individually. Particularly important comments were provided by, among other, Thomas Bath, Deborah Bleviss, Gary Breitenbeck, William Chandler, Jim Elkins, Robert Friedman, Howard Geller, James Hansen, Ned Helm, Tony Janetos, Stan Johnson, Julian Jones, Michael Kavanaugh, Andrew Lacis, Michael MacCracken, Elaine Matthews, Chris Neme, William Nordhaus, Steven Piccot, Steven Plotkin, Marc Ross, Stephen Schneider, Paul Steele, Pieter Tans, Thomas Wigley, Edward Williams, and Robert Williams.

This word was conducted within U.S. EPA's Office of Policy Analysis, directed by Richard Morgenstern, within the Office of Policy, Planning and Evaluation, administered by Linda Fisher. Technical support was provided by the Office of Research and Development, administered by Eric Brethauer.

ABSTRACT

The composition of Earth's atmosphere is changing. The concentration of carbon dioxide, the most important greenhouse gas accumulating in the atmosphere, has risen 25% since pre-industrial times. Significant increases in the concentrations of methane, chlorofluorocarbons, and nitrous oxide have also been observed. Present emission trends would lead to a continuing buildup of these gases in the atmosphere. Although there is a good deal of uncertainty about the timing, magnitude, and regional distribution of climate change that would occur if these trends are not reversed, significant global warming over the next century -- from 0.2 to 0.5 degrees C per decade -- is predicted by global climate computer models.

Drastic cuts in emissions would be required to stabilize atmospheric composition. Because greenhouse gases, once emitted, remain in the atmosphere for decades to centuries, stabilizing emissions at current levels would allow the greenhouse effect to continue to intensify for more than a century. Emissions of carbon dioxide might have to be reduced by 50-80% to hold its concentration constant.

While it is not possible to stabilize greenhouse gas concentrations immediately, world-wide implementation of measures to reduce emissions would decrease the risks of global warming, regardless of uncertainties about the response of the climate system. Scenario analyses indicate that if no policies to limit greenhouse gas emissions were undertaken, the equivalent of a doubling of carbon dioxide would occur between 2030 and 2040, and the Earth might be committed to a global warming of 2-4°C (3-7°F) by 2025 and 3-6°C (4-10°F) by 2050. Early application of existing and emerging technologies designed to, among other things, increase the efficiency of energy use, expand the use of non-fossil energy sources, reverse deforestation, and phase out chlorofluorocarbons could reduce the global warming commitment in 2025 by about one-fourth, and the rate of climate change during the next century by at least 60%. A global commitment to rapidly reducing greenhouse gas emissions might be able to stabilize the concentrations of these gases by the middle of the next century. perhaps limiting global warming to less than 2°C (3°F). The economic and technological analyses needed to determine the specific actions that would achieve such a large reduction at minimum cost have not yet been done. The economic feasibilities, costs, benefits, and other social and economic implications of such actions are not known. This study identifies a wide range of potential options and actions which appear promising based on available technical information. Further detailed study is required to determine the effectiveness and economic implications of each option.

There is a wide range of policy choices available that have the technical potential to reduce greenhouse gas emissions. Many also appear to be consistent with other economic, development, environmental, and social goals. Any effective strategy will require a variety of policies aimed at reducing emissions from many sources and obtaining the cooperation of many countries. Although a full assessment of the costs and benefits of each option has not been conducted, a number of potential actions or policies geared toward increasing energy efficiency, accelerating research and development, and reversing deforestation would have important benefits in addition to reducing greenhouse gas emissions. Decisions on the timing of U.S. policy responses should be based on a consideration of the multiple benefits and costs that might result from each policy, the additional commitment to warming caused by delaying action, and the role that U.S. leadership could play in promoting international cooperation to limit changes in climate variables to acceptable levels.

Much of the report's discussion necessarily cites information derived from U.S. experience and data because of the limitations of information about other regions. However, the report's discussion of emissions, potential response options, and their implications is from a world-wide perspective. Because of limitations in our knowledge, particularly about economic factors in many regions outside of the U.S., the report's findings and conclusions must be viewed as indicative and preliminary.

INTRODUCTION

The composition of the Earth's atmosphere is changing (see Figure 1). Although the specific rate and magnitude of future climate change are hard to predict, in the absence of policy responses the observed trends and projected increases in the atmospheric concentrations of greenhouse gases are likely to significantly alter the global climate during the next century. "Greenhouse" gases (carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide, among others) in the atmosphere absorb heat that radiates from the Earth's surface and emit some of this heat downward, warming the climate. Without this "greenhouse effect," the Earth would be about 30°C (60°F) colder than it is today. Human activities are now increasing the atmospheric concentrations of greenhouse gases on a global basis, thus intensifying the greenhouse effect. The rate of greenhouse gas buildup during the next century will depend heavily on future patterns of economic and technological development, which are, in turn, influenced by policies of local, state, national, and international institutions.

Purpose of This Study

To better define the potential effects of global climate change and identify the options that are available to limit human-caused climate change, Congress asked the U.S. Environmental Protection Agency (U.S. EPA) to undertake two studies. Congress directed that in one of these studies U.S. EPA focus on "the potential health and environmental effects of climate change." A companion report, *The Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989), responds to that request. The second request was that U.S. EPA undertake --

> An examination of policy options that if implemented would stabilize current levels of atmospheric greenhouse gas concentrations. This study should address the need for and implications of significant changes in energy policy, including energy efficiency and development of alternatives to fossil fuels; reductions in the use of CFCs; ways to reduce

other greenhouse gases such as methane and nitrous oxide; as well as the potential for and effects of reducing deforestation and increasing reforestation efforts.

This study responds to that request by examining the impact of a wide variety of policy options under a range of possible economic and technologic developments. The analysis shows that while it is not possible to stabilize greenhouse gas concentrations immediately, a global commitment to rapidly reduce greenhouse gas emissions might be able to stabilize their concentrations by the middle of the next century and even reduce concentrations toward current levels by the end of the next century. While humans may have already committed the earth to significant climate change during the next century, efforts undertaken now to limit the buildup of greenhouse gases in the atmosphere can dramatically reduce the rate and ultimate magnitude of such change.

Scope of This Study

The scope of this study is necessarily global and the time horizon is more than a century. To address this complex problem the Agency enlisted the help of leading experts in the governmental, non-governmental, and academic research communities. Five workshops, which were attended by over 300 people, were held to gather information and ideas about factors affecting atmospheric composition and about response options related to greenhouse gas emissions from agricultural and forestry practices, industrial processes, and energy consumption and supply, as well as the extent to which developing countries may be contributing to potential global warming. Experts at NASA, the U.S. Department of Energy (U.S. DOE), and the U.S. Department of Agriculture (U.S. DOA) contributed to this effort.

Based on the outcome of this information-gathering process, U.S. EPA developed an integrated analytical framework to organize the data and assumptions required to calculate (1) emissions of radiatively and chemically active gases, (2) concentrations of greenhouse gases, and (3) changes in global





Figure 1. Figure 1(a) depicts monthly concentrations of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. Figure 1(b) represents the annual emissions of CO_2 , in units of carbon, due to fossil-fuel combustion. (Sources: Keeling, 1983, and pers. communication; Komhyr et al., 1985; NOAA, 1987; Conway et al., 1988; Rotty, 1987, and pers. communication.)

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temperatures. This framework is highly simplified, as its primary purpose is to rapidly scan a broad range of policy options in order to test their general effectiveness in reducing atmospheric concentrations of greenhouse gases. This analysis represents the first attempt to quantify the relationship between certain underlying forces (e.g., population growth, economic growth, and technological change) and emissions of all of the important greenhouse gases. By using this framework we were able to estimate how assumed changes in these underlying forces would affect the composition of the atmosphere and global temperatures. It should be kept in mind that the uncertainties in deriving temperature changes from changes in greenhouse gas concentrations are substantial. In constructing this framework, we used the results of more sophisticated models of individual components as a basis for our analysis (see Appendix A for more discussion of this framework). While we believe that this framework generally reflects the current state of scientific knowledge, there are important limitations.

Current Policy Developments

The primary objective of this report is to begin discussion of policies that could be adopted by the global community to respond to climate change concerns. We have not specifically focused on policies for the United States, but current developments in U. S. policy are an important part of the background information for readers of this report.

Since this study was completed, many countries have already made commitments to goals or actions that help to reduce net greenhouse gas emissions. In the United States the focus has been on actions that also have benefits for reasons other than climate change. Because of these other benefits, such actions can be justified despite the very substantial scientific and economic uncertainties associated with climate change issues.

The 1990 Clean Air Act Amendments contain provisions to attain and maintain National Ambient Air Quality Standards by regulating emissions of volatile organic compounds, nitrogen oxides, and carbon monoxide. The Amendments will not only produce cleaner air, but also significantly affect greenhouse gases or their precursors. Major reductions of sulfur dioxide to 10 million tons below 1980 levels and of nitrogen oxides to 2 million tons below projected year 2000 levels will reduce greenhouse gas emissions by greatly encouraging energy efficiency. Phasing out CFCs, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs) in accordance with the Montreal Protocol and the Clean Air Act will substantially reduce emissions of greenhouse gases as well as protect the stratospheric ozone layer.

The President's proposed program for planting a billion trees a year will produce for wildlife. substantial benefits soil conservation, and energy saving, as well as directly take up CO₂ from the atmosphere. The increase in the Federal gasoline tax enacted in the Budget Reconciliation Act of 1990 will reduce emissions by encouraging energy efficiency in road transportation. Increased funding requested in the FY 1991 budget for research and development in solar and renewable energy and energy conservation will be important in identifying and developing technologies and practices that will allow us to meet our energy needs in environmentally efficient ways. New energy saving appliance standards promulgated by the Department of Energy will increase energy conservation and reduce demand.

The U. S. has committed to specific policy actions without specifying the future level of aggregate emissions that will be realized. Several other countries have committed to quantitative, aggregate, future emission goals but have not specified the policy actions that will ensure achievement of those goals. The U. S. actions may have effects on emissions as substantial as the target emissions levels being promised for future achievement by a number of other countries.

Limitations

The analytical framework used in this report attempts to incorporate some representation of the major processes that will influence the rate and magnitude of greenhouse warming during the next century within a structure that is reasonably transparent and easy to manipulate. In so doing we recognize a number of major limitations.

Because of the scope of the analysis, it was not possible to come up with comprehensive estimates of the costs or benefits associated with each policy option. We have instead relied on available engineering cost estimates and judgment to select options that appear to be the most attractive. Subsequent studies, currently under way, will provide more detailed economic analysis for the next few decades on a countryby-country basis. In particular there are serious limitations in economic activity, cost, and emission factor data for regions outside of the U.S., particularly for the developing Thus, the implications of each countries. policy option for such regions are preliminary and uncertain. The policy options presented herein should therefore be viewed as examples of what could be done to reduce the buildup of greenhouse gases, not as recommendations of what should be done.

Forecasting rates of economic growth and technological change over decadal time periods is difficult, if not inherently impossible. For this reason, the scenarios of this report should not be viewed as forecasts or predictions. While we believe that the scenarios presented in this report provide a useful basis for analyzing policy options, our alternative assumptions may not adequately reflect the plausible range of possibilities. For example, we have assumed that aggregate economic growth rates will generally decline over time from the levels assumed for 1985-2000; this may not be the case. Similarly, assumed improvements in energy-consuming and -producing technology in the No Response and/or the Stabilizing Policy scenarios (see Table 2 for a description) may prove to be too optimistic or pessimistic.

The use of simplified models also implies that some potentially important processes and interactions cannot be accounted for. These include the macroeconomic implications of the projected changes in climate and the options designed to limit these changes. Similarly, capital markets are not explicitly considered. This is particularly significant with regard to developing countries, as it is unclear if they will be able to obtain the capital needed to develop the energy supplies assumed in some of the scenarios. Additionally, the simplified atmospheric chemistry and ocean models employed may not adequately reflect the underlying processes, particularly as climate changes. Similarly, the parametric model used to relate global temperature increases to concentrations of greenhouse gases may not be valid for extrapolations beyond 6°C.

Behavioral changes that might be ٠ stimulated by climate change, by policies, or by individual choices to limit climate change also have not been considered. Individual decisionmakers will take actions to adapt to any changes in climatic conditions. The nature, costs, and benefits of these actions and behavioral changes are not adequately defined and understood. For example, future population levels will have an important impact on greenhouse gas emissions, but reduced rates of population growth have not been analyzed as a policy response.

HUMAN IMPACT ON THE CLIMATE SYSTEM

The Greenhouse Gas Buildup

Many greenhouse gases are currently accumulating in the atmosphere. The most important, in terms of past and current contribution to radiative forcing, is carbon dioxide (CO_2) , followed by methane (CH_4) , chlorofluorocarbons (CFCs), and nitrous oxide (N_2O) (see Figure 2 and Box 1). Carbon dioxide, a fundamental product of burning fossil fuels (coal, oil, and gas), is also released as a result of deforestation. There are many sources of methane, including rice cultivation, enteric fermentation in animals, releases during coal mining and natural gas production and distribution, waste decomposition in landfills, as well as many natural sources. CFCs, however, are produced only by the chemical industry. The sources of nitrous oxide are not well characterized, but most are probably related to soil processes; the most important anthropogenic sources are fertilizer use and various land-use changes such as burning. deforestation and savanna Greenhouse gases of natural origin include





Figure 2. Based on estimates of the increase in the concentration of each gas during the specified period. Other includes additional CFCs, halons, changes in ozone, and changes in stratospheric water vapor. The other category is quite uncertain. (Sources: 1880-1980: Ramanathan et al., 1985; 1980s: Hansen et al., 1988.)

Box 1. Concept of Global Warming Potential

Throughout this Report, relative contributions to climate change by greenhouse gas are calculated based on changes in atmospheric concentrations of each gas. These concentration changes alter the radiative balance of the climate system. The scientific community has in the past calculated contributions to radiative forcing using estimated changes in atmospheric concentrations over some time interval (e.g., 10 years); this approach is reflected in the left-hand figure below (and also in Figure 2) based on Hansen et al. (1988). When discussing the various greenhouse gases in a policy context, however, there is often a need for policymakers to have some simple means of estimating the relative impacts of emissions of each greenhouse gas to affect radiative forcing, and hence climate, without the complex, time-consuming task of determining the impacts on atmospheric concentrations. Since this Report was first prepared, several researchers have developed indices that translate the level of emissions of the various greenhouse gases into a common metric in order to compare the climate-forcing effects of the gases. The index has been called the Global Warming Potential (GWP), and is defined as the time integrated commitment to climate forcing from the instantaneous release of 1 kilogram of a trace gas expressed relative to that from 1 kilogram of carbon dioxide. For purposes of illustrating this concept, we have used the GWP methodology developed by the Intergovernmental Panel on Climate Change for an integration period of 100 years (IPCC, 1990) to express 1985 emissions on a CO₂-equivalent basis in order to compare the results to the methodology used by Hansen et al. (1988); see right-hand figure below. These two approaches produce very different results since Hansen et al. (1988) base their approach on the radiative forcing effects of estimated changes in atmospheric concentrations from 1980-90, while the use of GWPs measures the radiative forcing effects of emissions for a single year (i.e., 1985) over a 100-year time frame (see Addendum to Chapter II for a complete discussion of this concept). This report uses the Hansen et al. (1988) methodology when discussing relative current contributions of different gases and source categories. Use of the IPCC or other alternative integrating methodologies would change the values of these shares somewhat.



water vapor and all of those listed above except the chlorofluorocarbons.

Stabilizing emissions of greenhouse gases at current levels will not stabilize concentrations. Once emitted, greenhouse gases remain in the atmosphere for decades to centuries. As a result, if emissions remained constant at 1985 levels, the greenhouse effect would continue to intensify for more than a century. Carbon dioxide concentrations might reach 440-500 parts per million (ppm) by 2100, compared with about 350 ppm today, and about 290 ppm 100 years ago (see Figure 3). Nitrous oxide concentrations would probably about 20%: methane increase bv concentrations might remain roughly constant.

Drastic cuts in emissions would be required to stabilize atmospheric composition. This assertion is based on the fact that these gases remain in the atmosphere for a very long time and that constant emissions at current levels would lead to a continuing increase in concentrations. Emissions of CO_2 , for example, would have to be reduced by 50-80% to stabilize atmospheric concentrations (see Table 1). Even if all anthropogenic emissions (i.e., emissions caused by human activities) of CO_2 , CFCs, and N_2O were eliminated, the concentrations of these gases would remain elevated for decades. It would take more than 50 years, and possibly more than a century, following a cut-off in CO_2 emissions for the oceans and other sinks to absorb enough carbon to reduce the atmospheric concentration of CO₂ halfway toward its pre-industrial value.

The Impact of Greenhouse Gases on Global Climate

Uncertainties about the impact of the greenhouse gas buildup on global climate abound. These uncertainties are not about whether the greenhouse effect is real or whether increased greenhouse gas concentrations will raise global temperatures. Rather, the uncertainties concern the ultimate magnitude and timing of warming and the implications of that warming for the Earth's climate system, environment, and economies.

TABLE 1

Approximate Reductions in Anthropogenic Emissions Required to Stabilize Atmospheric Concentrations at Current Levels

GAS	REDUCTION REQUIRED
Carbon Dioride	50-80%
Methane	10-20%
Nitrous Oxide	80-85%
Chlorofluorocarbons	75-100%
Carbon Monoxide (CO)	Freeze
Oxides of Nitrogen (NÓ _x)	Freeze

The magnitude of future global warming will depend, in part, on how geophysical and biological feedbacks enhance or reduce the warming caused by the additional infrared radiation absorbed by increasing concentrations of greenhouse gases. The ultimate global average temperature increase that can be expected from a specific increase in the concentrations of greenhouse gases can be called the "climate sensitivity." This parameter provides a convenient index for the magnitude of climate change that would be associated with different scenarios of greenhouse gas buildup. (In this report we use a doubling of the concentration of CO₂ from pre-industrial levels, or the equivalent from increases in the concentrations of a number of greenhouse gases, as the benchmark case.)

Estimating the impact of increasing greenhouse gas concentrations on global climate has been a focus of research within the atmospheric science community for more than a decade. This research shows that:

• If nothing else changed in the Earth's climate system except a doubling of CO_2 (or the equivalent in other greenhouse gases), average global temperature would rise 1.2-1.3°C.



Figure 3. The response of atmospheric CO_2 concentrations to arbitrary emissions scenarios, based on two one-dimensional models of ocean CO_2 uptake. The emissions scenarios are relative to estimated 1985 levels of 5.9 billion tons of carbon per year. (Sources: Hansen et al., 1984; Lashof, 1989; Siegenthaler, 1983.)

• Increased global temperatures would raise atmospheric levels of water vapor and change the vertical temperature profile, raising the ultimate global warming caused by a doubling of CO_2 . Changes in snow and ice cover are also expected to enhance warming. There is strong consensus that if nothing other than these factors changed in the Earth's climate system, the global temperature would rise by 2-4°C.

• The impact of changes in clouds on global warming is highly uncertain. General circulation models now generally project that the global warming from doubling CO_2 could cause changes in clouds that would either enhance this warming or diminish it somewhat.

• A variety of other geophysical and biogenic feedbacks exist that have generally been neglected in global climate models. For example, future global warming has the potential to increase emissions of carbon from northern latitude reservoirs in the form of both methane and carbon dioxide, and to alter uptake of CO_2 by the biosphere and the oceans. Modeling analyses attempting to incorporate feedbacks result in a wider range of possible warming, i.e., 1.5 to 5.5° C, for an initial doubling of CO_2 .

Global warming of just a few degrees would represent an enormous change in climate. The difference in mean annual temperature between Boston and Washington is only 3.3° C, and the difference between Chicago and Atlanta is 6.7° C. The total global warming since the peak of the last ice age, 18,000 years ago, was only about 5° C. That change transformed the landscape of North America, shifting the Atlantic ocean inland by about one hundred miles, creating the Great Lakes, and changing the composition of forests throughout the continent.

The potential future impacts of climate change are difficult to predict and are beyond the scope of this report. Although global temperature change is used as an indicator of climate change throughout this report, it is important to bear in mind that regional changes in temperature, precipitation, storm frequency, and other variables will determine the environmental and economic impacts of climate change. Predictions of such regional changes in climate are highly uncertain at this time.

Sensitivity analyses can be undertaken to estimate potential impacts, as was done in the companion volume, *The Potential Effects of Global Climate Change on the United States*. The collective findings of that study suggest that the climatic changes associated with a global warming of roughly 2-4°C would result in

> a world different from the world that exists today. . . . Global climate change could have significant implications for natural ecosystems; for where and how we farm; for the availability of water to irrigate crops, produce power, and support shipping; for how we live in our cities; for the wetlands that spawn our fish; for the beaches we use for recreation; and for all levels of government and industry (Smith and Tirpak, 1989, p. xxx).

Natural Climate Variability

Because of long-period couplings between different components of the climate system, for example, between ocean and atmosphere, the Earth's climate would still vary without being perturbed by any external influences. This natural variability could act to add to, or subtract from, any human-made warming. Natural emissions and variations contribute significantly to climate change. Climate variations from glacial to interglacial periods have been caused naturally. Controlling anthropogenic greenhouse gas emissions will not prevent natural climate change.

SCENARIOS FOR POLICY ANALYSIS

Defining Scenarios

Defining scenarios that encompass more than a century is a daunting task. While this is an eternity for most economists and planners, it is but a moment for geologists. And indeed, decisions made in the next few decades, about how buildings are constructed, electricity is generated, and cities are laid out, for example, will have an impact on the climate in 2100 and beyond. Decisions about what kinds of automobiles and other industrial products to produce and how to produce them will also have a profound impact. These choices, which will affect the amount and type of fuel we use to travel, to heat and light our homes and offices, and to run our factories, will influence the magnitude of greenhouse gas emissions for many years.

To explore the climatic implications of such policy and investment decisions, we have constructed six scenarios of future patterns of economic development, population growth, and technological change. These scenarios start with alternative assumptions about the rate of economic growth and policies that influence emissions, such as those affecting levels of future energy demand, land-clearing rates, CFC production, etc. These scenarios are intended to be internally consistent pictures of how the world may evolve in the future. They are not forecasts and they do not bracket the full range of possible futures. Instead, they were chosen to provide a basis for evaluating strategies for stabilizing the atmosphere in the context of distinctly different, but plausible, conditions.

Specifically, the policy scenarios discussed in this report are meant to stimulate They do not constitute further study. conclusions about what would be the most feasible and cost-effective strategies or plans for responding to climate change and should not be interpreted as such. What they do show is that no single measure or limited set of a few measures would be an adequate response to climate change. They also show that there are a great many potential options, each one of which alone would have only a modest impact. Finally, they show that much more work is needed to evaluate the physical, social, and economic implications of each policy option and to identify the least socially and economically disruptive approaches.

Deciding on an overall climate change response strategy will be extremely difficult taking into account all of the unknowns and uncertainties. The need for world-wide cooperation in a strategy complicates the

policy-making problem. However, the U.S. has many potential options from which, if their implications are well understood, it can develop a response that is likely to be both feasible and effective. It is already proceeding in this manner by immediately implementing a series of actions that can be justified for other reasons or by their benefits even in the face of the uncertainties. However, there are uncertainties even about how far those actions which the U.S. is already taking should be pursued. Not all levels of energy efficiency, tree planting, or increased levels of R & D are likely to produce benefits in excess of their costs. All countries in their specific economic contexts need to consider the costs, benefits, and uncertainties of taking various actions.

It should be noted that these scenarios have not been updated to reflect the current status of the Montreal Protocol as strengthened by the London Agreement to completely phase out CFCs, halons, carbon tetrachloride, and methyl chloroform, and to encourage limits on HCFCs.

Two scenarios explore alternative pictures of how the world may evolve in the future assuming that policy choices allow unimpeded growth in emissions of greenhouse gases (these are referred to as the "No Response" scenarios). One of these scenarios, called a Rapidly Changing World (RCW), assumes rapid economic growth and technological change; the other, called the Slowly Changing World (SCW), represents a more pessimistic view of the evolution of the world's economies. A variant of the RCW scenario, Rapidly Changing World with Accelerated Emissions (RCWA), assumes that efficiency improvements occur more gradually and that policies tend to favor increased greenhouse gas emissions. Two additional scenarios (referred to as the "Stabilizing Policy" scenarios) start with the same economic and demographic assumptions as the RCW and SCW, but assume a world in which nations have adopted policies to limit anthropogenic emissions of greenhouse gases. These scenarios are called the Slowly Changing World with Stabilizing Policies (SCWP) and the Rapidly Changing World with Stabilizing Policies (RCWP). In addition, a variant of the RCWP assumes more Rapid Reductions in greenhouse gas emissions (RCWR). In all of the scenarios it
is assumed that the key national and international political institutions evolve gradually, with no major upheavals. An overview of the scenario assumptions is provided in Table 2.

The analysis for this study included a detailed examination of energy demand for the We chose this date because, year 2025. although substantial change will have occurred by then, some currently existing infrastructure will still be in place and much of the technology to be deployed over this period is already under development. Scenarios extending beyond this date are speculative, but they are included because they are necessary to evaluate the full implications of more immediate decisions and because greenhouse gases affect warming for many decades. Projections to 2100 are based on the patterns and relationships established between 1985 and 2025. The six scenarios analyzed in this study were developed using the Atmospheric Stabilization Framework. This analytical framework was constructed for the purpose of evaluating the impact of all anthropogenic activities on the level of greenhouse gas emissions, and consequently, on the rate and magnitude of global climate change. For a description of this Framework, the reader is referred to Chapter VI and Appendix A.

It should be understood that the discussions of climate change in Chapter 3 and the discussions of the climate changes associated with the various scenarios are subject to great scientific uncertainties. The general circulation models, which are the basis for simulating climate changes, while among the most sophisticated tools available, are relatively simple compared to the feedback mechanisms and processes that operate in the real atmosphere/oceans system. The model physics grossly oversimplify the real world. The models do not yet adequately describe the present climate and, thus, projections must be viewed with extreme caution.

Scenarios with Unimpeded Emissions Growth

In "A Slowly Changing World" (SCW) we consider the possibility that the recent experience of modest growth will continue indefinitely, with no concerted policy response

to the risk of climate change. Per capita income in developing regions that have very high population growth is stagnant for several decades, and shows modest increases elsewhere. Economic growth rates per capita increase slightly over time in all developing regions as population growth rates gradually decline. The population engaged in traditional agriculture continues to increase, as does speculative land clearing and demand for fuelwood. These factors lead to accelerated deforestation until tropical forests are virtually eliminated toward the middle of the next century. Because of slack demand, real energy prices increase slowly. Productivity in industry and agriculture improves at only a moderate rate. Correspondingly, the energy efficiency of buildings, vehicles, and consumer products improves at a slow rate.

In "A Rapidly Changing World" (RCW) rapid economic growth and technological change occur with little attention given to the global environment. Per capita income rises rapidly in most regions and consumers demand more energy services, which puts upward pressure on energy prices. The number of cars increases rapidly in developing countries, and air travel increases rapidly in industrialized countries. Energy efficiency is not much of a consideration in consumer choices, as income increases faster than real energy prices, but efficiency increases do occur as a result of technological improvements. Correspondingly, we assume that there is a high rate of innovation in industry and that capital equipment turns over rapidly, thereby accelerating reductions in energy required per unit of industrial output. An increasing share of energy is consumed in the form of electricity, which is produced mostly from coal. The fraction of global economic output produced in the developing countries increases dramatically as services become more important in industrialized countries and as industries such as steel, aluminum, and automaking grow in developing countries. Population growth rates decline more rapidly than in the Slowly Changing World scenario as educational and income levels rise. Deforestation continues at about current rates, spurred by land speculation and commercial logging, despite reduced rates of population growth. Note that the SCW and RCW scenarios are not bounding cases with respect

TABLE 2

Overview of Major Scenario Assumptions

Slowly Changing World

Slow GNP Growth Continued Rapid Population Growth Minimal Energy Price Increases Slow Technological Change Carbon-Intensive Fuel Mix Increasing Deforestation Montreal Protocol/Low Participation

Slowly Changing World with Stabilizing Policies

Slow GNP Growth Continued Rapid Population Growth Minimal Energy Price Increases/Taxes Rapid Efficiency Improvements Moderate Solar/Biomass Penetration Rapid Reforestation CFC Phaseout

Rapidly Changing World with Accelerated Emissions

High CFC Emissions Cheap Coal Cheap Synfuels High Oil and Gas Prices Slow Efficiency Improvements High Deforestation High-Cost Solar High-Cost Nuclear

Rapidly Changing World

Rapid GNP Growth Moderated Population Growth Modest Energy Price Increases Rapid Technological Improvements Very Carbon-Intensive Fuel Mix Moderate Deforestation Montreal Protocol/High Participation

Rapidly Changing World with Stabilizing Policies

Rapid GNP Growth Moderated Population Growth. Modest Energy Price Increases/Taxes Very Rapid Efficiency Improvements Rapid Solar/Biomass Penetration Rapid Reforestation CFC Phaseout

Rapidly Changing World with Rapid Emissions Reductions

Carbon Fee High MPG Cars High Efficiency Buildings High Efficiency Powerplants High Biomass Penetration Rapid Reforestation to emissions, rather the assumptions are intended to be logically related, and therefore, have partially offsetting implications.

Without stabilizing policies, rapid greenhouse gas buildup and global warming are likely. The two worlds described above lead to significant increases in emissions of carbon dioxide and other trace gases (see Table 3) and in atmospheric concentrations of the greenhouse gases (see Figure 4). CO_2 concentrations reach twice their pre-industrial levels in about 2080 in the SCW scenario. In the RCW this level is reached by 2055, and concentrations more than three times preindustrial values are reached by 2100. When all the trace gases are considered, an increase in the greenhouse effect equivalent to that which would occur from a doubling of CO_2 concentrations is reached by 2040 in the SCW and by 2030 in the RCW. By 2100 the total radiative forcing is equivalent to a tripling of CO_2 in the SCW and a factor of 5 increase in the RCW. These results are in good agreement with those of recent studies that have made less formal estimates based primarily on current trends in concentrations and/or emissions. A notable exception are the results for CFCs. The June 1990 London Amendments will result in even lower concentrations of CFCs. However, because the London Amendments were adopted after this analysis, they are not included in the scenarios.

Even a Slowly Changing World would produce a 2-3°C temperature increase during the next century. In the SCW scenario, realized global warming would increase by 1.0-1.5°C between 2000 and 2050 and by 2-3°C from 2000 to 2100 (temperature ranges are based on a climate sensitivity of 2-4°C unless otherwise noted; see Box 2 and Figure 5). The maximum realized rate of change associated with this scenario is 0.2-0.3°C per decade, which occurs sometime in the middle of the next century. The total equilibrium warming commitment is substantially higher, reaching 3->6°C by 2100 relative to pre-industrial levels (see Table 4).¹

The "equilibrium warming commitment" is the warming that would eventually result from a given atmospheric composition assuming that it were to remain fixed at that level. Because the oceans adjust thermally over many years, it takes years or decades to reach the equilibrium warming. "Realized warming" is that portion of the equilibrium warming that has been reached at any point in time (see Box 2).

Higher rates of economic growth are certainly the goal of most governments and could lead to higher rates of climate change as illustrated by the RCW scenario. The rate of change during the next century would be more than 50% greater than in the SCW: in the RCW, realized global warming increases by 1.3-2.0°C between 2000 and 2050, and by 3-5°C between 2000 and 2100. The total equilibrium warming commitment reaches $5->6^{\circ}$ C by 2100. In this case the maximum realized rate of change is 0.4-0.6°C per decade, which occurs sometime between 2070 and 2100.

The Impact of Policy Choices

Government policies, if applied globally, could significantly increase or decrease future warming. The warming suggested by the Slowly Changing and Rapidly Changing World cases is not inevitable; it is the result of the public and private choices implicit in these scenarios. While some future warming probably is locked in, the range of possible future commitments to warming is enormous.

Accelerated Emissions Scenario

Decisions that will be made in the near future may lead to increased emissions if there is no clear policy goal to reduce them. This potential is illustrated by a series of tests that were conducted to examine the effect of accelerated emissions on equilibrium warming commitment. Starting with the RCW scenario, eight key parameters were varied as proxies for recently-proposed policies that have the potential to significantly increase greenhouse gas emissions (e.g., accelerated development of synfuels) or the possible consequences of government inaction or failure (e.g., high use of CFCs and deforestation).

TABLE 3

Trace Gas Emissions

	1985	2025	2100
			·····
CU ₂ (rg C)	60	96	10.7
PCW	6.0	9.0 12 A	26.1
RCW RCWA	6.0	21.9	20.1
SCWA	6.0	5.2	J4.0 24
DCWD	6.0		2.0
RCWR	6.0	21	5.5
N O (Ta N) ^b	0.0	2 . •	0.0
N ₂ O (Ig N)	125	165	15.6
DCW	12.5	16.5	13.0
RCW DCWA	12.5	10.1	10.1
RCWA	12.5	18.5	22.0
SCWP	12.5	13.1	12.8
RCWP	12.5	13.3	12.6
RCWR	12.5	13.1	12.5
CH_4 (Tg CH_4)			
SCW	510	690	830
RCW	510	730	1.130
RCWA	510	910	1.580
SCWP	510	540	480
RCWP	510	560	525
RCWR	510	520	460
NO (T N)			
NU _x (Ig N)	F 4		<i>(</i>)
SCW	54	71	69
RCW	54	79	122
RCWA	54	105	187
SCWP	54	48	45
RCWP	54	56	49
RCWR	54	53	48
CO (Tg C)			
ŠŚĆW	500	830	620
RCW	500	720	1,190
RCWA	500	980	1.120
SCWP	500	290	250
RCWP	500	290	230
RCWR	500	270	240
CEC-12 (Gals d			
SCW	365	395	425
BCW	365	450	520
DCWA	245	450	1 495
SCUM	245	500	70
	305	JU 05	/0 00
RCWP	303	85	90
RCWR	365	85	90
HCFC-22 (Gg) ^d			
SCW	74	405	880
RCW	74	830	3,125
RCWA	74	830	3,125
SCWP	74	405	880
RCWP	74	830	3.125
RCWR	74	830	3.125
	• •		-,

^a Pg C = Petagrams of carbon; 1 Petagram = 10¹⁵ grams. ^b Tg N = Teragrams of nitrogen; 1 Teragram = 10¹² grams. ^c Gg = gigagram; 1 gigagram = 10⁹ grams. ^d These scenarios were produced prior to the negotiations for the London Amendments to the Montreal Protocol. The CFC phaseout policy assumed in these policy scenarios is similar overall to, but somewhat more stringent than, the London Amendments.

FIGURE 4



ATMOSPHERIC CONCENTRATIONS (3.0 Degree Celsius Climate Sensitivity)

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FIGURE 5

REALIZED WARMING NO RESPONSE SCENARIOS



Figure 5. Shaded areas represent the range based on an equilibrium climate sensitivity of 2-4°C to a doubling of CO_2 .

TABLE 4

Realized Warming - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
SCW	0.5	0.7	1.2	1.7	2.2	2.6
RCW	0.5	0.7	1.3	2.0	2.9	3.8
RCWA	0.5	0.7	1.5	2.8	4.5	>6.0
SCWP	0.5	0.7	0.9	1.1	1.2	1.2
RCWP	0.5	0.7	1.0	1.2	1.4	1.5
RCWR	0.5	0.7	0.9	0.9	0.9	0.8
Realized Warming - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
SCW	07	10	18	26	34	42
RCW	0.7	1.0	1.9	3.0	4.4	6.0
RCWA	0.7	1.1	21	42	>60*	>60
SCWP	07	10	14	17	19	21
RCWP	0.7	1.0	1.4	19	22	25
RCWR	0.7	1.0	1.4	1.5	1.5	1.4
Equilibrium Warming Commitment - 2°C Se	nsitivity 1985	2000	2025	2050	2075	2100
SCW	0.7	11	17	23	28	33
RCW	0.7	1.1	1.7	2.5	2.0 4 ()	5.5
PCWA	0.7	1.1	1.9 7 A	13		>60°
SCWP	0.7	1.1	13	14	14	14
RCWP	0.7	1.0	1.5	1.4	1.4	1.4
RCWR	0.7	1.0	1.2	1.5	1.0	0.9
Equilibrium Warming Commitment - 4°C Sensitivity 1985		2000	2025	2050	2075	2100
SCW	15	22	35	47	57	>60*
RCW	1.5	2.2	3.2	5.8	>60*	>60*
RCWA	1.5	23	47	>60*	>60*	>60
SCWP	1.5	2.5	25	27	28	28
RCWP	1.5	2.0	2.5	21	2.0	37
RCWR	1.5	2.0	2.0	7 1	10	17
	1.5	2.0	4.3	4.1	1.7	1./

Scenario Results For Realized And Equilibrium Warming

[•] Estimates of equilibrium warming commitments greater than 6°C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms. These estimates are represented by >6°C.

Box 2. Equilibrium and Realized Warming

Equilibrium Warming Commitment

The equilibrium warming commitment for any given year is the temperature increase that would occur in equilibrium if the atmospheric composition was fixed in that year. This temperature may not be *realized* for several decades, and may not be realized at all if greenhouse gas concentrations fall.

Realized Warming

Because the oceans have a large heat capacity the temperature change realized in the atmosphere lags considerably behind the equilibrium level (the difference between the equilibrium warming and the realized warming in any given year is called the unrealized warming). Realized warming has been estimated with a simple model of ocean heat uptake.

Climate Sensitivity

Because the response of the climate system to changes in greenhouse gas concentrations is quite uncertain due to the role of clouds and other processes, we also consider a range of "climate sensitivities." Climate sensitivity is defined as the equilibrium warming commitment due to a doubling of the concentration of carbon dioxide from pre-industrial levels. Given a particular emissions scenario and climate sensitivity, the realized warming is much more uncertain than the equilibrium warming commitment because the effective heat storage capacity of the oceans is not known. On the other hand, because the amount of unrealized warming increases with increasing climate sensitivity, for a given scenario, realized warming depends less on climate sensitivity than does equilibrium warming commitment.

Figure 6 illustrates the results of these tests as compared with the RCW scenario. The results are illustrated in terms of the incremental effect of each outcome on the equilibrium warming commitment in 2050 and 2100. As Figure 6 shows, the measures that amplify the warming to the greatest extent are those that reduce the rate of efficiency improvement (historically, energy efficiency has improved about 1-2%/year), reduce the cost of synfuels, and increase the assumed rate of growth in CFC production and use. Policies leading to accelerated deforestation would have a large impact in the near term, but a relatively small impact in 2100.

The impact of all of these policies in combination is quite dramatic. In this case, emissions of CO_2 would be nearly five times pre-industrial levels. The rate of warming

during the next century would be over 60% higher than in the RCW scenario.

Scenarios with Stabilizing Policies

Three scenarios were constructed to explore the impact of policy choices aimed at reducing the risk of global warming. The Slowly Changing World with Stabilizing Policies, the Rapidly Changing World with Stabilizing Policies, and the Rapidly Changing World with Rapid Reductions start with the same economic and demographic assumptions used in the SCW and RCW scenarios, respectively, but assume that government leadership is provided to ensure that a wide range of measures to reduce greenhouse gas emissions are implemented beginning in the 1990s. **FIGURE 6**

ACCELERATED EMISSIONS CASES: PERCENT INCREASE IN EQUILIBRIUM WARMING COMMITMENT



FIGURE 6 -- NOTES

Impact Of Accelerated Emissions Policies On Global Warming

^a Assumes a low level of participation in and compliance with the Montreal Protocol, excluding the London Amendments, which were adopted after these scenarios were completed. The assumptions used in this case are similar to those used in the "Low Case" analysis described in the U.S. EPA's Regulatory Impact Assessment report, i.e., about 75% participation among developed countries and 40% among developing countries. In the RCW case the U.S. was assumed to participate 100%, other developed countries 94%, and developing countries 65%.

^b Assumes that advances in the technology of coal extraction and transport rapidly reduce the market price of coal at the burner tip. In the RCW scenario, the economic efficiency of coal supply is assumed to improve at a rate of approximately 0.5% per year. In this case, it is assumed to improve at a rate of 1% per year.

^c Assumes that the price of synthetic oil and gas could be reduced by 50% and commercialization rapidly accelerated relative to the RCW case.

^d Assumes that OPEC (or some other political entity) could control production levels and thus raise the border prices of oil and gas. To simulate this effect, oil and gas resources were shifted to higher points on the regional supply curves. In addition, extraction costs for oil in each resource grade were increased relative to the assumptions in the RCW case. In 2025 these assumptions increased oil prices about \$1/barrel and gas prices about \$0.25/thousand cubic feet.

^e Assumes that technical gains in the engineering efficiency of energy use occur only half as rapidly as assumed in the RCW case. In the RCW case it is assumed that efficiency improves at rates of approximately 1-2% per year (approximately equal to historical rates). In the Slow Improvement case the assumed rates were reduced to only 0.5-1.0% per year. The lower rate of improvement is similar to the assumptions in recent projections for the U.S. DOE's National Energy Policy Plan.

^t Assumes annual deforestation increases at a rate equal to the rate of growth in population. In the RCW case the rate of deforestation increases at a slower rate, reaching 15 million hectares/year in 2097 compared to 34 million hectares/year by 2047 in the RCWA case.

⁸ Assumes that the cost of solar energy precludes the possibility of its making any significant contribution to global energy supply. In the RCW case costs approached 8.5 cents/kwh after 2050.

^b Assumes that the cost of electricity from fission electric systems becomes so high that their contribution to global energy supply is permanently limited. In this case, an environmental tax of about 6 cents/kwh (1988\$) on the price of electricity supplied by nuclear powerplants was phased in by 2050. In the RCW case nuclear costs were assumed to be 6.1 cents/kwh in 1985.

ⁱ All of the above assumptions were combined in one scenario. The result is not equal to the sum of the warming in the RCW and the eight individual cases because of interactions among the assumptions.

No single activity is the dominant source of greenhouse gases; therefore, no single measure can stabilize global climate. Many individual components, each having a modest impact on greenhouse gas emissions, can have a dramatic impact on the rate of climate change when combined. The Stabilizing Policy scenarios therefore assume that many policy initiatives are undertaken simultaneously. These scenarios assume that policies to promote energy efficiency in all sectors succeed in substantially reducing energy demand relative to the No Response scenarios (which already assume substantial efficiency improvements). Research and development investments in non-fossil energy supply options such as photovoltaics (solar cells), biomass-derived fuels and electricity (fuels made from plant material), and advanced nuclear reactors are assumed to make these options available and begin to become competitive by 2000. As a result, non-fossil energy sources meet a substantial fraction of total demand in later periods. There is considerable uncertainty as to whether these sources could actually be available on a competitive basis by the year 2000. In addition, whether these technologies would be economically attractive in the quantities projected in future scenario years is quite uncertain. The existing protocol to reduce CFC and halon emissions is assumed to be strengthened, leading to a phaseout of fullyhalogenated compounds and a freeze on methyl chloroform. (The London Amendments to the Montreal Protocol, adopted after this analysis was completed, call for the complete phaseout of CFCs, halons, carbon tetrachloride, methyl chloroform, and encourage limits on HCFCs.) A global effort to reverse deforestation transforms the biosphere from a source to a sink for carbon by 2000, and technological innovation and controls reduce agricultural, industrial, and transportation emissions. The impact of these measures on warming commitment in 2050 and 2100 is illustrated in Figures 7 and 8. The results of this analysis suggest that accelerated energy efficiency improvements, reforestation, modernization of biomass use, and carbon emissions fees could have the largest near-term impact on the rate of climate change. In the long run, advances in solar technology and biomass plantations also play

an essential role. These conclusions are based upon the assumptions made in these scenarios about these technologies and about competing technologies, such as nuclear fission. How sensitive they may be to variations in the assumptions, particularly to differences reflecting economic differences between the industrialized countries and the developing countries, is not fully understood. While the same general emissions reduction strategies are assumed in both the SCWP and RCWP cases, the degree and rate of improvement are greater in the RCWP scenario because technological innovation and capital stock replacement occur at a faster pace.

The policies considered in these scenarios do not require fundamental changes in lifestyles. For example, energy use in buildings is greatly reduced in the Stabilizing Policy scenarios relative to the No Response scenarios, but the floor space available per person and the amenity levels provided are assumed to be the same. Similarly, while automobile fuel efficiency is assumed to be much higher, restrictions on automobile ownership are not considered. The potential impact of policies on personal decisions that directly change lifestyles has not been examined.

It should be kept in mind that these Stabilizing Policy scenarios incorporate assessments of the technical feasibility of the measures included and general judgments about their likely economic character. Analyses of economic feasibility, market penetration, costs, benefits, and other socioeconomic implications have not been systematically completed. Knowledge is particularly lacking about these socioeconomic aspects under developing country conditions where scarcity of capital and of trained technical people could complicate efforts to implement these measures.

These policy assumptions result in a substantial reduction in the rate of greenhouse gas buildup, but not an immediate stabilization of the atmosphere (see Figure 9). In the RCWP scenario global CO_2 emissions decline about 10% by 2025 and remain roughly constant thereafter. This result implies substantial reductions in emissions from





Figure 7. The impact of individual measures on the equilibrium warming commitment in the RCW scenario. The simultaneous implementation of all the measures represents the RCWP scenario.

FIGURE 7 -- NOTES

Impact Of Stabilizing Policies On Global Warming

^a The average efficiency of cars and light trucks in the U.S. reaches 30 mpg (7.8 liters/100 km) by 2000; new cars achieve 40 mpg (5.9 liters/100 km). Global fleet-average automobile efficiency reaches 43 mpg by 2025 (5.5 liters/100 km). In the RCW case global vehicle efficiencies for cars and light trucks achieve 30 mpg by 2025.

^b The rates of energy efficiency improvements in the residential, commercial, and industrial sectors are increased about 0.3-0.8 percentage points annually from 1985 to 2025 compared to the RCW and about 0.2-0.3 percentage points annually from 2025-2100. In the RCW case energy efficiency improvements averaged about 1-2% annually from 1985-2025, and less than 1% after 2025.

^c Emissions fees are placed on fossil fuels in proportion to carbon content. Fees were placed only on production; maximum production fees (1988\$) are \$1.00/GJ for coal (about \$25/ton), \$0.80/GJ for oil (about \$5/barrel), and \$0.54/GJ for natural gas (about \$0.58/thousand cubic feet). These fees increase linearly from zero, with the maximum production fee charged by 2025. In the RCW case no emission fees were assumed.

^d Assumes that technological improvements in nuclear powerplant design reduce costs by about 0.6 cents/kwh (1988\$) by 2050. In the RCW case we assumed that nuclear costs in 1985 were 6.1 cents/kwh (1988\$).

^e Assumes that low-cost solar technology is available by 2025 at costs as low as 6.0 cents/kwh. In the RCW case these costs approached 8.5 cents/kwh, but these levels were not achieved until after 2050.

^f Assumes the cost of producing and converting biomass to modern fuels reaches \$4.35/GJ (1988\$) for gas (about \$4.70/thousand cubic feet) and \$6.00/GJ (1988\$) for liquids (about \$36/barrel) by 2025, with biomass penetrating more quickly than in the RCW case due to more land committed to production. The maximum amount of liquid or gaseous fuel available from biomass (i.e., after conversion losses) is 205 EJ. In the RCW case these prices were not attained until 2035, and biomass energy penetrates slowly because research and development is slow and because land is committed slowly to biomass energy production.

⁸ Assumes that economic incentives for gas use for electricity generation increase the gas share by 5% in 2000 (thereby reducing prices about 1.6%) and 10% in 2025 (thereby reducing prices about 3.1%). Gas consumption for electricity generation was about 21 EJ in the RCW case.

^b Assumes more stringent NO_x and CO controls on mobile and stationary sources, including all gasoline vehicles using three-way catalysts, in OECD countries by 2000, and in the rest of the world by 2025 (new light-duty vehicles in the rest of the world use oxidation catalysts from 2000 to 2025). In the RCW case only the U.S. adopts three-way catalysts (by 1985); the OECD countries adopt oxidation catalysts by 2000, and the rest of the world does not add any controls. From 2000 to 2025 conventional coal boilers used for electricity generation are retrofit with low NO_x burners, with 85% retrofit in the developed countries and 40% 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. In the RCW case no additional controls are assumed.

¹ A 100% phaseout of CFCs by 2003 and a freeze on methyl chloroform is imposed. There is 100% participation by industrialized countries and 94% participation by developing countries. In the RCW scenario we assumed compliance with the Montreal Protocol, which called for a 50% reduction in the use of the major CFCs. Note the London Amendments to the Montreal Protocol, calling for a phaseout of CFCs, halons, carbon tetrachloride, methyl chloroform, and encouraging limits on HCFCs, are not reflected in the scenario; these Amendments were negotiated after this analysis was completed.

^j The terrestrial biosphere becomes a net sink for carbon by 2000 through a rapid reduction in deforestation and a linear increase in the area of reforested land and biomass plantations. Net CO₂ uptake by 2025 is 0.7 Pg C. In the RCW case, the rate of deforestation continues to increase very gradually, reaching 15 Mha/yr in 2097.

^k Assumes that research and improved agricultural practices result in an annual 0.5% decline in the emissions from rice production, enteric fermentation, and fertilizer use. CH_4 emissions from landfills are assumed to decline at an annual rate of 2% in developed countries because of policies aimed at reducing solid waste and increasing landfill gas recovery, while emissions in developing countries continue to grow until 2025 and then remain flat due to incorporation of the same policies. Technological improvements reduce demand for cement by 25%. In the RCW case no emission rate changes were assumed for agricultural practices. CH_4 emissions from landfills were assumed to remain constant in developed countries and increase as the population grew in developing countries.

¹ Impact on global warming when all the above measures are implemented simultaneously. The sum of each individual reduction in warming is not precisely equal to the difference between the RCW and RCWP cases because not all the strategies are strictly additive.

FIGURE 8 RAPID REDUCTION STRATEGIES:

ADDITIONAL DECREASE IN EQUILIBRIUM WARMING COMMITMENT



Figure 8. The impact of additional measures applied to the RCWP scenario expressed as percent change relative to the equilibrium warming commitment in the RCW scenario. The simultaneous implementation of all the measures in combination with the measures in the RCWP scenarios represents the Rapid Reduction scenario.

FIGURE 8 -- NOTES

Impact Of Rapid Reduction Policies On Global Warming

^a High carbon emissions fees are imposed on the production of fossil fuels in proportion to the CO_2 emissions potential. In this case, fees of about \$4.00/GJ were imposed on coal (\$100/ton), \$3.20/GJ on oil (\$19/barrel), and \$2.15/GJ on natural gas (\$2.00/mcf). These fee levels are specified in 1988\$ and are phased in over the period between 1985 and 2025. No fees were assumed in the RCW case.

^b Assumes that the average efficiency of new cars in the U.S. reaches 50 mpg (4.7 liters/100 km) in 2000 and that global fleet-average auto efficiencies reach 65 mpg (3.6 liters/100 km) in 2025 and 100 mpg (2.4 liters/100 km) in 2050. Comparable assumptions for the RCWP case were 40, 50, and 75 mpg for 2000, 2025, and 2050, respectively.

^c Assumes that the rate of technical efficiency improvement in the residential and commercial sectors improves substantially beyond that assumed in the RCWP case. In this case, the rate of efficiency improvement in the residential and commercial sectors is increased so that a net gain in efficiency of 50% relative to the RCWP case is achieved in all regions. In the RCWP case rates of efficiency improvement averaged 1.5-3.0% per year from 1985-2025.

^d Assumes that by 2050 average powerplant conversion efficiency improves by 50% relative to 1985. In this case, the design efficiencies of all types of generating plants improve significantly. For example, by 2025 new oil-fired generating stations achieve an average conversion efficiency roughly equivalent to 5% greater than that achieved by combined-cycle units today. In the RCW case new oil-fired units achieve an average conversion efficiency equal to combined-cycle units today.

^e The availability of commercial biomass was doubled relative to the assumptions in the RCWP case. In this case the rate of increase in biomass productivity is assumed to be at the high end of the range suggested by the U.S. DOE Biofuels Program. Conversion costs were assumed to fall by one-third relative to the assumptions in the RCWP case.

^f A rapid rate of global reforestation is assumed. In this case deforestation is halted by 2000 and the biota become a net sink for CO_2 at a rate of about 1 Pg C per year by 2025, about twice the level of carbon storage assumed in the RCWP case.

⁸ Impact on warming when all of the above measures are implemented simultaneously. The impact is much less than the sum of the individual components because many of the measures are not additive.

FIGURE 9

REALIZED WARMING: NO RESPONSE AND STABILIZING POLICY SCENARIOS



(Based on 2.0 - 4.0 Degree Sensitivity)

Figure 9. Shaded areas represent the range based on an equilibrium climate sensitivity to doubling CO_2 of 2-4°C.

industrialized countries, however. U. S. emissions, for example, fall 40% by 2025. Carbon dioxide concentrations increase gradually throughout the time frame of the analysis despite roughly constant emissions (as discussed above). Total radiative forcing is close to being stabilized by 2100, but the level is equivalent to almost a doubling of preindustrial CO_2 concentrations in the RCWP and to a 65% increase in the SCWP.

The rate of climate change in the SCWP and RCWP scenarios is at least 60% less than in the corresponding worlds without policy responses, but the risk of substantial climate change is still significant. The rate of global temperature increase during the next century in these scenarios is 0.5-1.5°C, while the maximum rate of change is less than 0.2°C per decade between 2000 and 2025. This represents much more gradual change than in the No Response scenarios, but it does not ensure that the rate of warming will remain below 0.1°C per decade. Some experts have suggested that this rate of change represents the maximum to which many species of plants and animals could adapt. Total equilibrium warming commitment could exceed 3.5°C by 2100 in the RCWP case. Given the possibility that the climate sensitivity could be higher and that there could be large positive biogeochemical feedbacks that are not included in these calculations, there is a possibility that these scenarios could lead to extremely rapid climate change. It is also possible that the policies assumed in these scenarios could limit climate change to about 1°C if the true climate sensitivity of the Earth is low.

Only the most aggressive policy case reverses the greenhouse gas buildup early in the 21st century. The economic feasibility, costs, benefits, and other socioeconomic implications of such policies have not been determined at this time. The Rapid Reduction scenario explores the impact of policies that effect a rapid transition away from fossil fuels. In the Rapid Reduction scenario net global CO_2 emissions decline nearly 15% by 2000 and 65% by 2025. U.S. emissions decline 20% by 2000 and 50% by 2025. The atmospheric concentration of CO_2 peaks below 400 ppm around 2025, and total greenhouse forcing peaks at an equivalent CO_2 concentration of less than 450 ppm. After this point, equivalent CO₂ concentrations decline until by 2100 they are about equal to current levels of atmospheric greenhouse gas concentrations (on a CO_2 -equivalent basis). It is this level of concentration, and the policy options necessary to achieve this level, that Congress specifically requested U.S. EPA to evaluate. Despite declining concentrations, however, temperatures continue to rise to about 2050, peaking at 0.9-1.5°C above preindustrial levels. In this case the maximum rate of change is 0.09-0.16°C per decade between 2000 and 2025, but the average rate of change over the next century is much less than 0.1°C per decade. The measures that reduce the warming to the greatest extent in the Rapid Reduction case relative to the RCWP case are those that impose stiff carbon fees on the production of fossil fuels, improve the energy efficiency of buildings, and increase the assumed level of renewable resource availability. Options for phasing in carbon fees so as to minimize impacts on the global economy require additional analysis.

To reduce the amount of global warming to the rates projected in the RCWP and Rapid Reduction cases, Table 5 lists several policies that might have to be adopted by 2000 to begin reducing greenhouse gas emissions. These examples are meant to illustrate potential policy responses; a variety of policy combinations might achieve the reductions in global warming estimated in each case.

TECHNOLOGICAL OPTIONS FOR REDUCING GREENHOUSE GAS EMISSIONS

There is a wide variety of available, or potentially available, options to reduce greenhouse gas emissions that it is believed would not unduly interfere with meeting growing demands for goods and services. The current status and potential of these options are briefly reviewed below. In most cases, the costs and benefits of these options for responding to climate change cannot be fully quantified at this time, both because of scientific uncertainties about climate change itself and because of many economic

TABLE 5

Examples Of Potential Policy Responses By The Year 2000

RCWP Case

- Research on energy efficiency and non-fossil-fuel technology is accelerated
- New automobiles in the U.S. average 40 mpg
- New automobiles in the OECD use three-way catalytic converters to reduce CO and NO_x; the rest of world uses an oxidation catalyst
- Average space-heating requirements of new single-family homes are 50% below 1980 new home average
- Net global deforestation stops
- CFCs are phased out; production of methyl chloroform is frozen
- Fossil fuels are subject to emission fees that are set according to carbon content -- \$10/ton on coal, \$2/barrel on oil, \$0.20/thousand cubic feet on natural gas
- Accelerated research and development into solar photovoltaic technology allows solar power to compete with oil and natural gas (U.S. DOE long-term policy goals)
- Available municipal solid waste and agricultural wastes are converted to useful energy
- Accelerated research on biomass energy plantations increases current productivity by 65% (to 25 dry tons/hectare annually)

RCWR Case

- Research on energy efficiency and non-fossil-fuel technology is accelerated
- New automobiles in the U.S. average 50 mpg
- Major retrofit initiatives reduce energy use in existing commercial buildings by 40%
- Average space-heating requirements of new single-family homes are 90% below 1980 new home average
- Global deforestation stops; major reforestation programs are undertaken
- CFCs are phased out; production of methyl chloroform is frozen
- Fossil fuels are subject to emission fees that are set according to carbon content -- \$38/ton on coal, \$7/barrel on oil, \$0.75/thousand cubic feet on natural gas
- Commercialization incentives lead to significant market penetration for solar technologies
- 250 million bectares globally are committed to biomass energy plantations, i.e., 5% of forest and woodland area

uncertainties about the potential options themselves.

Improve Energy Efficiency

The introduction of technologies and practices that use less energy to accomplish a given task would have the largest impact on global warming in the near term. Both industrialized and developing countries can significantly improve energy efficiency. Although per capita energy consumption is very low in developing countries, there is a large potential to increase efficiency because energy use per unit of GNP is often extremely Indeed, the imperative for energy high. efficiency may be even stronger in developing countries to the extent that expending scarce capital on expanding energy supply systems can be avoided. Many of the technical options described below may be directly applicable in developing as well as industrialized countries, but alternative approaches suited to available resources will also be needed. In many cases improved management of existing facilities could have large payoffs. We estimate that accelerated improvements in energy efficiency account for about 25% of the difference between the RCWP and the RCW cases in 2050 (we note that this occurs even though fairly rapid improvements are already assumed in the RCW case).

Improved Transportation Efficiency

A number of known technologies have the technical potential to increase automobile fuel efficiency from current levels for new cars (25-33 mpg or 9.4-7.1 liters/100 km) to significantly higher levels. What could be achieved in the foreseeable future without downsizing vehicles and reducing safety and other desirable characteristics is uncertain. Given the currently available technical options and their likely costs of implementation, a fleet average new car economy level of 40 mpg by the year 2000 could require size and performance reductions. The RCWP scenario assumes that new cars in the industrialized countries achieve an average of 50 mpg (4.7 liters/100 km) in 2025 and 75 mpg (3.1 liters/100 km) in 2050 (somewhat lower rates of efficiency improvement are assumed in the SCWP scenario). In addition, major fuel efficiency improvements in diesel trucks and aircraft are possible. The Rapid Reduction case assumes more aggressive measures to improve efficiency.

Other Efficiency Gains

More efficient building shells, lighting, heating and cooling equipment, and appliances are currently commercially available. The most efficient new homes currently being built use only 30% as much heating energy per unit of floor area as the average existing house in the United States. Advanced prototypes and design calculations indicate that it is technically possible to build new homes that use only 10% of current average energy requirements. The economic feasibility, the likely market penetration, and the costs of implementing such technological options are uncertain. About 20% of U.S. electricity is consumed for lighting, mainly in residential and commercial buildings. A combination of currently available advanced technology and careful design has been shown to costeffectively reduce energy requirements for lighting by more than 75%. The RCWP scenario assumes that the average reduction in energy use per unit of residential and commercial floor space by 2025 in the U.S. is as much as 75% for fuel and 50% for electricity. Smaller improvements are assumed in other regions and in the SCWP scenario.

Advanced industrial processes currently available can significantly reduce the energy required to produce basic materials -especially if these processes are used in combination with recycling. For example, estimates of the reductions in energy intensity of U.S. steel production that are technically feasible range from 20 to 50 percent. How much of these savings would be economically feasible and at what cost is unknown. Electric motors are estimated to account for about 70% of U.S. industrial electricity use. Several case studies show that improved motors and motor controls now commercially available could reduce energy consumption by electric motors at least 15% relative to current averages.

While the promise of technically feasible efficiency gains is great, the uncertainties about the rate and scale of implementation of such measures are also great. Many of these gains would depend, in the U.S. and other developed countries, upon the rates at which the existing capital stock is replaced by new, more efficient capital equipment and facilities. Such rates depend upon a host of economic and other factors that are difficult to assess: the rates at which potential users learn about new technologies, the age and value of existing equipment and facilities, the availability and cost of credit, the degree that existing capital capacity is utilized, and so forth. For these reasons, market penetration rates of new technologies, and how such rates might be accelerated, are very uncertain.

Carbon Fee

One way to provide a market signal that CO₂ emissions have environmental consequences is to apply a "carbon" fee to the price of fossil fuels that is proportional to the carbon content of the fuel. Fees could be used in conjunction with performance standards and other strategies to encourage energy conservation and investments in energyefficient technology. A carbon fee would also affect the relative prices of fossil and nonfossil energy sources and the relative prices among the fossil fuels, reinforcing the policies discussed in the following sections. The revenues from such a fee could be used to reduce other taxes, reduce the national debt, and/or support other national goals. To be least disruptive, revenues would need to be offset by reductions in other taxes. Further analysis is required to determine these impacts on the economy. In particular, the full social costs and benefits of substantial reductions in an energy option, such as coal use, due to high carbon fees or to command-and-control regulations, have not been evaluated.

Given the scientific and economic uncertainties about the changes in climate that are likely to result from given changes in greenhouse gas concentrations, and the net costs to society of such climate changes, appropriate levels for setting greenhouse gas fees are unknown.

If greenhouse gas fees and other controls on emissions are not established on a comparable basis world-wide, the problem of emissions-intensive activities migrating to countries where fees were lower or controls less stringent could occur, thereby reducing the net effectiveness of the fees or controls.

Increase Use of Non-Fossil Energy Sources

There is a critical need for research on non-fossil energy technologies. The development of attractive non-fossil energy sources is critical to the success of any climate stabilization strategy over the long term. Under the assumptions of this report's scenarios, increased penetration of solar and advanced biomass technologies contribute little to reduced warming in 2025, but they are responsible for 24% of the difference between the RCWP and the RCW case in 2050, and over 25% of this difference in 2100. Figure 10 shows the relative contribution to primary energy supply of each fossil and non-fossil fuel under each of our scenarios. The exact mix of non-fossil energy supply technologies assumed in the policy scenarios is rather arbitrary, but makes little difference to greenhouse gas emissions. Some particularly promising nonfossil technologies are described below.

Nuclear Power

Nuclear fission produces about 5% of global primary energy supplies and its share has been growing. High cost and concerns about safety, nuclear proliferation, and radioactive waste disposal, however, have brought new orders for nuclear powerplants to a halt in many countries. Advanced designs, in particular the Modular High Temperature Gas-cooled Reactor, have recently been proposed in an attempt to overcome some of these problems. The role of nuclear power could be significantly expanded in the future if these efforts are successful and public confidence in this energy source is restored. Nuclear power's contribution to primary energy supply in the SCWP case increases to less than 7% in 2050 and to 8% in 2100 and in the RCWP case to 10% in 2050 and 18% in It is possible that the nuclear 2100. contribution could be substantially greater, if concerns about safety, nuclear proliferation, and waste disposal could be adequately dealt with and if costs could be reduced by moving toward the manufacture of standardized

FIGURE 10



PRIMARY ENERGY SUPPLY BY TYPE

Note: Full scale is doubled for the RCWA case.

Executive Summary

powerplants and away from the construction of one-of-a-kind facilities.

Solar Technologies

There is a range of solar technologies currently available or under development that could increase the use of solar energy. Direct use of solar thermal energy, either passively or in active systems, is already commercial for many water- and space-heating applications. In some locations wind energy systems are also currently commercial for some applications. In recent years engineering advances have resulted in significant cost reductions and improvements. Solar performance photovoltaic (PV) cells are currently competitive for many remote power generation needs, especially in developing countries. Dramatic progress has been made recently in reducing the costs of producing PV systems, particularly with thin-film amorphous silicon If current research and technology. manufacturing development efforts reach their objectives, PV could play a major role in meeting energy needs in the next century. The degree to which these objectives, particularly cost reduction, could be achieved by specific times and the size of the future contribution In the SCWP are, of course, uncertain. scenario solar sources of electricity are equivalent to 6% of primary energy supply from 2050 onward. A larger contribution is envisioned in the RCWP scenario: 10% in 2050, increasing to over 13% in 2100.

Hydro and Geothermal Energy

Other renewable resources can also increase their contribution to total energy Hydroelectric power is already supplies. contributing the equivalent of about 7% of global primary energy production, and geothermal power is making a small (less than 1%) but important contribution. There is potential to expand the contribution of these sources, although good hydro and geothermal sites are limited and environmental and social impacts of large-scale projects must be considered carefully. Significant questions concerning the economics of remaining available sites, and the likely environmental constraints on these sites, have not been analyzed in detail. Hydroelectric and

geothermal power expands to nearly 13% of global primary energy production in the SCWP scenario, but increases only to about 9% in the RCWP case (this relatively smaller contribution is due to the higher level of energy production; i.e., the absolute amount is higher, but the percentage is lower).

Commercialized Biomass

Biomass is currently being extensively utilized, accounting for roughly 10% of global energy consumption, primarily in traditional applications (e.g., cooking), which are not included in most official accounts of commercial energy use. Current and emerging technologies could vastly improve the efficiency of biomass use. In the near term there is substantial potential for obtaining more useful energy from municipal and agricultural wastes. More advanced technologies for producing, collecting, and converting biomass to gaseous and liquid fuels and electricity could become economically competitive within a decade. The prospects for integrating biomass gasification with advanced combustion turbines is particularly promising. While the technical potential for commercialized biomass is highly promising, important questions remain about the scale and degree of the economic potential. In particular, the availability of productive land that could be devoted to growing biomass fuels study. Furthermore, needs further environmental and societal impacts related to large-scale biomass use, which would have to be addressed, include competition with food production, ecological impacts, and emissions of volatile organic compounds. In the SCWP scenario biomass energy supplies 32% of primary energy needs in 2050 and 48% in 2100. Biomass supplies about 32% of primary energy by 2050 and 32% by 2100 in the RCWP scenario.

Reduce Emissions from Fossil Fuels

Inherent to the burning of fossil fuels is the generation of large amounts of CO_2 . Although it is technically possible to scrub CO_2 out of central station powerplants, it is estimated that this would probably at least double the cost of power generation, and an

environmentally acceptable method of disposal has not been demonstrated. All fossil fuels are not created equally, however. Burning coal produces about twice as much CO₂ per unit of energy released as does natural gas; the amount of CO_2 produced by oil is about 80% the amount produced of by coal. Furthermore, oil and gas have the potential to be used much more efficiently than coal in power generation, substantially increasing their CO_2 advantage. Thus fuel switching among fossil fuels can significantly reduce CO₂ emissions. Similarly, non-CO₂ emissions from fossil-fuel burning can be controlled, resulting in significant impacts on greenhouse gas concentrations. Also, when new fossil-fuel facilities need to be built, emissions can be minimized by installing the most efficient technologies, such as the use of Integrated Gasification/Combined Cycle (IGCC) systems for new coal-fired generation requirements.

The potential timing and market penetration of more efficient fossil-fuel-fired technologies are uncertain, particularly in the developing countries, where most of the growth in emissions is likely to take place. The potential impact of these technologies is significant, but their cost effectiveness is very uncertain.

Greater Use of Natural Gas

Because of its inherent CO₂ advantage over other fossil fuels, increased use of natural gas could significantly reduce total emissions. Two important considerations should be kept in mind, however. First, natural gas is a finite resource. Increased use of natural gas during the next few decades could provide an essential bridge as non-fossil energy sources are further developed, but unless a transition toward reduced dependence on fossil fuels is accomplished, reduced availability of natural gas in later periods could offset the gains from using gas in earlier periods. Second, natural gas is primarily methane, which is itself a powerful greenhouse gas. If a substantial amount of methane reaches the atmosphere through leaky transmission or distribution pipes, the advantage of natural gas can be significantly reduced or offset.

Emission Controls

Emissions of CO contribute to elevating methane concentrations, and NO_x emissions contribute to tropospheric ozone formation, both of which are important greenhouse gases. Thus, more stringent and comprehensive controls on CO and NO_x , such as three-way catalysts on automobiles and low- NO_x burners on boilers and kilns, would reduce greenhouse gas concentrations as well.

Reduce Emissions from Non-Energy Sources

CFC Phaseout

Halocarbons (which include CFCs and halons) are potent stratospheric ozone depleters as well as greenhouse gases. Concern over their role as a threat to the ozone layer led in September 1987 to "The Montreal Protocol on Substances That Deplete the Ozone Layer" (or the Montreal Protocol). The Montreal Protocol came into force on January 1, 1989, and has been ratified by 68 countries, representing just over 90% of current world consumption of these chemicals (as of February 1, 1991). The London Amendments to the Protocol, which call for the phaseout of CFCs, halons, carbon tetrachloride, and methyl chloroform, and encourages limits of HCFCs, were adopted in June 1990. These amendments were adopted after this analysis was completed.

Further reductions in CFCs are needed to slow the buildup of atmospheric concentrations. The major provisions of the Montreal Protocol include a 50% reduction from 1986 levels in the use of CFC-11, -12, -113, -114, and -115 by 1998; a freeze on the use of Halon 1211, 1301, and 2402 at 1986 levels starting in approximately 1992; and a delay of up to 10 years in compliance with the Protocol for developing countries with low levels of use per capita. As a result of this historic agreement, the very high growth rates in CFC concentrations assumed in some previous studies are unlikely to occur. However, because of the long atmospheric lifetimes of CFCs, the probability that not all countries will participate in the agreement, and the provision for increased use in developing countries, CFC concentrations will still rise significantly in the future unless the Protocol is strengthened (see Figure 4). An international meeting to discuss strengthening of the Protocol was held in June 1990 in London, England. The Amendments to the Protocol adopted in London were similar to, but not as stringent as, the phaseout assumed in this analysis.

Promising chemical substitutes. engineering controls, and process modifications that could eliminate most uses of CFCs have now been identified. In the policy scenarios we assume that the use of CFCs and halons is phased out and that emissions of methyl chloroform are frozen (no additional growth in CFC substitutes is assumed as a result of the phaseout beyond the levels assumed under the Protocol). Even under these assumptions total weighted halocarbon concentrations increase significantly from 1985 levels, in part because the chemical substitutes contribute significantly to greenhouse forcing, although the final concentrations are about one-third of the level in the corresponding No Response scenarios. The greenhouse forcing potential of CFC substitutes will have to be carefully evaluated to improve estimates of their potential role in climate change. In our analysis, phasing out CFCs was responsible for 9% of the decrease in warming in the RCWP in 2050 relative to the RCW.

Reforestation

Deforestation and biomass burning are significant sources of CO₂, CO, CH₄, NO₅, and N_2O . The world's total forest and woodland acreage has been reduced by about 15% since 1850, primarily to accommodate the expansion of cultivated lands. It is generally estimated that approximately 11 million hectares (Mha) of tropical forests are currently lost each year, while only 1.1 Mha are reforested per year. Generally, temperate and boreal forests appear to be in equilibrium. Estimates of net emissions of CO_2 to the atmosphere due to changes länd use (deforestation, in reforestation. logging, and changes in agricultural area) in 1980 range from approximately 10-30% of annual

anthropogenic CO₂ emissions to the atmosphere.

Reversing deforestation offers one of the most attractive policy responses to potential climate change. Although a vast area of land would have to be involved to make a significant contribution to reducing net CO₂ emissions, preliminary estimates suggest that the cost of absorbed or conserved carbon could be low in comparison to other options, at least initially. How rapidly reforestation costs would increase as lands with increasingly high productivity in other uses were transferred to forest use is not well understood. The areas of land that would be feasible and economic to transfer to forest use are also not well defined. Furthermore, a reforestation strategy could offer a stream of valuable ecological and economic benefits in addition to reducing CO_2 concentrations, such as production of forest products, maintenance of biodiversity, watershed protection, nonpoint pollution reduction, and recreation. Devising successful forestry programs presents unique challenges to scientists and policymakers because of the vast and heterogeneous landscape, uncertain ownership, lack of data, and the need for more research and field trials. Investments that would be small by the standards of the energy industry, however, could make an enormous impact on forestry.

In the Stabilizing Policy scenarios it is assumed that by 2000 the biosphere is transformed from a source to a sink for carbon. A combination of policies succeed in stopping deforestation by 2025, while up to one billion hectares of land is reforested by 2100 (some of this land is devoted to biomass energy plantations as discussed above). This assumed area of reforestation could exceed the area of the United States. Whether or not this much land could be made available on a global basis for reforestation, given the needs for uses for subsistence and commercial agriculture, has not been determined. Reforestation accounts for almost one-fifth of the decrease in warming by 2050 in the RCWP versus the RCW scenarios.

Agriculture, Landfills, and Cement

Domestic animals, rice cultivation, and use of nitrogenous fertilizers are significant

sources of greenhouse gases. Methane is produced as a by-product of digestive processes in herbivores, particularly ruminants (e.g., cattle, dairy cows, sheep, buffalo, and goats). Globally, domestic animals (predominantly cattle) are responsible for about 15% of total methane emissions. The gas is also produced by anaerobic decomposition in flooded rice fields and escapes to the atmosphere largely by transport through the rice plants. The amount of CH_4 released to the atmosphere is a complex function of rice species, number and duration of harvests, temperature, irrigation practices, crop residue management, and fertilizer use. Rice fields are estimated to contribute approximately 10-30% of the global emissions. Nitrous oxide is released through microbial processes in soils, both through denitrification and nitrification. The use of nitrogenous fertilizer enhances N_2O emissions since some of the applied N is converted to N₂O and released to the atmosphere. The amount of N_2O released varies a great deal depending on rainfall, temperature, the type of fertilizer applied, mode of application, and soil conditions. A preliminary estimate suggests that this source produces 1-20% of global N_2O emissions.

Future research and technological changes could reduce agricultural emissions. In the policy scenarios we do not assume changes in the demand for agricultural commodities, but rather changes in production systems that could reduce greenhouse gas emissions per unit of product. Although the impact of specific approaches cannot be quantified at present, a number of techniques, such as feed additives for cattle, changes in water management in rice production, and fertilizer coatings, have been identified for reducing methane and nitrous oxide emissions from agricultural sources. The extent to which these options are implemented depends on further research and demonstrations. For simplicity we have assumed that methane emissions per unit of rice, meat, and milk production decrease by 0.5% per year (emissions from animals not used in commercial meat or milk production are assumed to be constant). Emissions of nitrous oxide per unit of nitrogen fertilizer applied are also assumed to decrease by 0.5% per year for each fertilizer type. In addition, we assume

that after 2000 there is a shift away from those types of fertilizers with the highest emissions. Under these assumptions agricultural emissions are substantially lowered in the policy scenarios relative to the No Response scenarios, although absolute emissions do not decline.

Landfills represent a potentially controllable source of methane. Waste disposal in landfills and open dumps generates methane when decomposition of the organic material becomes anaerobic; approximately 80% of urban solid wastes is currently disposed in one of these ways. Most of the decomposition in landfills and some of the decomposition in open pits is anaerobic. Annual methane emissions from landfills and open pits represent about 10% of total methane emissions.

Landfilling can be expected to increase dramatically in developing countries as population growth, urbanization, and economic growth all imply increased disposal of municipal solid waste. The result is a three and fivefold increase in methane emissions from landfills in the SCW and RCW scenarios, respectively. The Stabilizing Policy scenarios assume that gas recovery systems, recycling, and waste reduction policies will be adopted, resulting in roughly constant global emissions from landfills.

Carbon dioxide is emitted in the calcining phase of the cement-making process when calcium carbonate $(CaCO_3)$ is converted to lime (CaO). For every ton of cement produced 0.14 tons of carbon are emitted as CO_2 from this reaction. World cement production increased from 130 million tons in 1950 to about one billion tons currently. Thus, current CO_2 emissions from calcining are 0.14 billion tons of carbon (0.14 Pg C), or more than 2% of total CO_2 emissions. In the Stabilizing Policy scenarios, advanced materials are assumed to reduce the demand for cement relative to the No Response scenarios, but emissions still grow significantly.

Reduced emissions from agriculture, landfills, and cement manufacture account for 12% of the reduced warming in the RCWP in 2050 relative to the RCW scenario.

A WIDE RANGE OF POLICY CHOICES FOR THE SHORT AND LONG TERM

The prospect of global climate change presents policymakers with a unique challenge. The scale of the problem is unprecedented in both space and time. Many choices are available and the consequences of these choices will be profound.

A wide range of policy choices is available for reducing greenhouse gas emissions. There is an important distinction between short-term and long-term policy options. In the short term, the most effective means of reducing emissions is through strategies that rely on pricing and regulation. There is a wide range of potential policy choices that may make sense despite the scientific and economic uncertainties. In the long term, policies to increase research and development of new technologies, to enhance markets through information programs and other means, and other actions making it possible to achieve world-wide economic growth while limiting emissions growth will be essential for long-term effects on the climate change problem.

The most direct means of allowing markets to incorporate the risk of climate change is to ensure that the prices of fossil fuels and other sources of greenhouse gases reflect their full social costs. It may be necessary to impose emission fees on these sources according to their relative contribution to global warming in order to accomplish this goal. Unfortunately, the costs and benefits of global warming are not fully known, and, therefore, the fees that would correspond to charging full social costs can not now be determined. Better information would be needed as a basis for establishing levels of fees. Fees would also raise revenues that could finance other programs or offset other taxes. The degree to which such fees are accepted will vary among countries, but acceptability would be enhanced if fees were equitably structured. The impact of fees on the global economy would depend on the size of the fees, how they were phased in, and how the revenues were used, among other factors. The effectiveness of fees in reducing world-wide greenhouse gas emissions would depend on the degree to which they are applied consistently throughout the world and therefore avoid encouraging emissions-intensive activities to relocate to low fee areas. These issues require additional analysis.

Regulatory programs would be a necessary complement if pricing strategies were not effective or had undesirable impacts. In the U.S., greenhouse gas emissions are influenced by existing federal regulatory programs to control air pollution, increase energy efficiency, and recycle solid waste. Reducing greenhouse gas emissions could be incorporated into the goals of these programs. New programs could focus directly on reducing greenhouse gas emissions through requirements such as emissions offsets (e.g., tree planting), performance standards, or marketable permits. Different kinds of regulatory approaches would have different degrees of efficiency and costs, differences in treating greenhouse gases in a comprehensive fashion, and differences in how they permit those regulated to make cost-optimal A full understanding of these decisions. differences and of the inherent advantages of using automatic market mechanisms to encourage environmentally sound behavior is needed, particularly with respect to regulatory approaches in countries with limited experience in market-oriented environmental regulation. Regulatory approaches, like other policies, would also have to deal with the need to avoid encouraging emissions-intensive activities to relocate to areas of less stringent regulation.

• State and local government policies in such areas as utility regulation, building codes, waste management, transportation planning, and urban forestry could make an important contribution to reducing greenhouse gas emissions.

• Voluntary private efforts to reduce greenhouse gas emissions have already provided significant precedents for wider action and could play a larger role in the future.

• Over the long term, other policies will be needed to reduce emissions and can complement pricing and regulatory strategies. Other policy options include redirecting research and development priorities in favor of technologies that could reduce greenhouse gas emissions, implementing information programs to enhance awareness of the problems and solutions, and making selective use of government procurement to promote markets for technological alternatives.

The United States is implementing a number of actions (described above) that can be justified because they produce benefits that are not subject to the uncertainties associated with climate change. Further study will most likely identify additional actions that fall into that category. At some point it may be desirable to consider actions that can not be justified by their non-climate benefits, but must depend for justification on the benefits from reducing the degree of climate change. It will be important, at that time, to have a full understanding of the economic, social, and other implications of such actions so that decisions despite the uncertainties will be based on the best information that can be developed. Some of the types of action that will need to be considered and some of the questions that will need to be addressed are discussed throughout this report.

• A number of other countries have made public commitments to take actions to reduce their greenhouse gas emissions by similar or greater proportions. While such actions will somewhat delay the increasing concentrations of greenhouse gases, the problem of achieving economic growth and improved well-being in the developing world while avoiding or limiting the emissions increases from such growth remains a key, unsolved problem.

Several studies have been conducted that identify the wide range of policy choices that are available for reducing emissions. For example, see A Compendium of Options for Government Policy to Encourage Private Sector Responses to Potential Climate Change (U.S. DOE, 1989), the National Energy Strategy (NES) which is currently under development by the U.S. DOE and other agencies within the Federal government, and Box 3 (which is an illustrative analysis based on preliminary estimates of the impacts of the policies discussed in Box 3).

The Timing of Policy Responses

The costs and benefits of actions taken to reduce greenhouse gas emissions are difficult to evaluate because of the many uncertainties associated with estimates of the magnitude, timing, and consequences of global climate change, as well as the difficulty of assessing the net social costs of strategies that involve widespread and long-term shifts in technological development. Given this situation it may be prudent to delay some costly actions to reduce greenhouse gas concentrations until the magnitude of the problem and the costs of responses are better established. The potential benefits of delay, however, must be balanced against the potential increased risks.

The models indicate that delaying the policy response to the greenhouse gas buildup would substantially increase the global commitment to future warming. For this reason, the U.S. is taking a number of policy actions (described earlier) that will produce a substantial response to the greenhouse gas buildup, particularly actions that can be justified for reasons not subject to the scientific and economic uncertainties about climate change. Analytical efforts to date have not been able to determine the appropriate level of trade-off between accepting additional costs associated with additional climate change and incurring additional costs to avoid that additional climate change. The Stabilizing Policy cases and the Rapid Reduction case both assume that immediate action is taken to begin reducing the rate of greenhouse gas buildup. The impact of delay was investigated by assuming that industrialized countries do not respond until 2010 and that developing countries wait until 2025. Once action is initiated, policies are assumed to be implemented at roughly the same rates as in the Stabilizing Policy cases. The result would be a significant increase in global warming (see Figure 11): the equilibrium warming commitment in 2050 would increase by about 40-50% relative to the scenarios that assume policy implementation beginning in 1990. It is clear that many nations are already taking or publicly committed to taking actions that are not reflected in this scenario. For example, the U.S. has committed to a number of policy

Box 3. Illustrative Analysis of Current U.S. Policy Initiatives

Several policy initiatives are currently under discussion or have been approved that could reduce the U.S. contribution to greenhouse gas emissions. These initiatives cover a wide range of activities that emit different types of greenhouse gases. Several examples of these initiatives include: (1) a recently-proposed reforestation program to plant one billion trees per year that would sequester carbon as the trees matured; (2) a total phaseout of the major CFCs and related chemicals that deplete the stratospheric ozone layer; (3) new landfill regulations that would restrict the amount of CH_4 emissions from decomposing wastes; and (4) several initiatives that would reduce the amount of energy consumed and thereby reduce CO_2 emissions, including revisions to the Clean Air Act to control acid rain and develop less polluting transportation fuels and proposals by the U.S. DOE to adopt more efficient appliance standards, improve lighting in Federal and commercial buildings, promote state least-cost utility planning, obtain U.S. HUD adoption of U.S. DOE building standards, and expand use of hydroelectric power and the transfer of photovoltaic technology.

These specific policy initiatives are used here as examples of the types of emission reduction policies that can be justified for reasons other than climate change. The options included are those for which estimates of emissions were readily available. Many other potential options exist which have not been systematically evaluated. As an illustration of the potential for reducing emissions, however, we have combined the emission reductions from all of the initiatives mentioned above into a single estimate using the concept of Global Warming Potentials (GWP) discussed in Box 1 and the Addendum to Chapter II to convert the emission reductions estimated from each initiative to a CO_2 -equivalent basis (expressed as carbon). The impact of these proposed initiatives on estimated U.S. greenhouse gas emissions is summarized in the figure below, which indicates that this illustrative package of proposed initiatives could reduce total U.S. greenhouse gas emissions about 13% below projected levels for the year 2000 to a level about 7% lower than estimated 1987 emissions on a CO_2 -equivalent basis. If only CO₂ emissions are considered, however, the percentage reduction is substantially less -- about 4% below projected 2000 emissions. Estimated reductions when only CO₂ is considered are much lower than reductions that consider all gases on a CO₂-equivalent basis because the largest source of emission reductions -- CFCs as a result of the London Amendments to the Montreal Protocol and 1990 Clean Air Act Amendments -- is not included. For a complete discussion of these results, see the Addendum to Chapter VII.



FIGURE 11

INCREASE IN REALIZED WARMING DUE TO GLOBAL DELAY IN POLICY OPTIONS

(Based on 3.0 Degree Sensitivity)



Figure 11. Assumes that industrialized countries delay action until 2010 and that developing countries delay action until 2025. Once action is initiated, policies are assumed to be implemented at roughly the same rate as in the Stabilizing Policy cases.

measures that will mitigate emissions. Although this delay scenario clearly does not correspond to currently planned actions, the basic point illustrated is still valid.

Policy development and implementation can be a lengthy process, particularly at the international level. Any decision to respond to the greenhouse gas buildup cannot be fully translated immediately into action. Roughly a decade was required for the process that led to international agreement to reduce emissions of CFCs, embodied in the Montreal Protocol, and it will take another decade to implement the agreedupon reductions. Agreements to reduce other greenhouse gas emissions could take much longer to achieve and implement.

The development of technologies to reduce greenhouse gas emissions will take many years. The majority of emissions are associated with activities that are fundamental to the global economy (transportation, heating and cooling of buildings, industrial production, land clearing, etc.); thus, reducing emissions by curtailing these activities would be highly disruptive and undesirable. While this report has identified a large menu of promising technologies that can meet our needs for goods and services while generating much lower emissions of greenhouse gases, many require additional research and development to become economically competitive. The time required to bring innovative technologies to market is unpredictable, but the process usually takes many years. And once a technology is cost-effective, it may take years before it achieves a large market share and decades more for the existing capital stock to be replaced. Depending on the sector, it may take 20-50 years or more to substantially alter the technological base of industrial societies, and the cost of reducing emissions could rise dramatically as the time allowed for achieving these reductions is decreased. While the rate of change in rapidly developing countries can be higher and may be influenced by government policies, once industrial infrastructure is built, it will be many years before it is replaced.

The Need for an International Response

If limiting U.S. and global emissions of greenhouse gases is desired, government action will be necessary. Throughout the world, market prices of energy from fossil fuels, products made with CFCs, forest and agricultural products, and other commodities responsible for greenhouse gas emissions do not reflect the risks of climate change. As a result, increases in population and economic activity will cause emissions to grow in the absence of countervailing government policies.

The risk of substantial warming is unavoidable if developing countries do not participate stabilizing strategies. in Increasing the availability of energy services is a high priority for developing countries attempting to meet basic human needs. Increased energy use in developing countries could lead to dramatic increases in greenhouse gas emissions unless stabilizing policies are adopted. The share of greenhouse gas emissions arising from developing countries (weighted by their estimated impact on global warming) increases from about 40% currently to 50% by 2025 and almost 60% by 2100 in the RCW scenario; the developing countries' contribution to greenhouse gas emissions also rises to about 50% in the SCW (see Figure 12). We examined the implications for global warming if industrialized countries adopted climate stabilizing policies without the participation of developing countries. policies adopted Assuming that in industrialized countries have some impact even in developing countries that do not participate in an international agreement, equilibrium warming commitment in 2050 is about 40% higher than in the Stabilizing Policy cases (see This implies that action by Figure 13). industrialized countries on their own can significantly slow the rate and magnitude of climate change, but that without the participation of the developing countries, the risk of substantial global warming is unavoidable. Even if developing countries participate, the degree to which it will be possible, at any point in time, to avoid



* See Appendix B for further discussion of these scenarios.

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FIGURE 13

INCREASE IN REALIZED WARMING WHEN DEVELOPING COUNTRIES DO NOT PARTICIPATE (Based on 3.0 Degree Sensitivity)



Figure 13. Assumes that industrialized countries follow the Stabilizing Policies scenarios while developing countries follow the No Response scenarios, except that there is some transfer of low-emissions technology to developing countries despite their failure to adopt stabilizing policies.

emissions increases in developing countries that would otherwise accompany economic growth is unknown.

Although most of the costs and benefits of responding to climate change cannot be quantified at this time, some potential actions would have other benefits. Benefits could include reductions in conventional pollutants, increased energy security, and reductions in the balance of payments deficit, as well as reduced risk of warming. Similarly, reversing deforestation has a wide range of benefits, including maintenance of biological diversity, reduction in soil erosion and reservoir siltation, and local climatic amelioration. The phaseout of production of CFCs. halons. carbon tetrachloride, and methyl chloroform under the Montreal Protocol will be most significant in reducing the risk of stratospheric ozone depletion and will also make an important contribution to reducing the risk of climate change. The U.S. is taking, or is committed to taking, a number of other actions that have benefits other than those related to climate change. In total, these U.S. actions are estimated to have significant effects on U.S. emissions of greenhouse gases. Some of the options discussed here, such as reduced agricultural emissions, improved biomass production, and heavy reliance on photovoltaics, would require further research and development to ensure their availability. Relatively small investments in such research could yield important payoffs.

NOTES

1. Estimates of equilibrium warming commitments greater than 6° C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms. These estimates are represented by >6°C.

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CHAPTER I

INTRODUCTION

THE GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

The greenhouse effect is a natural phenomenon that plays a central role in determining the Earth's climate. Sunlight passes through the atmosphere and warms the Earth's surface. The Earth then radiates infrared energy, some of which escapes back into space. But certain gases (known as greenhouse gases) that occur naturally in the atmosphere absorb most of the infrared radiation and emit some of this energy back toward the Earth, warming the surface. This effect is, to a great extent, responsible for making the Earth would be approximately 30°C colder.

Concerns about the greenhouse effect arise because anthropogenic emissions of greenhouse gases may further warm the Earth.¹ Greenhouse gases -- primarily carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons (CFCs), and tropospheric ozone (O₃) -- are produced as byproducts of human activities. When these gases are emitted into the atmosphere and their concentrations increase, the greenhouse effect is compounded. The result is an increase in mean global temperatures.

There is scientific consensus that increases in greenhouse gas emissions will result in climate change (Bolin et al., 1986; NAS, 1979, 1983, 1987; WMO, 1985). However, considerable uncertainty exists with regard to the ultimate magnitude of the warming, its timing, and the regional patterns In addition, there is great of change. uncertainty about changes in climate variability and regional impacts. Nonetheless, there is a growing political consensus that greenhouse gas emissions must be reduced. As stated by the major industrial nations (the "G-7" countries) at the Paris summit in July 1989: "We strongly advocate common efforts to limit emissions of carbon dioxide and other greenhouse gases which threaten to induce climate change, endangering the environment and ultimately the economy." (Economic Declaration from Summit of the Arch, July 16, 1989, Paris, France).

CONGRESSIONAL REQUEST FOR REPORTS

The United States Environmental Protection Agency (U.S. EPA) has studied the effects of global warming for several years. The goal of its efforts has been to use the best available information and models to assess the effects of climatic change and to evaluate policy strategies for both limiting and adapting to such change.

In 1986, Congress asked U.S. EPA to develop two reports on global warming. Congress directed U.S. EPA to include in one of these studies:

> An examination of policy options that if implemented would stabilize current levels of atmospheric greenhouse gas concentrations. This study should address the need for and implications of significant changes in energy policy, including energy efficiency and development of alternatives to fossil fuels; reductions in the use of CFCs; ways to reduce other greenhouse gases such as methane and nitrous oxide; as well as the potential for and effects of reducing deforestation and increasing reforestation efforts.

These issues are the focus of this report.

This report differs from most previous studies of the climate change issue in that it is primarily a policy assessment. Although some aspects of the relevant scientific issues are reviewed, this document is not intended as a comprehensive scientific assessment. A recent review of the state of the science is contained in the U.S. Department of Energy's State of the Art series (MacCracken and Luther, 1985a, 1985b; Strain and Cure, 1985; Trabalka, 1985).

Congress also asked U.S. EPA to prepare a companion report on the health and environmental effects of climate change in the U.S., which would examine the impact of climate change on agriculture, forests, and water resources, as well as on other ecosystems and society. In response to the latter request, U.S. EPA produced its report entitled, The Potential Effects of Global Climate Change on the United States (Smith and Tirpak, 1989). That report provides insights into the ranges of possible future effects that may occur under alternative climate change scenarios, and establishes qualitative sensitivities of different environmental systems and processes to changes in climate. The report also examines potential changes in hydrology, agriculture, forestry, and infrastructure in the Southeast, Great Lakes, California, and Great Plains regions of the United States.

Goals of this Study

Congress presented U.S. EPA with a very challenging task. From a policy perspective, it is not enough to know how emissions would have to change from current levels in order to stabilize the atmosphere. Instead, policy options must be evaluated in the context of expected economic and technological development and the uncertainties that prevent us from knowing precisely how a given level of emissions will affect the rate and magnitude of climate change. It is also necessary for the scope of this study to be global and the time horizon to be more than a century, because of the long lags built into both the economic and climatic systems (we chose 1985-2100 as the time frame for the analysis). We do not attempt predictions with such a scope, but scenarios are useful to explore policy options.

Based on these considerations U.S. EPA established four major goals:

• To assemble data on global trends in emissions and concentrations of all major greenhouse gases and activities that affect these gases.

• To develop an integrated analytical framework to study how different assumptions about the global economy and the climate system could influence future greenhouse gas concentrations and global temperatures.

• To identify promising technologies and practices that could limit greenhouse gas emissions.

• To identify policy options that could influence future greenhouse gas concentrations and global warming.

To achieve these goals U.S. EPA conducted an extensive literature review and data gathering process. The Agency held several informal panel meetings and enlisted the help of leading experts in the governmental, non-governmental, and academic research communities. U.S. EPA also conducted five workshops, which were attended by over three hundred people, to gather information and ideas regarding factors affecting atmospheric composition and options related to greenhouse gas emissions from . agriculture and land-use change, electric utilities, end uses of energy, and developing countries. Experts in NASA, the Department of Energy, and the Department of Agriculture were actively engaged. A draft of this report was produced in February 1989 and was reviewed by U.S. EPA's Science Advisory Board, other federal agencies, and a wide variety of individuals and organizations from outside the government. This final report has greatly benefitted from this review process, but U.S. EPA assumes responsibility for the content of this document.

Report Format

The structure of this report is designed to answer the following questions in turn: What is the greenhouse effect? What evidence is there that the greenhouse effect is increasing? How will the Earth's climate respond to changes in greenhouse gas concentrations? What activities are responsible for the greenhouse gas emissions? What technologies are available for limiting greenhouse gas emissions? How might emissions and climate change in the future? And what domestic and international policy options, if implemented, would help to stabilize global climate?

This chapter provides a general introduction to the climate change issue and reviews selected previous studies. Chapter II discusses the greenhouse gases, their sources and sinks, chemical properties, current
CLIMATE CHANGE TERMINOLOGY

An attempt has been made throughout this report to avoid technical jargon, yet the use of some specialized terminology is inevitable. The specialized terms used in this Report are defined below.

Climate System

The interactive components of our planet which determine the climate. This includes the atmosphere, oceans, land surface, sea ice, snow, glaciers, and the biosphere. Climate change can be measured in terms of any part of the system, but it is most convenient to use surface air temperature as a measure of climate, since it is the parameter for which we have the best record and it is most directly relevant to the component of the biosphere that we know best -- humans.

Radiative Forcing (also called "external forcing," "forcing," or "perturbation")

A change imposed on the climate system (as opposed to generated by the internal dynamics of the climate system) that modifies the radiative balance of the climate system. Examples include: changes in the output of the sun or the orbit of the Earth about the sun, increased concentrations of particles in the atmosphere due to volcanoes or human activity, and increased concentrations of greenhouse gases in the atmosphere due to human activity. Radiative forcing is often specified as the net change in energy flux at the tropopause (W/m^2) or the equilibrium change in surface temperature in the absence of feedbacks (°C).

Climate Feedbacks

Processes that alter the response of the climate system to radiative forcings. We distinguish between physical climate feedbacks and biogeochemical climate feedbacks. Physical climate feedbacks are processes of the atmosphere, ocean, and land surface, such as increases in water vapor, changes in cloudiness, and decreases in land- and sea-ice accompanying global warming. Biogeochemical feedbacks involve changes in global biology and chemistry, such as the effect of changes in ocean circulation on carbon dioxide concentrations and changes in albedo from shifts in ecosystems. The impact of climate feedbacks is generally measured in terms of their effect on climate sensitivity. Positive feedbacks increase climate sensitivity, while negative feedbacks reduce it.

Climate Sensitivity (or equilibrium sensitivity)

The ultimate change in climate that can be expected from a given radiative forcing. Climate sensitivity is generally measured as the change in global average surface air temperature when equilibrium between incoming and outgoing radiation is re-established following a change in radiative forcing. A common benchmark, which we use in this report, is the equilibrium temperature increase associated with a doubling of the concentration of carbon dioxide from pre-industrial levels. The National Academy of Sciences has estimated that this sensitivity is in the range of $1.5-4.5^{\circ}$ C, with a recent analysis suggesting $1.5-5.5^{\circ}$ C; a reasonable central uncertainty range is $2-4^{\circ}$ C.

CLIMATE CHANGE TERMINOLOGY (continued)

Transient Response

The time-dependent response of climate to radiative forcing. Climate responds gradually to changes in radiative forcing, primarily because of the heat capacity of the oceans. The transient mode is characterized by an imbalance between incoming and outgoing radiation. Given the changing concentrations of greenhouse gases, the Earth's climate will be in a transient mode for the foreseeable future. Most general circulation models (see below), however, have so far examined equilibrium conditions because transient effects are much more difficult to analyze.

Albedo

The fraction of incoming solar radiation that is reflected back into space.

Flux

Flow per unit time per unit area. The flow can be of energy (e.g., watts per square meter $[W/m^2]$) or mass (e.g., grams per square meter per day [g m⁻²d⁻¹]).

General Circulation Model (GCM)

A computer model of the Earth's climate based on equations that describe, among other things, the conservation of energy, momentum, and mass, and which explicitly calculates the distribution of wind, temperature, precipitation and other climatic variables. Such models are applied to the atmosphere, to the oceans, or to both coupled together.

Solar Luminosity, Solar Constant

Solar luminosity is the total amount of energy emitted by the sun. The so-called "solar constant" is the average amount of energy received at the top of the Earth's atmosphere at the mean Earth-sun distance; this amount varies with changes in solar luminosity.

Troposphere, Tropopause, Stratosphere

The troposphere is the lower atmosphere, from the ground to an altitude of about 8 kilometers (km) at the poles, 12 km in mid latitudes and 18 km in the tropics. The tropopause marks the top of the troposphere; temperature decreases with altitude below the tropopause and increases with altitude above the tropopause to the top of the stratosphere. The stratosphere extends from the tropopause to about 50 km. The troposphere and stratosphere together contain more than 99.9% of the mass of the atmosphere.

atmospheric concentrations and distributions, and related uncertainties. Chapter III relates the greenhouse gases to the process of climate change. Once this link is made, Chapter IV examines those human activities that affect trace-gas emissions and ultimately influence climate change. Chapter V gives a detailed description of existing and emerging technologies that should be considered in the formulation of a comprehensive strategy for Chapter VI mitigating global warming. discusses the scenarios developed for this report to assist us in thinking about possible future emissions and climate change, both with current policies and with policies that could decrease or increase future greenhouse gas Chapter VII outlines domestic emissions. policy options, and the concluding chapter international (Chapter VIII) discusses mechanisms for responding to climate change. Three appendices provide additional detail on the analysis for interested readers. Appendix A describes the modelling framework used to develop the scenarios presented in Chapter VI. Appendix B provides additional details on how each of the scenarios was implemented. Appendix C presents the results of many sensitivity analyses that explore in detail how alternative assumptions on key parameters could affect the rate and magnitude of global climate change presented in Chapter VI.

THE GREENHOUSE GASES

Once emitted, greenhouse gases remain in the atmosphere for decades to centuries, As a result, if emissions remained constant at 1985 levels, the greenhouse effect would continue to intensify for more than a century. Carbon dioxide concentrations would reach 440-500 parts per million by volume (ppm) by 2100, compared with about 350 ppm today, and about 290 ppm 100 years ago. CFC concentrations would increase by more than a factor of three from current levels, while nitrous oxide concentrations would increase by about 20%; and methane concentrations might remain roughly constant. Indeed, in many cases drastic cuts in emissions would be required to stabilize atmospheric composition.

Carbon Dioxide

Carbon dioxide is the most abundant and single most important greenhouse gas in the atmosphere. Its concentration has increased by about 25% since the industrial revolution. Detailed measurements since 1958 show an increase from 315 to 351 ppm (see Figure 1-1). These data clearly demonstrate that human activities are now of such a magnitude as to produce global consequences. Current emissions are estimated at 5.5 billion tons of carbon (Pg C) from fossil-fuel combustion and 0.4-2.6 Pg C from deforestation.² Most of this CO_2 remains in the atmosphere or is absorbed by the ocean. Even though only about half of current emissions remain in the atmosphere, currently available models of CO_2 uptake by the ocean suggest that substantially more than a 50% cut emissions is required to stabilize in concentrations at current levels (see Table 1-1; Figure 1-2).

TABLE 1-1

Approximate Reductions in Anthropogenic Emissions Required to Stabilize Atmospheric Concentrations at Current Levels

REDUCTION REQUIRED
50-80%
10-20%
80-85%
75-100%
Freeze
Freeze

Methane

The concentration of methane has more than doubled during the last three centuries. Methane, which is currently increasing at a rate of 1% per year, is responsible for about 20% of current increases in the greenhouse effect. Of the major greenhouse gases, only CH₄ concentrations can be stabilized with modest cuts in anthropogenic emissions: a 10-20% suffice to stabilize cut would concentrations at current levels due to methane's relatively short atmospheric lifetime (assuming that the lifetime remains constant, which may require that hydrocarbon and carbon monoxide emissions be stabilized).





Figure 1-1. a) Monthly concentrations of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. (Sources: Keeling, 1983, personal communication; Komhyr et al., 1985; NOAA, 1987; Conway et al., 1988.) b) Annual emissions of CO_2 , in units of carbon, due to fossilfuel combustion. (Sources: Rotty, 1987; Rotty, personal communication.)

The steadily increasing concentration of atmospheric CO_2 at Mauna Loa since the 1950s is caused primarily by the CO_2 inputs from fossil-fuel combustion. Note that CO_2 concentrations have continued to increase since 1979, despite relatively constant emissions; this is because emissions have remained substantially larger than net removal.

FIGURE 1-2



Figure 1-2. The response of atmospheric CO_2 concentrations to arbitrary emissions scenarios based on two one-dimensional models of ocean CO_2 uptake. See Chapter VI for a description of scenarios and models. (Sources: Hansen et al., 1984; Lashof, 1989; Siegenthaler, 1983).

Nitrous Oxide

The concentration of nitrous oxide has increased by 5-10% since pre-industrial times. Nitrous oxide is currently increasing at a rate of 0.25% per year, which represents an imbalance of about 30% between sources and sinks. Assuming that the observed increase in N₂O concentrations is due to anthropogenic sources and that natural emissions have not changed, then an 80-85% cut in anthropogenic emissions would be required to stabilize N₂O at current levels.

Chlorofluorocarbons

Chlorofluorocarbons were introduced into the atmosphere for the first time during this century. The most common species are CFC-12 (CF₂Cl₂) and CFC-11 (CFCl₃), which had atmospheric concentrations in 1986 of 392 and 226 parts per trillion by volume (ppt), respectively. While these concentrations are tiny compared with that of CO₂, each additional CFC molecule has about 15,000 times more impact on climate, and CFCs are increasing very rapidly -- about 4% per year since 1978. A focus of attention because of their potential to deplete stratospheric ozone, the increasing concentrations of CFCs also account for about 20% of current increases in the greenhouse effect. For CFC-11 and CFC-12, cuts of 75% and 85%, respectively, of current global emissions would be required to stabilize concentrations. However, in order to stabilize stratospheric chlorine levels -- of particular concern for stratospheric ozone depletion -- a 100% phaseout of fullyhalogenated compounds (those that do not contain hydrogen) and a freeze on the use of methyl chloroform would be required.

Other Gases Influencing Composition

Emissions of carbon monoxide (CO), nitrogen oxides (NO_x) , and other species, in addition to the greenhouse gases just described, are also changing the chemistry of the atmosphere. This change in atmospheric chemistry alters the distribution of ozone and the oxidizing power of the atmosphere, changing the atmospheric lifetimes of the greenhouse gases. If the concentrations of the long-lived gases were stabilized, it might only be necessary to freeze emissions of the shortlived gases at current levels to stabilize atmospheric composition.

PREVIOUS STUDIES

Evidence that the composition of the atmosphere is changing has led to a series of studies analyzing the potential magnitude of future greenhouse gas emissions. A few of these studies have carried the analysis further, making projections of the timing and severity of future global warming. The first generation of these studies focused principally on energy use and CO₂ emissions (see, e.g., NAS, 1979; Clark et al., 1982; IIASA, 1983; Nordhaus and Yohe, 1983; Rose et al., 1983; Seidel and Keyes, 1983; Edmonds and Reilly, 1983b, 1984; Legasov et al. 1984; Goldemberg et al., 1985, 1987; and Keepin et al., 1986). Subsequent studies have recognized that other radiativelyactive trace gases significantly amplify the effects of CO₂ (see, e.g., Lacis et al., 1981; Ramanathan et al., 1985; Dickinson and Cicerone, 1986; WMO, 1985; and Mintzer, 1987). In the following sections, some of the most important of these earlier analyses are reviewed in order to provide a basis for comparison with this study.

Estimates of the Climatic Effects of Greenhouse Gas Buildup

The first serious analysis of the effect of increasing CO₂ concentrations on global warming was conducted by the Swedish (1896). chemist Svante Arrhennius Arrhennius, concerned about the rapidly increasing rate of fossil-fuel use in Europe, recognized that the resulting increase in the atmospheric concentration of CO₂ would alter the thermal balance of the atmosphere. Using simplified, one-dimensional model, a Arrhennius estimated that if the atmospheric concentration of CO_2 doubled, the surface of the planet would warm by about 5°C. (The expected equilibrium climate change associated with a doubling of CO_2 has become a benchmark. That is, many studies examine the consequences of greenhouse gas increases with a total warming effect equivalent to that from a doubling of the concentration of CO_2 .)

In 1979, a study by the U.S. National Academy of Sciences (NAS) evaluated the impact on global climate of doubling the concentration of CO_2 relative to the preindustrial atmosphere (NAS, 1979). The NAS study concluded that the planet's surface would most likely be 1.5-4.5°C warmer under such conditions. Subsequent re-evaluations by NAS (1983, 1987) as well as the "State-of-the-Art" report issued by the U.S. Department of Energy (U.S. DOE) (MacCracken and Luther, 1985a) have reaffirmed this estimate.

Recent work by Dickinson (1986) suggests that the effects of a greenhouse gas buildup radiatively equivalent to doubling the pre-industrial concentration of CO_2 might warm the planet to a greater extent than had previously been expected. Focusing on the uncertainties in current understanding of atmospheric feedback processes, Dickinson estimated that the warming effect of such a buildup was likely to be between 1.5° and 5.5°C. Dickinson's "best guess" was that the actual equilibrium warming would be between 2.5° and 4.5°C.

Studies of Future CO₂ Emissions

For the next eighty years after Arrhennius issued his warning, little attention was paid to the potential global consequences of fossil-fuel combustion. By the mid-1970s, measurements of atmospheric CO_2 concentrations at Mauna Loa begun by Keeling during the International Geophysical Year (1957-1958) provided indisputable evidence of a long-term increasing trend (see Figure 1-1), while the oil embargo of 1973 and the nuclear power debate focused attention on future energy supplies. Increasing interest was placed on the problems of projecting future global energy use and on estimating the resulting CO_2 emissions.

A major international study of future energy use was conducted by the International Institute for Applied Systems Analysis (IIASA, 1981, 1983). Employing an international group of almost 200 scientists, the IIASA team developed a set of computer models to estimate regional economic growth, energy demand, energy supply, and future CO_2 emissions. Although the models were never completely integrated, the first phase of the IIASA study produced two complete scenarios of global energy use. The IIASA low scenario generated CO_2 emissions of about 10 petagrams of carbon per year (Pg C/yr) in 2030. The IIASA high scenario projected emissions of about 17 Pg C/yr in 2030. In the second phase of the IIASA study a third scenario was outlined, emphasizing increased use of natural gas. In this third scenario, CO_2 emissions in 2030 were only about 9.4 Pg C/yr.

In 1983 Edmonds and Reilly, two U.S. developed a detailed partial economists. equilibrium model to investigate the effects of policies alternative energy and their implications for future CO_2 emissions (Edmonds and Reilly, 1983a). This model disaggregates the world into nine geopolitical regions. It offers a highly detailed picture of the supply side of the world's commercial energy business but only limited detail on the demand side. It considers nine primary and four secondary forms of commercial energy (including biomass grown on plantations) but ignores non-commercial uses of biomass for Using explicit assumptions about fuel. regional population changes and economic growth and combining them with assumptions about technological change and the costs of extracting various grades of fuel resources in each region, the model calculates supply and demand schedules for each type of fuel.

For their first major report, Edmonds and Reilly (1983b) developed a Base Case energy future for the period 1975 to 2050. In this scenario, CO_2 emissions in 2050 were approximately 26.3 Pg C/yr. The authors generated several other scenarios in this study that reflected the effect of various taxes imposed on fuel supply and use. These taxes reduced CO_2 emissions by varying amounts, with emissions in some scenarios falling as low as 15.7 Pg C/yr in 2050. In 1984 Edmonds and Reilly produced a new set of scenarios for U.S. DOE by varying other key parameters in the model (Edmonds and Reilly, 1984). In these new scenarios, CO_2 emissions in 2050 vary from about 7 to 47 Pg C/yr, with a new "Base Case" value of about 15 Pg C/yr. The principal force contributing to the difference between the results of the two studies conducted by Edmonds and Reilly is the higher coal price applied in the second study.

A number of other studies have used the Edmonds-Reilly (E-R) model to project future energy use and CO_2 emissions. The most important of these were studies conducted by the U.S. EPA (Seidel and Keyes, 1983) and Rose et al. (1983). The U.S. EPA study used the E-R model to generate 13 scenarios for the period 1975-2100, which were used as a basis for investigating whether actions taken now to reduce fossil-fuel consumption could significantly delay a future global warming. Six baseline and seven policydriven scenarios were investigated in this study. The scenarios generated in the U.S. EPA study projected CO₂ emissions in 2050 at levels of 10-18 Pg C/yr. The authors concluded from these scenarios that the timing of a 2°C warming is not very sensitive to the effects of the energy policies they tested.

Rose and his colleagues at the Massachusetts Institute of Technology (MIT) also used the E-R model to study the effect of various energy policy options on the timing and extent of future CO₂ emissions (Rose et al., 1983). Eleven scenarios were investigated, covering the period from 1975 to 2050 and incorporating a much wider range of assumptions and policies than those tested in the U.S. EPA study. Rose et al. studied the effects of increased energy efficiency, increased fossil-fuel prices, higher nuclear energy supply costs, a moratorium on building nuclear plants, lower photovoltaic costs, higher oil prices, and a cutoff of oil imports from the Middle East. The MIT study went beyond the E-R model results to provide detailed estimates of the materials required for construction and operation of energy facilities in each scenario. In the MIT scenarios, emissions of CO₂ in 2050 ranged from less than 3 to about 15 Pg C/yr. The most important new conclusion of Rose et al. was that a feasible "option space exists in which the CO₂/climate problem is much ameliorated" through energy policy choices and improvements in technology.

In 1983 the National Academy of Sciences completed a Congressionallymandated study to evaluate, among other things, the effects of fossil-fuel development activities authorized by the Energy Security Act of 1980 (NAS, 1983). One of the chapters in this study, authored by energy economists Nordhaus and Yohe, used a compact model of global economic growth and energy use to analyze CO₂ emissions between 1975 and 2100 (Nordhaus and Yohe, 1983). Unlike the partial equilibrium approach employed in the E-R model, the Nordhaus and Yohe (N-Y) model used a generalized Cobb-Douglas production function to estimate future energy demand. In this approach global GNP is estimated as a function of assumptions about average rates of change in labor productivity, population, and energy consumption. Demand for energy is separated into two categories, fossil and non-fossil. Projections of CO_2 emissions (based on the weighted average release rate from fossil fuels) were used as inputs to a simple airborne fraction model of the carbon cycle.

The N-Y analysis used an approach called "probabilistic scenario analysis" to evaluate the effects on CO₂ emissions of alternative assumptions used in the model. The results of 1000 cases were examined. The CO_2 emissions trajectories in these cases were presented as percentiles in the overall distribution among the 1000 scenarios. Using approach to uncertainty analysis, this Nordhaus and Yohe concluded that the 50th percentile for carbon emissions in 2050 was approximately 15 Pg C/yr. The 95th percentile case suggested that emissions in 2050 would likely be less than 26 Pg C/yr, while the 5th percentile case indicated that emissions would likely be greater than 5 Pg C/yr.

The probabilistic approach was subsequently applied to the more detailed E-R model using Monte Carlo analysis (Edmonds et al., 1986; Reilly et al., 1987). The results of this analysis suggest a larger total range of uncertainty and a substantially lower median emissions estimate compared with the Nordhaus and Yohe (1983) results. When the likely correlations between model parameters are taken into account. Edmonds et al. obtain emissions of 7.7 Pg C/yr in 2050 for the 50th percentile case with 5th and 95th percentile bounds of 2.3 and 58.1 Pg C/yr, respectively. Note that the median result is about half of the Base Case scenario obtained in earlier analysis by Edmonds and Reilly (1984).

In 1984 Legasov et al. published one of a continuing series of Soviet analyses of future global energy use and its environmental implications. Legasov et al. analyzed two scenarios in which energy demand reaches 6 and 20 kilowatts per capita by the end of the next century. Annual per capita energy consumption is treated as a logistic function, approaching these levels asymptotically in 2100. Assuming a global population of 10 billion persons, the minimal variant implies a global energy demand of 60 terawatts (TW), about six times the current level by $2100.^3$ CO₂ emissions in this scenario follow a bell-shaped trajectory, peaking at about 13.3 Pg C/yr in 2050.

Goldemberg and his colleagues have used a completely different approach to projecting future energy use and its consequences for CO₂ emissions (Goldemberg et al., 1985, 1987, 1988). The Goldemberg et al. analysis is based on an end-use-oriented approach to evaluating the demand for energy services, rather than the availability of energy supply. Based on detailed studies of energy demand in four countries (U.S., Sweden, India, and Brazil), Goldemberg and his colleagues developed a scenario of future energy requirements in both industrialized and developing countries. Although the study does not represent a forecast of future energy demand, it provides an "existence proof," demonstrating the feasibility of a world economy that continues to grow while consuming much less energy than it would if historical trends continue.

Emphasizing the potential to improve the efficiency of energy supply and use, per capita energy demand in the industrialized countries is cut by 50% in the Goldemberg et al. scenarios. During the same 40-year period, per capita demand for energy in the developing countries grows by about 10%, with commercial fuels displacing traditional biomass fuels at a rapid and increasing rate. Global energy demand remains essentially constant in the base case with CO_2 emissions in 2020 of 5.9 Pg C/yr, only about 5% higher than today's level.

A limitation of the Goldemberg et al. studies is that the impact of market imperfections and the rate of capital stock turnover are not fully addressed. Nonetheless, these studies, along with the Rose et al. analysis, demonstrate that economic growth can be decoupled from increases in CO_2 emissions. Experience over the last 15 years in the U.S., Western Europe, and Japan suggests that this conclusion is correct. A study by Keepin et al. (1986) reviewed and re-evaluated the range of previous energy and CO_2 projections, including those summarized here. It concluded that the feasible range for future energy in 2050 was somewhere between about 10 and 35 TW, with CO_2 emissions between 2 and 20 Pg C/yr.

Studies of the Combined Effects of Greenhouse Gas Buildup

In the last few years a number of analysts have investigated the combined effects on global surface temperature of a buildup of CO_2 and other trace gases. Preliminary analysis of the impact of concentration increases during the 1970s was presented by Lacis et al. (1981), and estimates of future impacts were included in Seidel and Keyes (1983). A seminal article by Ramanathan et al. (1985) focused attention on the subject. This study used a one-dimensional radiativeconvective model to estimate the impact of a continuation of current trends in the buildup of more than two dozen radiatively active trace gases between 1980 and 2030. Ramanathan and his colleagues calculated an expected value for the equilibrium warming of about 1.5°C over this period, with a little less than half of that amount due to the buildup of CO_2 alone. (The Ramanathan et al. analysis included the effects of water-vapor feedback, but not the other known feedback mechanisms; see CHAPTER III.) The most important conclusion of the analysis by Ramanathan et al. is that if current trends continue and uncertainties in the future emissions projections are accounted for, the warming effects of the non-CO₂ trace gases will amplify the warming due to the buildup of CO_2 alone by a factor of between 1.5 and 3.

In 1986, Dickinson and Cicerone extended the work of Ramanathan et al. to evaluate a range of trace-gas scenarios covering the period from 1985 to 2050. Using the radiative-convective model developed by Ramanathan et al., and considering a range of emissions growth rates for the most important greenhouse gases, Dickinson and Cicerone (1986) estimated that equilibrium global average surface temperatures would rise at least 1°C and possibly more than 5°C by 2050, when the full range of atmospheric feedback processes was considered.

Each of the analyses described above was based on the assumption that historical trends in the growth of greenhouse gas emissions continue for the next 40-50 years. Mintzer (1987) has developed a model to consider the alternative: that policy and investment choices made in the next several decades will substantially alter the growth rates of future emissions. Mintzer's analysis uses a composite tool called the Model of Warming Commitment to link future rates of economic growth the increasing atmospheric to concentrations of carbon dioxide, nitrous oxide, chlorofluorocarbons, methane, and tropospheric ozone. The results are reported as the date of atmospheric commitment to a warming equivalent to doubling pre-industrial CO_2 concentrations and as the magnitude of warming commitment in 2075.

Mintzer's initial analysis considered four policy-driven global scenarios, including a Base Case representing a continuation of current trends. All four scenarios support a global population of about 10 billion people and the same levels of regional economic growth. Most recent analyses, including the ones cited above and Mintzer's Base Case, indicate that a continuation of current trends would lead to a warming commitment equivalent to doubling the pre-industrial concentration of CO_2 by about 2030. In Mintzer's Base Case, by 2075, the planet is committed to an eventual warming of about 3-9°C. Alternatively, in the High Emissions case, policies that increase coal use, spur deforestation, extend the use of the most dangerous CFCs, and limit improvements in energy efficiency will accelerate the onset of the "doubled CO₂ equivalent" atmosphere to about 2010 and commit the planet to a warming of about 5-15°C in 2075. By contrast, in Mintzer's Slow Buildup scenario, a warming associated with the doubled CO_2 equivalent atmosphere is postponed beyond the end of the simulation period in 2075. In the Slow Buildup scenario this level of risk reduction is achieved by aggressively pursuing policies to increase energy efficiency, limit tropical deforestation, reduce the use of the most dangerous CFCs, and shift the fuel mix from carbon-intensive fuels like coal to hydrogen-intensive fuels like natural gas, and ultimately, to energy sources that emit no CO_2 .

More recently, Rotmans et al. (1988) used a framework similar to the Model of Warming Commitment to develop scenarios of greenhouse warming based on alternative policy assumptions. Also, Rotmans and Eggink (1988) have analyzed the role of methane in greenhouse warming.

Major Uncertainties

Major uncertainties underlie many aspects of our understanding of the climate change problem, including both scientific and socioeconomic parameters. The physical uncertainties include uptake of heat and CO₂ by the ocean and any other sinks, geophysical and biogeochemical feedback mechanisms, and natural rates of emission of the greenhouse gases. The social and economic uncertainties include population growth, GNP growth, structural changes in economic systems, rates of technological change, future reliance on fossil fuels, and future compliance with the Montreal Protocol. Future rates of greenhouse gas emissions cannot be predicted with certainty. Future emissions rates will be determined by the emerging pattern of human industrial and agricultural activities as well as by the effects of feedback processes in the Earth's biogeophysical system whose details are not well understood at the present time.

All existing climate models encompass large uncertainties that limit the accuracy of the models and the level of geographic detail that can be considered. Even the best general circulation models (GCMs) are limited by the assumptions necessarily made about the influence of clouds, vegetation, ice and snow, soil moisture, and terrain, all of which affect the energy balance of the Earth's surface. Two of the largest uncertainties involve our limited understanding of the roles that clouds and the ocean play in the climate system.

Conclusions From Previous Studies

Despite the significant uncertainties that underlie our understanding of climate change, several important conclusions emerge from the existing literature. First, emissions of a number of other trace gases will amplify the future warming effect of any further buildup in the atmospheric concentration of CO_2 . Second, it is too late to prevent all future global warming. Trace gases released over the last century have already committed the planet to an ultimate warming (of 1-2°C) that may be greater than any other in the period of written human history. Finally, policy choices and investment decisions made during the next decade that are designed to increase the efficiency of energy use and shift the fuel mix away from fossil fuels could slow the rate of buildup sufficiently to avoid the most catastrophic potential impacts of rapid climate change. Alternatively, decisions to rapidly expand the use of coal, extend the use of the most dangerous CFCs, and rapidly destroy the remaining tropical forests could "push up the calendar," accelerating the onset of a dangerous global warming.

The rate at which climate may change must be of particular concern to policymakers. The temperature increases resulting from doubling the concentration of CO_2 that are predicted by most GCMs are comparable to the increase that has occurred since the last ice age. The difference is that the period of time within which this increase could happen is much shorter. Atmospheric scientists predict that within approximately 100 years we could experience temperature increases equivalent to those that have occurred over the past 18,000 years (about 5°C; see It is not clear that our CHAPTER III). ecosystems and economic systems will be able to adjust to such a rapid change in global mean temperatures. Increases in world population. coupled with limited environmental and agricultural resources, increase the vulnerability of social systems to climatic change.

The potential impacts of climatic change are highly uncertain and are beyond the scope of this report. They are addressed in the companion volume, *The Potential Effects of Global Climate Change on the United States* (Smith and Tirpak, 1989). The collective findings of this study suggest that the climatic changes associated with a global warming of roughly 2-4°C would result in

> a world different from the world that exists today. Global climate change could have significant implications for natural ecosystems; for where and how we

farm; for the availability of water to irrigate crops, produce power, and support shipping; for how we live in our cities; for the wetlands that spawn our fish; for the beaches we use for recreation; and for all levels of government and industry.

Although sensitivities were identified in this report, detailed regional predictions of climate change cannot be made at this time. Thus, potential responses to the greenhouse gas buildup must be viewed in the context of risk management or insurance-buying.

A second major concern is that the greenhouse gases have very long lifetimes once they are introduced into the atmosphere. Although there is a substantial lag between the time a greenhouse gas is introduced into the atmosphere and when its full impact on climate is realized, once the gases are in the atmosphere they will remain there for a long time. The longer the delay before mitigating action is taken, the larger will be the commitment to further global warming.

Policymakers must determine how best to minimize the costs of global warming to the peoples of the world and the damage to ecosystems. But global warming is a complex problem for which there is no single, simple solution. No single policy initiative will completely mitigate man-made climate change. The sources, sectors, and countries contributing to the emissions of greenhouse gases are numerous (see CHAPTER IV).

Compounding the difficulty of identifying solutions to the greenhouse problem is that the greenhouse gases do not all have the same forcing effect on global temperatures. In fact, CO_2 is the least effective absorbent of infrared radiation of all of the greenhouse gases per additional molecule added to the atmosphere. Because the combined effect of the other greenhouse gases is comparable to the effect of CO_2 , mitigatory policies cannot be directed solely at reducing CO_2 emissions. The sources of methane, CFCs, nitrous oxide, and other gases must therefore be carefully considered.

As we explore the options for limiting greenhouse gas emissions in this report, it is

important to remember two salient points: (1) global warming is an international problem whose solution will require extensive cooperation between both industrialized and developing countries; and (2) no single economic sector can be held entirely responsible for the greenhouse effect. In focusing on strategies to stabilize climate in this Report, we recognize that the optimal mix of adaptation and prevention is uncertain. The Earth is already committed to some degree of climate change, so adaptation to some level of change is essential. Adaptation strategies can be adopted unilaterally, and the costs will be spread out into the future when countries may be better able to afford them. Imposing climate change on our grandchildren, however, raises serious concerns regarding intergenerational equity. And the highest rates of potential change may be considered unacceptable, requiring some degree of Stabilizing strategies would prevention. require global cooperation of an unprecedented nature and could be costly for some countries. The activities responsible for greenhouse gas emissions are economically valuable, the distribution of emissions is large, and the responsible countries reflect diverse economies and a variety of interests. At the same time, there are policies that can reduce greenhouse gas emissions while promoting other environmental, economic, and social goals.

CURRENT DOMESTIC AND INTERNATIONAL ACTIVITIES

Subsequent to the Congressional request to produce this report and the companion document on potential effects of climate change, there have been a wide variety of new domestic and international initiatives related to climate change.

Domestic Research and Policy Activities

The Global Climate Protection Act of 1987 requires that:

The President, through the Environmental Protection Agency, shall be responsible for developing and proposing to Congress a coordinated national policy on global climate change. This Act is a very broad mandate that requires close cooperation between U.S. EPA and other agencies (including NASA, NOAA, the Corps of Engineers, and the Departments of Energy, Agriculture, and the Interior, the National Climate Program Office, and the Domestic Policy Council).

The Global Climate Protection Act also requires that the Secretary of State and the U.S. EPA Administrator jointly submit, by the end of 1989, a report analyzing current international scientific understanding of the greenhouse effect, assessing U.S. efforts to gain international cooperation in limiting global climate change, and describing the U.S. strategy for seeking further international cooperation to limit global climate change. This report, along with those being developed by other federal agencies, will provide a foundation upon which a national policy can be formulated.

During 1989, several states passed legislation or signed executive orders specifically addressing global warming. The most common approach has been the creation of procedures to study the feasibility of reducing greenhouse gas emissions by a specific amount by some target date. In Oregon, a bill passed in July requires a state strategy to reduce greenhouse emissions 20% from 1988 levels by 2005. In Vermont, an executive order calls for a similar plan to reduce both greenhouse gas emissions and acid rain precursors by 15% below current levels by the year 2000; additional restrictions on CFCs were adopted by the legislature. A New York executive order accompanying release of a state energy plan in September set a goal of reducing CO₂ emissions 20% by 2008. A study of how to achieve that goal will be conducted jointly by the Energy Office, Department of Environmental Conservation, and the Public Service Commission for presentation to the Governor by April 30, 1990. A New Jersey executive order on global warming requires state agencies to purchase the most energy efficient equipment available "where such equipment or techniques will result in lower costs over the lifetime of the equipment." In Missouri, the state legislature created a commission to study the effects of ozone depletion and global warming on the state and to identify means of reducing the

state's emissions; findings and recommendations are due in late spring 1990.

International Activities

The greenhouse gas problem is an international issue. In order to respond effectively to this problem, the nations of the world must act in concert. Several international organizations have recognized the need for multilateral cooperation and have become involved with the global climate change issue. The United Nations Environment Programme (UNEP) is responsible for conducting climate impact assessments. The World Meteorological Organization (WMO) is supporting research on and monitoring of atmospheric and physical The International Council of sciences. Scientific Unions (ICSU) is developing an international geosphere-biosphere program.

The U.S. government is supporting the Intergovernmental Panel on Climate Change (IPCC) established under the auspices of UNÉP and WMO. The IPCC, which held its first meeting in November help ensure an orderly 1988. will international effort in responding to the threat of global climate change. At its first meeting the IPCC established three working groups: the first, to assess the state of scientific knowledge on the issue, is chaired by the United Kingdom; the second, to assess the potential social and economic effects from a warming, is chaired by the Soviet Union; and the third, to examine possible response strategies, including options for limiting emissions and adapting to change, is chaired by the United States. An interim report by the IPCC summarizing its key findings was reviewed at the Second World Climate Conference in November 1990.

The U.S. government has also taken a more active role in international discussions on climate change. At the Malta Summit in December 1989, President Bush offered (1) to convene an international meeting at the White House in the spring of 1990 for top level scientific, environmental, and economic officials to discuss global climate change issues, and (2) to host a conference to negotiate a framework treaty on global climate change. The White House Conference on Science and Economics Research Related to Global Change was held in Washington in April of 1990, stressing the need for enhanced levels of cooperation with respect to the science and impacts of climate change and the economic implications of possible response strategies. The U.S.-hosted international meeting to begin the negotiations for a framework convention on climate change was held in the Washington area in February, 1991.

International concern over the impacts of climate change was also reflected by the major industrialized countries at the annual Economic Summit held in Paris, France. The G-7 countries not only endorsed efforts to limit greenhouse gases, but also stated that "... a framework or umbrella convention on climate change to set out general principles or guidelines is urgently required to mobilize and rationalize the efforts made bv the international community" (Economic Declaration, Summit of the Arch, July 16, The call for an international 1989). framework convention on climate has also been endorsed by the Ministerial Conference on Atmospheric Pollution and Climatic Change held in the Netherlands (November 1989), the 15th session of the UNEP Governing Council, and the XLI session of the WMO Executive Council.

The Economic Summit of the G-7 countries in Houston in July 1990 reiterated support for the negotiation of a framework convention on climate change. The Summit also stated that the G-7 countries are ready to begin negotiations on a global forest convention or agreement, which is needed to curb deforestation, protect biodiversity, stimulate positive forestry actions, and address threats to the world's forests. While such a convention is needed for reasons other than climate change, it would also have climate change benefits.

In addition, several countries have held or plan to hold international conferences on global climate change and are analyzing domestic policy options. These include Canada, The Federal Republic of Germany, the United Kingdom, Italy, Japan, India, Egypt, and the Netherlands. The global warming issue is an international concern. In order to develop a responsible program, the U.S. government must consider the feasibility of achieving both domestic and international acceptance and implementation of policy initiatives. Otherwise, the effectiveness of programs instituted by any one country could be compromised by the lack of participation by other countries. International collaboration must be pursued.

NOTES

1. Anthropogenic means resulting from human activities. Thus, by anthropogenic emissions we mean those emissions caused by man's activities, as opposed to those resulting from natural causes.

2. One billion tons of carbon = 10^{15} grams of carbon = 1 petagram of carbon (Pg C).

3. 1 terawatt = 10^{12} watts = 31.5×10^{18} joules per year = 31.5 exajoules (EJ) per year = 29.9Quadrillion British Thermal Units (Quads) per year.

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GREENHOUSE GAS TRENDS

FINDINGS

The composition of the atmosphere is changing as a result of human activities. Increases in the concentrations of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N_2O) , and chlorofluorocarbons (CFCs) are well documented. In addition, tropospheric (lower atmospheric) chemistry and stratospheric (upper atmospheric) chemistry are being modified as a result of the addition into the atmosphere of these gases as well as emissions of carbon monoxide, nitrogen oxides, and other compounds. Specifically, we find that:

The concentration of carbon dioxide in . the atmosphere has increased by 25% since the industrial revolution. Detailed measurements since 1958 show an increase of about 35 parts per million by volume. Both land clearing and fossil-fuel combustion have contributed to this rise, but the fossil-fuel source has dominated in recent years. Carbon dioxide is increasing at a rate of about 0.4% per year and is responsible for about half of the current increases in the greenhouse effect. Only 50-60% of the fossil-fuel CO₂ remains in the atmosphere. The total net uptake of CO_2 by the oceans and the net uptake/release of \overline{CO}_2 by the terrestrial biosphere cannot be precisely determined at this time.

The concentration of methane has more than doubled during the last three centuries. There is considerable uncertainty about the total emissions from specific sources of methane, but the observed increase is probably due to increases in a number of sources as well as to changes in tropospheric chemistry. Agricultural sources, particularly rice cultivation and animal husbandry, have probably been the most significant contributors historical increases in to There is the potential, concentrations. however, for rapid growth in emissions from landfills, coal seams, permafrost, natural gas exploration and pipeline leakage, and biomass burning associated with future forest clearing. Methane is increasing at a rate of $\sim 1\%$ per year and is responsible for about 20% of the current increases in the greenhouse effect. Per

molecule in the atmosphere, CH_4 is about 20 times more powerful than CO_2 at current concentrations.

The concentration of nitrous oxide has increased by 5-10% since pre-industrial times. The cause of this increase is highly uncertain, but it appears that the use of nitrogenous fertilizer, as well as the activities of land clearing, biomass burning, and fossil-fuel combustion have all contributed. Nitrous oxide, which is about 200 times more powerful on a per molecule basis than CO_2 as a greenhouse gas, can also contribute to stratospheric ozone depletion. Nitrous oxide is currently increasing at a rate of about 0.2-0.3% per year, which represents an imbalance between sources and sinks of about 30%. Nitrous oxide is responsible for about 5% of the current increases in the greenhouse effect.

CFCs were introduced into the atmosphere for the first time during this century; the most abundant species are CFC-12 and CFC-11, which had atmospheric concentrations in 1986 of 392 and 226 parts per trillion by volume, respectively. While these concentrations are tiny compared with that of CO_2 , these compounds are about 15,000 times more powerful, on a per molecule basis, than carbon dioxide as a greenhouse gas and are increasing very rapidly -- about 5% per year from 1978 to 1983. Of major concern because of their potential to deplete stratospheric ozone, the CFCs also represent about 20% of the current increases in the greenhouse effect.

The chemistry of the atmosphere is changing as a result of emissions of carbon monoxide, nitrogen oxides, and volatile organic compounds, among other species, and because of changes in the greenhouse gases just This change in atmospheric described. chemistry alters the amount and distribution of ozone and the oxidizing power of the atmosphere, which changes the lifetimes of CH₄ and other greenhouse gases. Changes in global ozone, both stratospheric and tropospheric, are quite uncertain and may have contributed to an increase or decrease in the warming commitment during the last decade.

INTRODUCTION

The composition of the Earth's atmosphere is changing. Detailed background atmospheric concentration measurements of trace gases combined with analyses of ancient air trapped in Antarctic and Greenland ice now give a compelling picture, not only of recent trends, but also of major changes that have occurred since pre-industrial times. Mounting evidence that the atmosphere is changing has increased the urgency to understand the processes that control atmospheric composition and the significance of the changes that are taking place. In this chapter we examine what is known and not known about the gases expected to be most important in altering climate during the coming decades. For each gas, we present data regarding its concentration history and geographic distribution, its sources and sinks, and its chemical and radiative interactions in the atmosphere. This information is summarized in Table 2-1, which appears at the end of this chapter.

The concentrations of a number of greenhouse gases have already increased substantially over pre-industrial levels. The estimated relative radiative forcing from the major gases (excluding water vapor and clouds) is illustrated in Figure 2-1 for the period 1880-1980 and for the expected concentration changes during the 1980s (see ADDENDUM TO CHAPTER II). Carbon dioxide (CO_2) accounted for about two-thirds of the total forcing over the last century, but its relative importance has declined to about half the total in recent years because of the more rapid growth in other gases during the last few decades (see CHAPTER IV). Particularly important has been the recent growth in concentrations of chlorofluoro-(CH₄) has Methane carbons (CFCs). remained the second most important greenhouse gas, responsible for 15-20% of the forcing. With the recent signing of the Montreal Protocol on Substances that Deplete the Ozone Layer and the subsequent London Amendments, growth in CFC concentrations is likely to be substantially restrained compared with what has been assumed until recently (e.g., Ramanathan et al., 1985; see CHAPTERS IV and V). The relative importance of CO_2 is therefore likely to increase again in the future

unless these emissions are also restricted (see CHAPTER VI).

The radiative impact of greenhouse gases is characterized here in terms of the effect of concentration changes on surface temperatures in the absence of climate feedbacks. Climate feedbacks are defined and discussed in Chapter III, where the climatic effects of changes in greenhouse gases are put into the broader context of other factors that influence climate. The human activities that apparently responsible are for the concentration trends documented in this chapter are described in Chapter IV.

CARBON DIOXIDE

Concentration History and Geographic Distribution

Carbon dioxide is the most abundant and single most important greenhouse gas (other than water vapor) in the atmosphere. Its role in the radiative balance and its potential for altering the climate of the Earth have been recognized for over a hundred years. Chemical measurements of atmospheric CO_2 were made in the 19th century at a few locations (see Fraser, Elliott et al., 1986; From and Keeling, 1986). However, the modern high-precision record of CO₂ in the atmosphere did not begin until 1958, the International Geophysical Year (IGY), when C.D. Keeling of Scripps Institution of Oceanography pioneered measurements of CO₂ using an infrared gas analyzer at Mauna Loa Observatory (MLO) in Hawaii and at the Since 1974, background South Pole. measurements of atmospheric CO₂ have been made continuously at four stations (Pt. Barrow, Alaska: Mauna Loa, Hawaii: American Samoa; and the South Pole) as part of the Geophysical Monitoring for Climatic Change (GMCC) program of the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. In addition to the continuous monitoring stations, NOAA/GMCC also operates a cooperative sampling network. Flask samples of air are collected weekly from these sites and shipped to the GMCC facility in Boulder, Colorado, for analysis. The sampling network began before 1970 at a few initial sites, expanded to a network of 15 stations in 1979,





Figure 2-1. Based on estimates of the increase in concentration of each gas during the specified period. The "Other" category includes other halons, tropospheric ozone, and stratospheric water vapor. The contribution to warming of the "Other" category is highly uncertain. (Sources: 1880-1980: Ramanathan et al., 1985; 1980s: Hansen et al., 1988.)

and, as of 1986, consisted of ~ 26 stations (Komhyr et al., 1985; Gammon et al., 1986; Conway et al., 1988). In addition to the U.S. programs, surface measurements of atmospheric CO₂ around the globe are made by many countries, including Australia, Canada, France, Italy, Japan, New Zealand, Spain, West Germany, and Switzerland.

Mauna Loa

The MLO CO_2 record is shown in Figure 1-1 in Chapter I. CO_2 steadily increased from 315 parts per million by volume (ppm) in 1958 to 351 ppm in 1988. This corresponds to an increase at the rate of 0.36% per year, or a mean increase of 1.1 ± 0.2 ppm per year. From 1958 to 1988, CO2 at Mauna Loa increased by 36 ppm; over the same period, fossil-fuel combustion (shown also in Figure 1-1) was a source of 123 petagrams $(Pg)^1$ of carbon (C) as CO_2 to the atmosphere, which is equivalent to 59 ppm of CO₂. The apparent fraction of the fossil-fuel sources of CO_2 that remained in the atmosphere during this period is thus 57%. Because other net sources of CO₂, particularly deforestation (see below), may have been important during this period, the actual fraction of anthropogenic (induced by human activities) carbon emissions remaining in the atmosphere is uncertain.

The apparent airborne fraction of CO_2 has not remained constant. Averaged over 1959-1975, the fraction was 54.7%, while that for 1975-1988 was 61.3% (Keeling, 1989). This increase could signal either enhanced CO_2 release from deforestation or reduced capacity of the land-ocean system to absorb excess CO_2 . It could also signal a positive feedback between greenhouse warming and the natural carbon cycling on land and at sea. Because of the implications for accelerated greenhouse warming, understanding the increase in the airborne fraction of CO_2 must be of highest priority.

Superimposed on the increasing secular trend of atmospheric CO_2 are regular seasonal oscillations: the concentration peaks in May/June, decreases steadily through the summer, and reaches a minimum in September/October. The seasonal peak-to-trough amplitude is ~5.8 ppm. The seasonal cycle of CO_2 at Mauna Loa and at

other northern hemispheric locations is caused primarily by the natural dynamics of the terrestrial biosphere: there is net removal of CO_2 from the atmosphere via photosynthesis during the growing season, and net return of CO_2 to the atmosphere via respiration and decomposition processes during the rest of the year.

Despite its regular appearance, there are interannual variations in the CO_{2} concentration measured at MLO. Annual mean concentration changes do not remain uniform throughout the duration of the record but have large fluctuations around the mean (Keeling, 1983). These excursions of atmospheric CO₂ from the mean generally occur during El Niño-Southern Oscillation events, where the large-scale perturbations of atmospheric temperature, precipitation, and other circulation statistics also alter the biological, chemical, and physical aspects of carbon cycling among the atmosphere, land, and ocean reservoirs. More recently, Keeling et al. (1989) have also found an 11-year cycle in CO₂, which correlates with the 11-year cycle found in the surface air temperature record compiled by Hansen and Lebedeff (1987). These excursions highlight the possibility of climatic feedbacks in the carbon cycle; they do not mask the increasing secular trend, which mainly reflects the trend in fossil-fuel combustion.

The seasonal amplitude also does not remain constant and has a $\pm 10\%$ variation about the mean. Recent analysis reveals a statistically significant positive trend in the seasonal amplitude between 1976 and 1986 (Bacastow et al., 1985; Enting, 1987). The causes of this amplitude trend have not been unambiguously identified; hypotheses involve shifts in the seasonality of photosynthesis and respiration, faster cycling of carbon as a result of climatic warming, and the direct effects of CO_2 on plants (also referred to as the CO_2 fertilization effect).

Ice-core Data

Bubbles in natural ice contain samples of ancient air. Analysis by gas chromatography and laser infrared spectroscopy of gases occluded in gas bubbles in polar ice has provided a unique reconstruction of atmospheric CO_2 history prior to the modern high-precision instrumental record (Oeschger and Stauffer, 1986). Deep ice cores have been drilled from many locations in both Greenland and Antarctica.

From the ice-core data, it is deduced that in pre-industrial times (i.e., before about 1800), the CO₂ concentration was 285 \pm 10 ppm and has increased at an accelerating rate since the industrial era (Neftel et al., 1985; Raynaud and Barnola, 1985; Pearman et al., 1986) (see Figure 2-2). The ice-core data reveal the possible existence of natural fluctuations on the order of \pm 10 ppm occurring at decadal time scales during the last few thousand years (Delmas et al., 1986; Neftel et al., 1982; Stauffer et al., 1985; Raynaud and Barnola, 1985; Oeschger and Stauffer, 1986).

Recent analysis of the 2083-meter-deep ice core from Vostok, East Antarctica, provides for the first time information on CO_2 variations in the last 160,000 years (Barnola et al., 1987; see Figure 3-3 in CHAPTER III). Large CO_2 changes were associated with the transitions between glacial and interglacial CO₂ concentrations were low conditions. (~200 ppm) during the two glaciations and high (~ 285 ppm) during the two major warm periods. The Vostok ice-core data also emphasize that current levels of atmospheric CO_2 are higher than they have ever been in the past 160,000 years. The CO₂ increase since 1958 is larger than the natural CO_2 fluctuations seen in the Greenland and Antarctic ice-core record.

The variation of CO_2 over this record is approximately in step with the surrogate temperature record deduced from the same ice core (Jouzel et al., 1987), confirming the role of CO_2 in influencing the radiation balance of the earth.

GMCC Network

The CO₂ concentrations from the ~ 25 globally distributed sites in the NOAA/GMCC cooperative flask sampling network have been reviewed in Komhyr et al. (1985) and Conway et al. (1988). The distribution for 1981-1985 is shown in Figure 2-3. There are large-scale, coherent, temporal and spatial variations of

 CO_2 in the atmosphere. Concentrations of CO_2 at all the stations are increasing at the rate of ~1.5 ppm per year (ppm/yr), similar to the rate of increase at Mauna Loa.

Annually averaged CO₂ concentrations are higher in the Northern Hemisphere than in the Southern Hemisphere. The interhemispheric difference was ~1 ppm in the 1960s and is ~ 3.0 ppm now, reflecting the Northern Hemisphere mid-latitude source (about 90%) of fossil-fuel CO2. This gradient has remained approximately constant in the past decade. Also evident in the north-south distribution of atmospheric CO_2 is the relative maximum of ~1 ppm in the equatorial regions, caused mainly by the outgassing of CO_2 from the supersaturated surface waters of the equatorial oceans. Although tropical deforestation may also contribute to the equatorial maximum in atmospheric CO₂, models of the global carbon cycle suggest that the observations are inconsistent with a net deforestation source greater than approximately 1.5 Pg C/yr (Pearman et al., 1983; Keeling and Heimann, 1986; Tans et al., 1989).

There is a coherent seasonal cycle at all the observing stations: the Northern Hemisphere cycles resemble that at Mauna Loa. The seasonal amplitude is largest, ~ 16 ppm, at Pt. Barrow, Alaska, and decreases toward the equator to ~6 ppm at Mauna Loa (see Figure 2-3). The CO_2 concentration is flat through the year in the equatorial region and is of opposite seasonality in the Southern Hemisphere. The seasonal cycle in the Northern Hemisphere is caused primarily by seasonal exchanges with the terrestrial biosphere (Fung et al., 1987; Pearman and Hyson, 1986), while in the Southern Hemisphere, oceanic and terrestrial exchanges are equally important in determining the seasonal oscillations in the atmosphere (Pearman and Hyson, 1986). The CO_2 seasonal cycle shows a consistent amplitude increase with time for some sites (Cleveland et al., 1983; Thompson et al., 1986).

The geographical variations of CO_2 growth rates at the GMCC sites show more clearly the El Niño perturbations, as noted already in the Mauna Loa data. For example, the El Niño-caused cessation of upwelling that



FIGURE 2-2

Figure 2-2. The history of atmospheric CO_2 presented here is based on ice-core measurements (open spaces, closed triangles) and atmospheric measurements (crosses). The data show that CO_2 began to increase in the 1800s, probably due to the conversion of forests to agricultural land. The rapid rise since the 1950s, due primarily to fossil-fuel combustion, is at a rate unprecedented in the ice-core record. (Sources: Neftel et al., 1985; Friedli et al., 1986; Keeling, pers. communication; all cited in Siegenthaler and Oeschger, 1987.)





Figure 2-3. The distribution of CO_2 by latitude from 1981-1985 shows that CO_2 is increasing globally. Superimposed on the increasing trend are coherent seasonal oscillations reflective of seasonal dynamics of terrestrial vegetation. The seasonal cycle is strongest at high northern latitudes, and is weak and of opposite phase in the Southern Hemisphere, reflecting the distribution of terrestrial vegetation. The data are from the NOAA/GMCC flask sampling network. (Sources: Komhyr et al., 1985; NOAA, 1987; Conway et al., 1988.) resulted in the devastation of the fishing industry and marine wildlife in the eastern equatorial Pacific is also evidenced by reduced outgassing of CO_2 to the atmosphere (Feely et al., 1987) and a concomitant decrease in the global CO_2 growth rate (Conway et al., 1988). These variations in the growth rate contain information about the response of the carbon system to climatic perturbations, some of which are currently under investigation.

Sources and Sinks

The atmosphere exchanges CO_2 with the terrestrial biosphere and with the oceans. must Averaged over decades, sources approximately equal sinks if the system is to remain in quasi-steady state; however, the individual flux in each direction may be large (50-100 Pg C/yr). The fluxes of carbon to the atmosphere associated with anthropogenic activities are roughly ten times smaller than the natural fluxes of carbon. However, the anthropogenic fluxes are unidirectional and thus are net sources of carbon to the atmosphere (see Figure 2-4).

Fossil Carbon Dioxide

The combustion of fossil fuels, in liquid, solid, and gas forms, is the major anthropogenic source of CO_2 to the atmosphere. A recent documentation and summary of the fossil-fuel source of CO_2 is given by Rotty (1987a, 1987b). In 1985, about 5.2 Pg C were released in the form of CO_2 as a result of fossil-fuel combustion. Of this, the U.S., USSR, and China contributed 23%, 19%, 10%, respectively (Rotty, pers. and communication). The emissions for 1987 were 5.5 Pg C. The history and mix of activities and fuels giving rise to these emissions are discussed in detail in Chapter IV.

Biospheric Cycle

The terrestrial biosphere absorbs CO_2 from the atmosphere via photosynthesis on the order of 80 Pg C/yr. Approximately the same amount is returned to the atmosphere annually via autotrophic and heterotrophic respiration and decomposition processes. While the net exchange of the unperturbed biosphere is close to zero over a period of one year, the seasonal asynchronicity of the exchange gives rise to the regular oscillations seen in the atmospheric CO_2 records.

In general, the conversion of forests to pastures and agriculture is a net source of CO_{γ} to the atmosphere. CO_2 is released as a result of burning and decay of dead plant matter and oxidation of soil organic matter. The amount of this release exceeds the amount of CO_2 absorbed as a result of regrowth of live vegetation and accumulation of soil organic matter. Recently, Houghton et al. (1987) and Detwiler and Hall (1988) estimated a net source of 0.4-2.6 Pg C/yr to the atmosphere from land-use changes. Deforestation in the tropics accounted for nearly all the flux. In temperate and boreal regions the carbon absorbed from the atmosphere via regrowth of forests is countered by the carbon released by the oxidation of wood products; the result is a net release to the atmosphere of 0.1 Pg C/yr (Melillo et al., 1988). The regional and temporal patterns and causes of deforestation are taken up in Chapter IV.

Natural changes in terrestrial biospheric dynamics may result from climate warming and/or from increased CO₂ concentrations in The possibility of such the atmosphere. natural changes is suggested by the increasing amplitude of CO_2 oscillations in the atmosphere (Bacastow et al., 1985; Cleveland et al., 1983; Thompson et al. 1986; Enting, 1987). The amplitude change may signal a tendency towards a biospheric sink of CO_2 , as photosynthesis responds to increasing CO_2 temperatures and concentrations (Pearman and Hyson, 1981; D'Arrigo et al., 1987; Kohlmaier et al., 1987). The amplitude change can also mean increased sources via respiration and decay, which are strongly temperature-dependent processes (Houghton, 1987). Several recent modeling studies (see section below) have inferred, from north-south profiles of atmospheric CO_2 , that vegetation and soils in temperate latitudes in the northern hemisphere have acted as a net sink for excess CO₂ from fossil-fuel burning. Because growth and decay cycles are intimately linked, it is difficult to tell whether atmosphere-biosphere interactions will act as a positive or a negative feedback without further theoretical and field studies (see BIOGEOCHEMICAL CLIMATE FEEDBACKS in CHAPTER III).





Figure 2-4. (a) Major reservoirs of the global carbon cycle. Reservoirs (or stocks) are in Pg C. (b) Fluxes of carbon are in Pg C/yr. (Source: Adapted from Keeling, 1983.)

Ocean Uptake

The exchange of CO_2 across the air-sea interface depends on the degree of CO_2 supersaturation in the surface waters of the oceans and the rate at which CO_2 is transferred across the interface itself. Because of the very nature of shipboard measurements, data on oceanic CO_2 partial pressure (pCO₂) are sparse, both spatially and temporally. Most of the data have come from oceanographic research programs, mainly Scripps Institution of Oceanography in the 1960s (Keeling, 1968), Geochemical Sections (GEOSECS) in the 1970s (Takahashi et al., 1980, 1981), Transient Tracers in the Oceans (TTO) in the early 1980s (Brewer et al., 1986), and more recently from NOAA survey cruises and from ships of opportunity.

Depending on the regional interplay among temperature, carbon supply from upwelling, and carbon consumption by biological activities, the seasonal cycle of CO_2 in surface water may peak at different times of the year in different oceanic regions (Peng et al., 1987; Takahashi et al., 1986, 1988). This makes it extremely difficult to interpret the sparse oceanic carbon data in the context of the global carbon cycle. The interpretation is aided by data from carbon-14 and other transient tracers in the ocean.

Based on the available data and an understanding of carbon dynamics in the ocean, it is estimated that on an annual basis about 100 Pg C/yr is exchanged between the atmosphere and the ocean. This exchange results in a net outgassing of approximately 1 Pg C/yr from the equatorial oceans and a net absorption of about the same amount by the mid to high latitude oceans.

Superimposed on this exchange of 100 Pg C/yr in either direction is the penetration of fossil-fuel CO_2 into the oceans. The capacity of the ocean to take up the excess CO_2 has been postulated by many authors (e.g., Oeschger et al., 1975; Broecker et al., 1979). Because of the variability of the oceanic carbon system and the precision of ocean carbon measurements, the oceanic signature of fossil-fuel CO_2 has not been

demonstrated unambiguously from direct measurements. A particular difficulty is the lack of baseline or historical data of oceanic CO_2 from which to estimate changes. As water masses in the ocean interior move primarily along constant density (isopycnal) contours, concentration differences between the ocean surface and interior locations along the same isopycnal have been used to infer the anthropogenic CO_2 signal (Brewer, 1978; Chen. 1982a, 1982b). Considerable controversy exists about this procedure, as mixing and biological processes also alter CO_{2} concentrations; correction schemes for these other processes remain problematic due to insufficient data (Broecker et al., 1982; Shiller, 1981, 1982; Chen et al., 1982). Takahashi et al. (1983) have demonstrated that in the Atlantic, the partial pressure of CO_2 in the 8 ocean (pCO_2) increased by ±8 microatmospheres (µatm) from 1958 to the mid 1970s.

The expectation of fossil-fuel uptake by the oceans is encouraged by observations of anthropogenic tracers penetrating gradually into the oceanic thermocline. These tracers include tritium and carbon-14, by-products of nuclear testing in the 1960s, and CFCs, recent man-made compounds. The magnitude of the fossil-fuel uptake is estimated using numerical models calibrated by these tracers. These models range in complexity from simple onedimensional box-diffusion models to threedimensional general circulation models of the ocean (Siegenthaler, 1983; Maier-Reimer and Hasselman, 1987; Peng, 1986; Jöös and Siegenthaler, 1989; Sarmiento et al., 1989). The magnitude of the uptake varies depending on the model architecture and the tracer used to calibrate the model, but does not exceed \sim 35% of the fossil-fuel source. This percentage is considerably less than that required by the CO₂ budget, i.e. $\sim 45\%$ of the fossil-fuel source plus 100% of the release from deforestation.

It is generally assumed that the major sink for anthropogenic CO_2 is the large expanse of southern oceans where there are strong winds and cold waters. A recent study (Tans et al., 1990), using the north-south profile of CO_2 in the atmosphere to constrain

THE RADIATIVE EFFECTS OF GREENHOUSE GASES

The radiative effects of greenhouse gases have received a great deal of attention over the last decade. Recent reviews are given by Dickinson and Cicerone (1986) and Ramanathan et al. In the absence of an (1987). atmosphere the Earth would radiate energy to space as a black body with a temperature of about 250K (-23°C). Figure 2-5 shows the actual emissions, indicating the absorption bands of the major greenhouse gases. Not shown is water vapor, which has continuous absorption throughout this spectral range and dominates all other gases at wavelengths < 8 micrometers (µm) and >18 µm (Dickinson and Cicerone, The 15 μm band of CO₂ 1986). dominates absorption in the spectral range from 12 to 18 µm, and its absorption in the other parts of the spectrum amounts to 15% or less of its impact in this region.

The shaded region in Figure 2-5, between about 7 and 13 μ m, is called the atmospheric window because it is relatively transparent to outgoing 70-90% of the radiation radiation: emitted by the surface and clouds in these wavelengths escapes to space (Ramanathan et al., 1987). Many trace gases happen to have absorption bands in this window region and are therefore very effective greenhouse absorbers. For example, CFC-11 and CFC-12 are about 15,000 times more effective than CO_2 per incremental increase in concentration (see Table 2-2).

the budget, argues that the CO_2 sink must be predominately in the northern hemisphere. Because the northern oceans are better surveyed and are observed to be only a small sink for CO_2 (Takahashi et al., 1989), Tans et al. hypothesize that there must be a significant land sink to balance the CO_2 budget and match the north-south gradient. The need for a land sink for anthropogenic CO_2 has long been suggested by the ocean models. This hypothesis has since been supported by several independent studies (Enting and Mansbridge, 1989; Etcheto et al., 1989).

Chemical and Radiative Properties/ Interactions

Carbon dioxide is chemically inert in the atmosphere, but it has a very important impact on the Earth's radiation budget and hence on climate and the chemistry of the atmosphere. After water vapor, CO_2 is the most abundant and most significant infrared (IR) absorbing gas in the atmosphere. As discussed in Chapter III, the Earth's climate is determined by the point at which incoming solar (shortwave) radiation is balanced by IR (long-wave) emissions to space from the warm surface and atmosphere. Increasing the concentration of CO_2 and other greenhouse gases in the atmosphere elevates the average surface temperature required to achieve this balance. Doubling the atmospheric CO_2 concentration from 315 to 630 ppm would produce a radiative forcing (the equilibrium surface temperature increase in the absence of climate of 1.2-1.3°C. feedbacks) At current concentrations CO₂ already absorbs most of the radiation emitted from the Earth's surface in the wavelengths where it is active. As a result, each additional molecule of CO₂ added to the atmosphere has a smaller effect than the previous one. Hence, radiative forcing scales logarithmically, rather than linearly, with increases in the concentration of atmospheric CO_2 . For example, a 50 ppm increase in CO_2 from 350 to 400 ppm yields a radiative forcing of 0.23°C, while the same increment from 550 to 600 ppm yields a radiative forcing of only 0.16°C. Despite the reduced greenhouse effectiveness of each molecule of CO2 as concentrations increase, CO₂ will remain the dominant greenhouse gas in the future, responsible for 50% or more of the increased greenhouse effect during the next century for plausible scenarios of future trace gas emissions (Hansen et al., 1988; see CHAPTER **VI**).

FIGURE 2-5



Gas Absorption Bands

Figure 2-5. Infrared (long-wave) emissions to space from the Earth. Many of the absorption bands of the greenhouse gases fall within the atmospheric window -- a region of the spectrum, between 7 and 13 μ m, in which there is little else to prevent radiation from the Earth escaping directly into space. (Source: UNEP, 1987.)

TABLE 2-2

Radiative Forcing for a Uniform Increase in Trace Gases From Current Levels

Compound	Radiative Forcing (No Feedbacks) (°C/ppb)	Radiative Forcing Relative to CO ₂	
CO ₂	.000005	1	
CH ₄	.0001	20	
N ₂ O	.001	200	
CFC-11	.07	14,000	
CFC-12	.08	16,000	
CFC-13	.10	20,000	
Halon 1301	.10	20,000	
F-116	.08	16,000	
CCI4	.05	10,000	
CHCI3	.04	8,000	
F-14	.04	8,000	
HCFC-22	.03	6,000	
CH ₂ Cl ₂	.02	4,000	
CH3CCI3	.01	2,000	
C ₂ H ₂	.01	2,000	
SO ₂	.01	2,000	

Source: Adapted from Ramanathan et al., 1985.

METHANE

Concentration History and Geographic Distribution

High-precision atmospheric measurements of CH_4 have been made in the past decade at many different locations. The data show clearly that the globally averaged concentration of methane, 1670 parts per billion by volume (ppb) in 1988, has been increasing at the rate of about 14-16 ppb per year (Blake and Rowland, 1986, 1988) (see Figure 2-6). Since 1982, air samples from ~ 25 globally distributed sites of the NOAA/GMCC cooperative network have been analyzed for CH_4 (Steele et al., 1987). In addition to flask continuous measurements sampling, of atmospheric CH_4 are now made at Cape Meares, Oregon (Khalil and Rasmussen, 1983); Pt. Barrow, Alaska; and Mauna Loa, Hawaii (NOAA, 1987).

The data show that CH_4 , like CO_2 , exhibits very coherent spatial and temporal variations. CH_4 is approximately uniform from mid to high latitudes in the Southern Hemisphere and increases northward. The Northern Hemisphere average concentration is approximately 100 ppb higher than that in the Southern Hemisphere. The seasonal cycle in the Southern Hemisphere (about 35 ppb peak to peak) shows a minimum in the summer, consistent with higher summer abundances of the hydroxyl radical (OH) and temperaturedependent destruction rates. In the Northern Hemisphere, the seasonal cycle is more complex, showing the interaction mainly between chemical destruction and emissions from high-latitude peat bogs.

Analysis of air bubbles in ice cores shows that in pre-industrial years, CH_4 was ~700 ppb and exhibited a 2.5 factor increase to its present value in only the last 100 years (Stauffer et al., 1985; Pearman et al., 1986) (see Figure 2-6). The 2083-meter ice core recovered by the Soviet Antarctic Expedition at Vostok, Antarctica, shows that the CH_4 concentration was as low as 340 ppb during the penultimate ice age (~155 kyBP) and nearly doubled to 610 ppb in the following interglacial period (130 kyBP). The trend in CH_4 closely followed the trend in air temperature deduced from deuterium (Raynaud et al., 1988). These measurements show that current concentrations of CH_4 , like that of CO_2 , are higher than they have been in the past 160,000 years.

Sources and Sinks

Methane is produced via anaerobic decomposition in biological systems. It is also a major component of natural gas and of coal gas. While the major sources of CH_4 have been identified, their individual contributions to the global budget are highly uncertain. A recent review of the sources and sinks of CH_4 is given by Cicerone and Oremland (1988) (see Figure 2-7).

The major sink of CH_4 is reaction with OH radicals in the atmosphere.² Based on chemical considerations, it is estimated that the global sink of methane is about 500 teragrams (Tg) CH_4/yr .³ By inference, the annual global source equals the sink plus the annual increase, i.e., about 550 Tg CH_4/yr . Cicerone and Oremland (1988) estimate a range of 400 to 640 Tg/yr for the annual global source.

Estimates of methane emissions from natural wetlands have ranged from 11-150 Tg/yr (e.g., Seiler, 1984; Khalil and Rasmussen, 1983). A recent study by Matthews and Fung (1987) estimated that there are 530 million hectares of natural wetlands that account for a global emission of ~ 110 Tg CH₄/yr. Of this, about 50% of the CH_{4} is emitted from productive peat bogs at high latitudes in the Northern Hemisphere, a regional emission that is likely to increase with greenhouse warming. While this study has employed more extensive field data than earlier estimates (e.g., Sebacher et al., 1986; Harriss et al., 1985), uncertainties in the global estimate remain due to the heterogeneity of natural wetlands and their CH₄ fluxes.

Rice paddies are environments very similar to natural wetlands in terms of CH_4 production and emission to the atmosphere. In 1984, there were 148 million hectares of rice harvest area globally, with ~50% in India and China. Methane emission studies have been performed in controlled mid-latitude environments (Cicerone et al., 1983; Holzapfel-Pschorn and Seiler, 1986). These studies have identified the following factors, among others, that affect CH_4 fluxes to the





Figure 2-6. Recent measurements of atmospheric CH_4 show that CH_4 has been increasing at the rate of about 1%/yr in the last decade (upper panel). Ice-core data (lower panel) show that CH_4 was relatively constant in the 1800s, and began to increase rapidly at the beginning of the 20th century. Like CO_2 , the recent trend in CH_4 (shown as +++ in the lower panel) is unprecedented in the history of CH_4 from ice cores. The ice-core data are from Siple Station, Antarctica. Stars and triangles represent results obtained from melt and dry extraction, respectively. The ellipses indicate the uncertainties in the concentrations as well as in the mean age of the sample. (Sources: Blake and Rowland, 1988 -- Copyright 1988 by the AAAS; Stauffer et al., 1985 -- Copyright 1985 by the AAAS.)





Figure 2-7. Human activities in the agricultural sector (animal husbandry, rice production, and biomass burning) and the energy sector (fossil-fuel production) are the major sources of atmospheric CH_4 . Natural sources, from wetlands, oceans, and lakes, may contribute less than 25% of total emissions. (Sources: Cicerone and Oremland, 1988; Crutzen et al., 1986; Lerner et al., 1988; United Nations, 1987; IRRI, 1986.)

atmosphere: temperature, soil properties, fertilizer type, and irrigation practices. These factors make global extrapolation of CH_4 emissions very difficult. Cicerone and Oremland (1988) estimate a global emission of 60-170 Tg CH_4/yr .

Methane is also produced by enteric fermentation in animals, especially ruminants. The amount of CH₄ produced is dependent on enteric ecology, the composition and quantity of feed, and the energy expenditure of the individual animal. Estimates of emission rates range from 94 kg CH₄/animal/year from West German dairy cattle, to -35kg CH₄/animal/year from Indian cattle fed on kitchen refuse, to 5-8 kg CH₄/animal/year from sheep. Using these emission coefficients and population statistics of animals in the world, Crutzen et al. (1986) obtained a global emission of 78 Tg CH_4 for 1983. This emission includes ~ 5 Tg CH₄ from wild animals and <1 Tg CH₄ from humans. About 75% of the emissions are from cattle and dairy cows. India, the USSR, Brazil, the U.S., and China are the five major countries in terms of CH_{4} emission from domestic animals (Lerner et al., 1988).

Other natural sources of CH_4 include termites, and exchange with oceans and lakes. The source from termites is highly uncertain and controversial. Estimates of annual global emissions range from close to zero (Seiler, Conrad et al., 1984) to 20 Tg (Fraser, Rasmussen et al., 1986), and as high as 200 Tg CH_4 (Zimmerman et al., 1982, 1984), on the order of half the global emission. The oceanic source is small, estimated to be 5-20 Tg CH_4/yr (Cicerone and Oremland, 1988).

There are several anthropogenic sources Methane is produced by of methane. incomplete combustion during biomass burning, mainly in the tropics. The amount of CH_4 produced depends on the material burned and the degree of combustion. Estimates range from 50-100 Tg CH₄/yr (see Cicerone and Oremland, 1988). While a few studies have attempted to understand and measure CH₄ emission during biomass burning (Crutzen et al., 1979, 1985), extrapolation to a global estimate is difficult because of the lack of global data on area burned, fire frequency, and characteristics of fuels and fires. The feasibility of monitoring fires from space

(Matson and Holben, 1987; Matson et al., 1987) will improve this estimate significantly.

Methane is also produced in large municipal and industrial landfills, where biodegradable carbon in the refuse decomposes into CO2 and CH4. As in the case of many other CH₄ sources, the fraction of gas produced that escapes to the atmosphere is debated. Recently, Bingemer and Crutzen (1987) estimated that this source produces 30-70 Tg CH_{a}/yr . These estimates assume that a large fraction of all organic carbon deposited in landfills eventually is subject to methanogenesis and subsequent emission to the atmosphere. Cicerone and Oremland (1988) also adopt a range of 30-70 Tg CH₄/yr.

Methane is the major component $(\sim 90\%)$ of natural gas, and so the leakage of natural gas from pipelines and the venting of natural gas from oil and gas wells represent sources of CH_4 entering the atmosphere. Although natural gas production and consumption statistics are available globally, the nature of this fugitive CH_4 source makes it difficult to estimate how much this source contributes to the atmospheric abundance of CH_{4} . From U.S. and Canadian natural gas statistics, it is estimated that approximately 2-2.5% of the marketable gas is unaccounted for. Assuming that all of the unaccounted for gas is lost to the atmosphere, 25-30 Tg CH_{4}/yr from line loss is obtained by global extrapolation (Cicerone and Oremland, 1988). An additional 15 Tg CH_{4}/yr is released from natural gas sources, assuming that $\sim 20\%$ of the gas that is vented and flared at oil and gas wells is not combusted, escaping to the atmosphere as CH_4 (Darmstadter et al., 1987). Together these estimates suggest a source of up to 50 Tg CH_{a}/yr from natural gas production and consumption. Much of the unaccounted for gas, however, may represent meter discrepancies, and venting of natural gas declining in recent years has been (Darmstadter et al., 1987). On the other hand, gas distribution systems outside of North America may have much greater leak rates. Thus a reasonable range for these sources may be 20-50 Tg CH₄/yr.

Methane is also the major component of gas trapped in coal. The percentage of the CH_4 component increases with the age and

depth of the coal and is released to the atmosphere during mining and processing/ crushing of coal. Globally, the amount of CH₄ in coal is ~0.5% of the mass of coal extracted. This source is estimated to be 15-45 Tg CH₄/yr in 1980 (Darmstadter et al., 1987; Cicerone and Oremland, 1988).

A highly uncertain but potentially large source of CH_4 is clathrates: stable methane hydrates in sediments under permafrost and on continental margins (Kvenvolden, 1988). The magnitude of the current CH_4 release from this source is unknown. Climate warming presents the potential for destabilization of the hydrates and subsequent release of CH_4 to the atmosphere (see CHAPTER III).

Chemical and Radiative Properties/ Interactions

Methane is active both radiatively and chemically in the atmosphere. At present levels, an additional molecule of CH_4 will contribute a radiative forcing that is equivalent to that contributed by approximately 20 molecules of CO_2 (e.g., Ramanathan et al., 1985; Donner and Ramanathan, 1980; Lacis et al., 1981). These radiative transfer calculations suggest that a doubling of atmospheric CH_4 (1.6-3.2 ppm) will contribute a radiative forcing of 0.16°C (Hansen et al., 1988).

The destruction rate of CH₄ is dependent on the amount of OH (and hence water vapor) in the atmosphere as well as on temperature. The globally averaged lifetime (atmospheric abundance divided by destruction rate) of CH_4 is approximately 10 years, the local lifetime being shorter in the tropics. Using estimates of the average concentration of atmospheric hydroxyl radicals derived from measurements of methyl chloroform, Prinn et (1987) have deduced the average al. atmospheric lifetime of CH_4 to be 9.6 (+2.2, -1.5) years. The reaction between CH_4 and OHeventually produces carbon monoxide (CO); CO itself reacts with OH, producing CO_2 (Thompson and Cicerone, 1986). Thus, an increase in the background levels of either CH₄ or CO can reduce OH and the oxidizing power of the entire atmosphere. It is estimated that increases in CO alone from 1960 to 1985 would have lowered OH concentrations in the atmosphere, increased the methane lifetime, and resulted in a 15-20%

increase in CH_4 concentrations (Khalil and Rasmussen, 1985; Levine et al., 1985; Thompson and Cicerone, 1986).

Because of the interactions between CO, CH₄, and OH in the atmosphere, it is difficult to predict the effects of climate change on OH destruction of CH₄, as increasing atmospheric water vapor and increased precipitation (and removal of OH reservoirs like nitric acid [HNO₃] and hydrogen peroxide [H₂O₂]) have opposite effects on OH concentrations. Changes in nitrogen oxides (NO_x) and tropospheric ozone (O₃) also strongly affect atmospheric OH (see below).

NITROUS OXIDE

Concentration History and Geographic Distribution

Nitrous oxide (N_2O) is present in minute amounts in the atmosphere but it is nonetheless of great importance. Its concentration is three orders of magnitude less than that of CO_2 , but its radiative forcing per molecule is about 200 times greater. The first high-precision measurements of atmospheric N_2O from the late 1970s showed unambiguously an increasing trend in its concentration (Weiss, 1981). Continuous measurements at four Atmospheric Lifetime Experiment/Global Atmospheric Gases Experiment (ALE/GAGE) sites have been made since 1979 (see Figure 2-8). Flask samples of air from five sites of the cooperative network of NOAA/GMCC are also being analyzed for N₂O (Thompson et al., 1985; Komhyr et al., 1991).

The concentration of atmospheric N₂O was 307 ppb in 1988, and its annual growth rate is ~0.7-0.8 ppb per year, or 0.2-0.3% per year (Prinn et al., 1990; Elkins and Rossen, 1989). The concentrations at the Northern Hemisphere sites are 0.8-1.0 ppb higher than those at the Southern Hemisphere sites, suggesting the dominance of a northern source (Elkins and Rossen, 1989; Butler et al., 1989; Elkins et al., 1988).

Ice-core data show that the preindustrial concentration of N₂O was 285 \pm 10 ppb averaged between 1600-1800 (Pearman et al., 1986; Khalil and Rasmussen, 1987). Unlike CO₂, whose concentration began to





Figure 2-8. Concentration of atmospheric N_2O has been increasing at the rate of 0.2-0.3%/yr in the last decade (upper panel). The ice-core record (lower panel) shows that N_2O was relatively constant from the 1600s to the beginning of the 20th century and began increasing rapidly in the last 50 years. (Sources: Khalil and Rasmussen, pers. communication; Pearman et al., 1986 -- Reprinted by permission from *Nature*, vol, 320, pp. 248-250. Copyright © 1986 Macmillan Journals Limited.)

increase significantly in the 1800s, N_2O remained fairly constant until the 1900s, and then began increasing more rapidly in the 1940s (Pearman et al., 1986; Khalil and Rasmussen, 1987). (See the ice-core data in Figure 2-8.) Measurements of N_2O in the Vostok ice core show lower atmospheric N_2O values of 244 ±20 ppb during the last climatic transition (about 12,000 BC) with a slight increase as the climate was warming up (Zardini et al., 1989).

Sources and Sinks

While a lot of progress has been made during the last five years in quantifying the sources and sinks of N_2O in the atmosphere, there remain considerable uncertainties in the global budget and in the contributions of individual source terms. The uncertainties arise not only because of the scarcity of measurements of N_2O fluxes, but also, as in the case for CH_4 , because of the complexity of the biogeochemical interactions and heterogeneous landscape where N_2O is produced.

Nitrous oxide is simultaneously produced and consumed in soils via the metabolic pathways of denitrification, nitrification, nitrate dissimilation, and nitrate assimilation. These processes are affected by various environmental parameters such as temperature, moisture, the presence of plants, and the characteristics and composition of the soils (e.g., Seiler and Conrad, 1987; Sahrawat and Keeney, 1986). The flux of N_2O to the atmosphere also depends on the location of the N_2O -producing and N_2O -consuming microorganisms and their relative activity within the soil column (Conrad and Seiler, 1985). Because of the complexity of the N_2O production and destruction processes, and the inherent heterogeneity of soils, it is difficult to estimate the contribution of natural soils to the global N₂O budget. Slemr et al. (1984) calculated N_2O emissions from natural temperate and subtropical soils to be 4.5 Tg N/yr. Recent measurements (Livingston et al., 1988; Matson and Vitousek, 1987) show that N_2O emission rates from tropical soils are higher than those from temperate soils and that a relationship exists between the N_2O flux and the rate of nutrient cycling in the tropical forest soils. A source of 3.7 Tg N/yr is estimated from dry and wet tropical forests

(Matson and Vitousek, 1989). Seiler and Conrad (1987) give a very tentative estimate of 6 ± 3 Tg N/yr from natural soils globally.

Measurements of supersaturation of N_2O in the oceans indicate that the oceans contribute additional N_2O to the atmosphere (Elkins et al., 1978; Seiler and Conrad, 1981; Weiss, 1981). Seiler and Conrad (1987) estimated the oceanic contribution to be 2 ± 1 Tg/year. Recent oceanographic measurements of N₂O suggest that there is large variability, both temporally and spatially, in the oceanic flux of N_2O to the atmosphere. The flux is affected by El Niño events and differences in ocean circulation patterns (Butler et al., 1989; Elkins, pers. communication). Because the oceanic reservoir of N₂O is between 900 and 1100 Tg N, about one-half and two-thirds the size of the atmospheric reservoir (Butler, pers. communication), changes in ocean circulation as a result of climate change may have significant impact on the atmospheric N_2O concentrations.

Little is known about N_2O emissions from terrestrial freshwater systems. Extrapolating from measurements in the Netherlands and in Israel of elevated N_2O levels in aquifers contaminated by the disposal of human or animal waste, cultivation, and fertilization, Ronen et al. (1988) estimated a global source 0.8-1.7 Tg N/yr from contaminated aquifers.

Nitrous oxide is also produced during combustion, but the importance of this source is unclear at this time. A study of this N_2O source, reported by Hao et al. (1987), found that the amount of N_2O in flue gases was correlated with the nitrogen content of fuels. Using statistics on solid- and liquid-fuel production, they estimated an emission of 3.2 Tg N₂O-N in 1982. Very recent studies, however, suggest that many of the N₂O measurements, including those of Hao et al. (1987), may have been affected by a sampling artifact. A reaction between water, sulfur dioxide (SO₂), and NO_x generates N_2O in sample cylinders over a period of hours, sometimes increasing N₂O concentrations by more than an order of magnitude, unless the samples are carefully dried or N_2O is measured immediately (Muzio and Kramlich, 1988; Muzio et al., 1989; Montgomery et al., 1989). Reanalysis of measurements made in
the U.S., excluding those that were apparently affected by this reaction, found no significant difference between N_2O emissions from gas and coal-fired boilers (Piccot, pers. communication). Recent measurements conducted bv the U.S. Environmental Protection Agency (U.S. EPA) with an on-line analyzer confirm this finding: in both utility and small experimental boilers N_2O concentrations in the exhaust gases were always less than 5 ppm and generally less than 2 ppm (Hall, pers. communication). This suggests that the relationship between N_2O and fuel-nitrogen found by Hao et al. (1987) may have actually been due to differences in SO_2 and NO_x emissions. Emissions of N_2O do appear to vary with combustion technology. Preliminary measurements suggest that fluidized-bed combustors and catalyst-equipped automobiles may have substantially elevated N_2O emissions (De Soot. pers. communication). Total N_2O emissions from fossil-fuel combustion cannot be estimated with any confidence at this time, but may be less than 1 Tg N/yr (see CHAPTER VI).

The addition of nitrogenous fertilizers to soils enhances the emission of N_2O and other nitrogen gases to the atmosphere. This emission depends on temperature, soil moisture, rainfall, fertilizer type, fertilizer amount, and the way the fertilizer is applied. It also depends on the properties of the soils and the crops grown. The fraction of fertilizer nitrogen lost to the atmosphere as N₂O ranges from $\sim 0.001 - 0.05\%$ for nitrate, $\sim 0.01 - 0.1\%$ for ammonium fertilizers, to $\sim 0.5 - 5\%$ for With a global anhydrous ammonia. consumption of approximately 70.5 million tons nitrogen as nitrogenous fertilizers in 1984, an N₂O contribution of 0.14-2.4 Tg N/yr is estimated. Although the amount of N_2O emissions associated with the use of nitrogenous fertilizers is estimated to be small compared to emissions from natural sources, such emissions are, nonetheless, a source subject to rapid growth.

Land-use modification in the tropics may also contribute N_2O to the atmosphere. N_2O is produced during biomass burning, but because direct estimates of total N_2O emissions are difficult, N_2O emissions are estimated by ratios with emissions of CO_2 or other nitrogen gases. Crutzen (1983) estimated this source to be 1-2 Tg N/yr, although the accuracy of this estimate is highly uncertain. It may indeed be an over-estimate and subject to the same sampling artifact as that encountered in fossil-fuel combustion. A reanalysis by Crutzen et al. (1989) yielded very low estimates: 0.06-0.3 Tg N/yr from biomass burning.

Recently, Bowden and Bormann (1986) found enhanced N₂O fluxes to the atmosphere from cleared areas in a temperate forest and elevated N₂O concentrations in ground water adjacent to the cut watershed. Similarly, threefold increases in N₂O fluxes were found in pastures and forest clearings in the Amazon (Luizão et al., 1989). Extrapolating the Amazonian results to all deforested areas in the globe, a source of 0.8-1.3 Tg N/yr is estimated. In contrast, Robertson and Tiedje (1988) postulate, on the basis of observations in Central America, that the loss of primary tropical rain forest may decrease the emissions of N_2O to the atmosphere if vegetation did not return. These studies suggest that rapid deforestation in the tropics may significantly alter the N_2O budget, although an estimate of its contribution to the global budget has not been attempted.

Chemical and Radiative Properties/ Interactions

Relative to CO_2 , N_2O has a low concentration in the atmosphere, and its rate of increase is much smaller than that of the other trace gases. Yet it still plays an important role in the radiative and chemical budgets of the atmosphere. The seemingly small growth rate, ~0.25%/year, reflects a large imbalance (~30%) between the sources and sinks. The extremely long lifetime of N_2O , ~160 years, means that the system has a very long memory of its emission history.

Nitrous oxide is an effective greenhouse gas. The radiative forcing of one molecule of N_2O is equivalent to that of about 200 molecules of CO_2 ; an increase of 50% in N_2O and a doubling of CH_4 would yield approximately the same radiative forcing, even though the N_2O concentration is less, by a factor of 5, than that of CH_4 . A 50% increase in the current burden of N_2O in the atmosphere will yield a radiative forcing of about 0.15°C (without any feedbacks). Nitrous oxide is not chemically reactive in the troposphere and is destroyed in the stratosphere by photolysis and by reaction with atomic oxygen in the excited state $[O(^{1}D)]$. The latter reaction makes N₂O the dominant precursor of odd nitrogen in the stratosphere. Thus, the observed increase in N₂O should lead to increases in stratospheric NO_x, which would significantly alter stratospheric ozone chemistry.

CHLOROFLUOROCARBONS

Concentration History and Geographic Distribution

High-precision measurements of CFC-11 (CCl₃F) and CFC-12 (CCl₂F₂) began in 1970 with the development of gas chromatograph techniques using electron capture detectors (Lovelock, 1971). Like CO_2 and CH_4 , surface measurements have consisted of high-frequency observations at a few dedicated sites as well as flask samples of air collected from a global network of stations or from irregular global transects.

High-frequency in situ measurements of surface concentrations have been or are currently being made at the five coastal/island ALE/GAGE stations (Cunnold et al., 1986; Prinn et al., 1983; Rasmussen and Khalil, 1986; Simmonds et al., 1987). In addition, analysis of CFC concentrations in the flask samples of air collected at the NOAA/GMCC globally distributed network of sites have begun at the GMCC facility in Boulder (Thompson et al., 1985; NOAA, 1987).

CFC-12 is the most abundant chlorofluorocarbon in the atmosphere. Its average tropospheric concentration in 1986 was 392 parts per trillion by volume (ppt), corresponding to a total burden of about 8.1 Tg. Its concentration rose rapidly in the 1970s and is currently increasing at about 4%/yr.

With a total burden of about 5.2 Tg, CFC-11 is the second most abundant chlorofluorocarbon in the atmosphere. Its average concentration in 1986 was 226 ppt, and is also increasing currently at 4%/yr.

Other important sources of atmospheric chlorine include methyl chloride (CH_3Cl , the major natural source of stratospheric chlorine)

at a concentration of 600 ppt (no measured trend); methyl chloroform (CH₃CCl₃) at 125 ppt in 1986, increasing at ~5%/yr; carbon tetrachloride (CCl₄), at about 100 ppt, increasing at 1%/yr; HCFC-22 (formerly denoted CFC-22; CHClF₂), at ~80 ppt in 1986, increasing at 7%/yr, and CFC-113 (C_2 Cl₃F₃) at 30-70 ppt in 1986, increasing at greater than 10%/yr (Prinn, 1988).

Bromocarbons that are moderately longlived in the troposphere supply bromine to the stratosphere where it plays an important role in ozone destruction, especially with high levels of active chlorine such as are associated with the Antarctic ozone hole. Methyl bromide (CH₃Br, 15 ppt in 1985) is natural, with some industrial sources, and is the major source of stratospheric bromine. The halons 1211 (CBrClF₂) and 1301 (CBrF₃) currently are small sources (-2 ppt each) but are growing rapidly (>10%/yr).

Sources and Sinks

CFCs are solely a product of the chemical industry. CFC-11 is used in blowing plastic foams and in aerosol cans. CFC-12 is used primarily in refrigeration and aerosol cans. Comprehensive data on production of CFC-11 and CFC-12 are published by the Fluorocarbon Program Panel (FPP) of the Chemical Manufacturers Association (CMA). The peak year for CFC-11 and -12 production by reporting companies was 1974, in which a total of 812.5 gigagrams (Gg) of CFC-11 plus CFC-12 was produced.4 Annual CFC production decreased somewhat following a ban on "non-essential" aerosol uses in the United States, Canada, and Sweden. Nonaerosol uses have continued to increase, as has CFC-113, and the total has risen rapidly in recent years, with estimated global production of CFCs -11, -12, and -113 in 1985 at about Of this total about 70% was 950 Gg. consumed by the U.S., the European Economic Community, and Japan (see Figure 4-9 in CHAPTER IV).

The CMA data do not cover the USSR. The FPP has estimated Soviet production; however, these estimates are considered unreliable. Data for China and the countries of Eastern Europe are lacking entirely, rendering modest uncertainties (\sim 15%) in the magnitude of world emissions for CFC-12 and smaller uncertainties for those of CFC-11. Cunnold et al. (1986) and Fraser et al. (1983) have found that the measured trend of CFC-11 and CFC-12 concentrations is relatively consistent with the CMA estimates of CFC-11 release but not CFC-12 release, which suggests that the USSR and Eastern Europe contribute a substantial amount to CFC-12 emissions.

Methyl chloroform (CH_3CCl_3) is widely used in the manufacturing industry as a solvent for degreasing, CFC-113 is used in the electronics industry, mainly for circuit board cleaning, and HCFC-22 is used mainly in refrigeration. The sources of these gases have been estimated in various studies, but a survey of sources for CFC-113 and HCFC-22 -equivalent to that conducted for CFC-11 and CFC-12 -- has not been done. A survey of methyl chloroform has been published recently (Midgley, 1989).

Fully halogenated CFCs (those that contain no hydrogen) are destroyed almost solely by photolysis in the stratosphere. The atmospheric lifetimes of CFCs estimated from the ALE/GAGE analyses are 111⁺²²² years for $74_{.17}^{+31}$ years for CFC-11, and CFC-12, 40 years for approximately carbon tetrachloride. Compounds containing hydrogen (HCFCs) react with OH in the troposphere, have lifetimes on the order of 20 years or less, and pose less threat to the ozone layer because their concentrations do not build up to as large values as would equivalent CFCs. The ALE/GAGE lifetime for CH₃CCl₃ is $6.3^{+1.2}_{-0.9}$ years (Prinn et al., 1990), and the corresponding lifetime for HCFC-22 is 15 years. All of these species can contribute to the stratospheric burden of chlorine, but the longer-lived CFCs can accumulate, reaching higher concentrations before a steady state balance is achieved.

Chemical and Radiative Properties/ Interactions

CFCs absorb infrared radiation in the window region of the atmospheric spectrum (see Figure 2-5). Although CFCs are present in minute amounts (ppt) in the atmosphere, together they are one of the dominant greenhouse gases. At present they have the highest annual fractional increase of all the greenhouse gases (\sim 4-10%/yr). Furthermore, the radiative forcing due to each additional

molecule of CFC is equivalent to that due to about 15,000 molecules of CO_2 , and at present levels, this radiative forcing would increase linearly with added CFC molecules (Ramanathan et al., 1987). A 2 ppb increase in both CFC-11 and CFC-12 would contribute a radiative forcing of 0.3°C, equivalent to that from a 65 ppm increase in CO_2 . In the 1980s, CFC-11 and CFC-12 together contributed about 15% of the increase in global greenhouse forcing.

The dissociation products of halocarbons are the dominant sources of chlorine and bromine for the stratosphere (WMO, 1985). These elements are major components in the catalytic cycles that control ozone abundance. Trends for the major halocarbon reservoirs in the stratosphere (HCl and HF) have been observed from the ground and in latitudinal surveys with aircraft. Within the limits of observational uncertainties, the estimated trends in these species are consistent with trends in the source gases themselves.

OZONE

Concentration History and Geographic Distribution

Ozone is both produced and destroyed in situ in the atmosphere. While the other trace gases are relatively well-mixed vertically, the non-uniform vertical distribution of O_3 in the atmosphere is of prime importance in determining its radiative and chemical effects (see Figure 2-9). We often focus separately on stratospheric and tropospheric ozone. Stratospheric O_3 represents the majority of the total and controls the absorption of solar ultraviolet radiation. Tropospheric O_3 plays an important role in air quality and could contribute to major greenhouse forcing.

Tropospheric Ozone

Ozone sondes from a diverse and globally distributed network provide our only record of possible trends in tropospheric O_3 . A review of ozone sonde and surface data have been given by Logan (1985), Tiao et al. (1986), and more recently by Crutzen (1988). Since the 1970s, surface O_3 concentrations are measured routinely at the four continuous monitoring stations operated by NOAA/GMCC: Pt. Barrow, Alaska; Mauna Lao,





Figure 2-9. On the left, temperature profile and ozone distribution in the atmosphere. On the right, sensitivity of global surface temperature to changes in vertical ozone distribution. Ozone increases in Region I (below ~ 30 km) and ozone decreases in Region II (above ~ 30 km) warm the surface temperature. The results are from a 1-D radiative transfer model in which 10 Dobson unit ozone increments are added to each layer. The heavy solid line is a least square fit to step-wise calculations. (Sources: Watson et al., 1986; Lacis et al., 1990 -- Copyright 1990 by the American Geophysical Union.)

Hawaii; American Samoa; and the South Pole (see e.g., NOAA, 1987). NOAA/GMCC also participates in international cooperative ozone sonde profiling activities. Because of the reactivity of O_3 near the surface and its short lifetime in the planetary boundary layer, surface measurements are *not* representative of the average troposphere.

The O₃ data taken near populated and industrial regions in the 1930s to the 1950s generally show an annually averaged concentration of 10-20 ppb at the surface, with a seasonal cycle that peaked in summer. The data show a generally increasing trend, especially in the summer, in surface concentrations of O_3 at sites in western Europe, the U.S., and northern Japan. For example, a factor of 2 increase, from ~30 ppb in 1933 to ~ 60 ppb in the 1980s, is found in the summer concentrations in south Germany and Switzerland. Similarly, summertime concentrations of O_3 at the surface in rural areas in the eastern U.S. have increased by 20-100% since the 1940s (Logan, 1985). The surface O₃ trend is 1%/yr or more at those sites in close proximity to population and industrial centers. At Pt. Barrow and at Mauna Loa, geographically removed from but still under the influence of urban centers, surface O₃ was about 25 ppb in 1986 with summer values of 35-40 ppb. A small positive trend (0.7 $\pm 0.5\%/vr$) is detected at these two sites from 1973-1986.

Analysis of the ozone sonde data at these populated sites shows a small but significant positive trend in mid-tropospheric ozone. In general, the mid-tropospheric trends are smaller than those at the surface of the same O_3 profile, and trends in the upper troposphere and lower stratosphere are negative, ~-0.5%/yr.

At remote locations, surface O_3 exhibits a behavior very different from that near populated and industrial regions. At remote sites in the Canadian Arctic and in Tasmania, Australia, for example, the seasonal cycle of surface O_3 has a minimum, rather than a maximum, in summer or autumn. Surface O_3 at the South Pole was 20 ppb in 1986, similar to that measured in Western Europe in the 1930s. Also, unlike populated sites in the Northern Hemisphere, O_3 at remote sites in the Northern Hemisphere exhibits no significant trends near the surface, but significant positive trends at 700 millibars (mb) and 500 mb. Mid-tropospheric O_3 at Resolute, Canada (75°N), for example, is found to be increasing at 1%/yr, while there is a negative trend in the lower stratosphere. In the Southern Hemisphere, however, there appear to be no significant trends in surface or mid-tropospheric O_3 , although O_3 in the lower stratosphere has clearly decreased and the seasonal cycle at the South Pole has doubled in amplitude.

Stratospheric Ozone

The recent record of O₃ concentrations in the upper atmosphere has been reviewed by a NASA panel of experts (International Ozone Trends Panel, see Executive Summary in Watson et al., 1988). They report a statistically significant decrease in the total column abundance of O₃ above the known natural variations using ground-based Dobson instruments from 1969 to 1986 at mid and high northern latitudes during winter. Satellite data, calibrated by coincident Dobson measurements, show a decrease of about 2-3% from October 1978 (solar maximum) to October 1985 (solar minimum) in the column O₃ concentrations between 53°S and 53°N. The cause of this decrease over such a short record has not been identified but may be due to increases in chlorine, the decline in solar activity, or the global impact of the Antarctic ozone hole. The observations of stratospheric O_3 in the Northern Hemisphere indicate that O₃ abundances have declined over the past 20 years. The small decreases (1-2%), if any, in the summer months are consistent with the predicted change due to increasing CFCs. However, the measured ozone loss poleward of 40°N in winter is greater (by a factor of 2-3) than that predicted by theory (Watson et al., 1988; Rowland, 1989). This unexplained depletion of O_3 in the north is not of the same magnitude as the Antarctic ozone hole but may be associated with the unusual chemistry occurring over Antarctica, marking the start of a greater global decline.

Sources and Sinks

Ozone is not emitted directly by human activity, but its concentration in the troposphere is strongly governed by anthropogenic emissions of NO_x and

hydrocarbons, and in the stratosphere by CFCs among others. Because of the short lifetimes of NO_x and many of the other chemical species important in tropospheric O_2 chemistry, O_3 concentrations exhibit large variability horizontally, vertically, and temporally. Ozone's annual concentration, seasonal cycle, and trend have different behaviors in different parts of the globe so that the observations from a few regions cannot be viewed as globally representative. Global trends in tropospheric O₃ cannot be unambiguously extracted from trends in column O₃ either. Stratospheric O₃ dominates the column abundance (90% of the total) and its decreasing trend may obscure positive or negative trends in tropospheric ozone. The determining difficulty in the globally representative trend in tropospheric O₃ translates into uncertainties in the O₃ contributions to the greenhouse warming.

Chemical and Radiative Properties/ Interactions

Radiative forcing of O_3 is more complex than that of the other greenhouse gases because (1) O_3 is the major source of atmospheric heating due to ultraviolet and visible absorption bands, in addition to being a greenhouse gas and (2) O_3 trends are not uniform in the atmosphere -- anthropogenic effects are expected to include upper stratospheric losses, lower tropospheric increases, and latitudinally dependent changes.

Radiative transfer calculations reveal that the ozone's climate forcing changes sign at about 25-30 km altitude (see Figure 2-9). Ozone increases below this level lead to surface warming because its greenhouse effect dominates its impact on solar radiation, while O_3 added to the stratosphere above ~ 30 km increases stratospheric absorption of solar energy at the expense of solar energy that would otherwise have been absorbed at lower altitudes. On a per molecule basis, potential O_3 changes with the largest net effect on surface temperatures are those occurring near the tropopause where the temperature contrast between absorbed and emitted thermal radiation is greatest. Ozone changes near the surface produce little greenhouse forcing since the thermal radiation from the surface absorbed by ozone is nearly the same temperature as that which is re-emitted.

While the radiative effects of O_3 are understood theoretically, quantifying surface temperature changes due to O3 perturbations is difficult because of the large natural variability in tropospheric ozone and the lack of global coverage in the observations. Available ozone trend data are limited to northern mid latitudes. Some of the reported data showed decreases in O_3 in the upper troposphere and lower stratosphere. Using these data, Lacis et al. (1990) find that during the 1970s surface cooling resulted from these changes and was equal in magnitude to about half of the warming contributed by CO_2 increases during the same time period. These results differ from previous assessments (e.g., Ramanathan et al., 1985; Wang et al., 1988) that were based on one-dimensional photochemical model results which predict ozone increases in the lower stratosphere and upper troposphere, and thus produce surface Predictions of two-dimensional warming. photochemical models for increases in CFCs suggest that ozone should decrease in the lower stratosphere at middle and high latitudes, but increase in the tropics (Ko et al., 1984; WMO, 1985). This implies a strongly latitude-dependent climate forcing for O_3 distributional changes with surface cooling in the middle and high latitudes and warming in the tropics. However, these two-dimensional models did not include the chlorine-catalyzed loss associated with heterogeneous chemistry that leads to substantial ozone loss in the lower stratosphere (the Antarctic ozone hole).

The global nature of O_3 changes in the upper troposphere and lower stratosphere cannot be deduced, at this point, from current observations. This makes highly uncertain the evaluation of O_3 contributions to the global greenhouse warming.

OTHER FACTORS AFFECTING COMPOSITION

In addition to those greenhouse gases cited above that have a direct impact on the radiative balance of the Earth, we must consider those forces that control the chemical balance of the atmosphere, in turn controlling the abundance of greenhouse gases. With the exception of ozone, the greenhouse gases are generally not very reactive in the atmosphere; they have long chemical lifetimes, on the order of 10 to 200 years; and they accumulate in the atmosphere until their rate of chemical destruction balances their emissions. The chemistry of the stratosphere and troposphere provides the oxidizing power to destroy the majority of trace pollutants in the Earth's atmosphere (a major exception is CO_2 , see above). We outline below those primary and secondary components of the Earth's atmosphere that affect the chemically reactive gases and note changes that may have occurred in the recent past and those possible in the future.

Global Tropospheric Chemistry

The Hydroxyl Radical

In the troposphere, many species are removed in a chain of reactions beginning with the hydroxyl radical (OH) and ending with the deposition or rainout of a soluble compound, or with the complete oxidation of the original compound (i.e., net: $CH_4 + 2O_2 \rightarrow CO_2 +$ $2H_2O$). For CH_4 , most hydrocarbons, and halocarbons containing a hydrogen atom (e.g., anthropogenic HCFCs such as $CHClF_2$), the chemical lifetime will vary inversely with the suitable average of the global OH concentration.

The OH radicals in the troposphere are short-lived (<1 second) and are produced by sunlight in the presence of O_3 and H_2O ; they are consumed rapidly by reaction with CO, CH_4 , and other hydrocarbons. Moderate levels of nitrogen oxides (NO_x: NO and NO₂) can play an important role in recycling the odd-hydrogen (HO_x) from HO₂ to OH, thus building up the concentrations of OH; high levels of NO,, however, can reduce both OH and O_3 . The short lifetime of OH means that, when we integrate the loss of even a wellmixed gas like CH₄ against consumption by reaction with OH, we are integrating over the myriad of conditions of the troposphere in terms of sunlight, O₃, H₂O, CO, CH₄, NO₄, These tropospheric conditions and others. vary over scales that range from smooth in latitude and height to irregular in plumes downwind from metropolitan areas. At present we are just developing models for OH that can describe these varied conditions and accurately integrate the global loss of a greenhouse gas such as CH₄; shorter-lived gases pose a greater problem.

In spite of these problems modeling the chemically complex, heterogenous conditions of the global troposphere, we do understand tropospheric chemistry sufficiently to make some simple generalizations:

• Most loss of CH_4 occurs in the tropics, particularly in marine environments remote from the influence of urban areas and the continental boundary layer,

• Increasing concentrations of CO and CH_4 will reduce levels of OH,

• Large scale perturbations to tropospheric O_3 and H_2O (from climate change) may have equally significant impacts on OH concentrations,

• Changes in anthropogenic emissions of NO_x are expected to lead to significant increases in northern hemispheric O_3 and lead to moderate increases in globally integrated OH.

Carbon Monoxide

Carbon monoxide has a photochemical lifetime of about one month in the tropics; that lifetime becomes indefinitely long (and is controlled by transport) in the winter at high latitudes. The globally averaged destruction of CO corresponds to an estimated lifetime of 2.5 months. Carbon monoxide is lost almost exclusively through tropospheric reactions with OH (and in this non-linear system, CO is also a major sink for OH). There are some estimates of plant/soil uptake of CO, but these are not of major significance.

observations Detailed of CO concentrations are available over the past decade (Dianov-Klokov and Yurganov, 1981; Khalil and Rasmussen, 1988) and there are sporadic measurements since 1950 (Rinsland and Levine, 1985). These data indicate that CO concentrations have grown modestly, but consistently (1-6%/yr), in the northern mid-latitudes over the last few decades. There is no convincing evidence for growth in the Southern Hemisphere (Seiler, Giehl et al., 1984; Cicerone, 1988). This pattern is consistent with a growing anthropogenic source, since the short lifetime precludes significant interhemispheric transport. Since CH_4 concentrations have also increased similarly (about 1%, as noted above), we would expect a similar change of opposite sign in tropospheric OH.

Nitrogen Oxides

One form of odd-nitrogen, denoted as NO_x , is defined as the sum of two species, $NO + NO_2$. NO_x is created in lightning, in natural fires, in fossil-fuel combustion, and in the stratosphere from N_2O . The NO_x levels over the continental boundary layer and in the aircraft flight lanes of the Northern Hemisphere are likely to have increased over the last several decades. Nevertheless, the levels of NO_x in the clean marine environment are so low that they might be accounted for entirely by natural sources (i.e., lightning, fires, stratospheric HNO₃).

The anticipated changes in NO_x levels over limited regions of the Northern Hemisphere are expected to have only a small direct effect on the globally integrated OH concentration. A more important impact of NO_x emissions is likely for tropospheric O₃, where a substantial fraction of the global tropospheric ozone production is predicted to take place in small regions with elevated levels of NO_x and hydrocarbons (Liu et al., 1987). These issues are unresolved and are currently the focus of photochemical studies with multi-dimensional tracer models.

Stratospheric Ozone and Circulation

Some species such as N_2O and CFCs do not react with OH, and these gases are destroyed only in the stratosphere by short-wavelength ultraviolet light and by reactions with the energetic state of atomic oxygen, $O(^{1}D)$. For CFCs and N_2O the abundances will be perturbed by changes in the rate of stratosphere-troposphere circulation and changes in the stratospheric O_3 that shields the solar ultraviolet radiation. Major perturbations to stratospheric O_3 and circulation may also alter the concentrations of tropospheric O_3 , since the stratosphere represents a significant source for this gas.

Predictions have been made over the past decade that stratospheric O₃ will change due to increasing levels of CFCs, and that the circulation of the stratosphere may be altered in response to changes in climate induced by greenhouse gases. Recent detection of the Antarctic ozone hole has dramatized the ability of the atmosphere to change rapidly in response to perturbations. There are currently underway many theoretical studies of the impact of the ozone hole on stratospheric circulation, O₂ fluxes, and the mean chemistry of the stratosphere (e.g., N_2O losses). As discussed above, there are also indications of a declining trend in Northern Hemisphere O₃ that may be associated with "Antarctic" chemistry. In summary, if stratospheric O_3 changes in the next few decades are large, they may lead to alterations in the lifetimes of the long-lived greenhouse gases and also perturb tropospheric chemistry through the supply of O_3 and through the increase in solar ultraviolet light available to generate OH.

CONCLUSION

Anthropogenic emissions of both longlived greenhouse gases and short-lived highly reactive species are altering the composition of the atmosphere. The concentrations of CO_2 and CH₄ have increased dramatically since the pre-industrial era, and CFCs have been introduced into the atmosphere for the first time. As a result of the rapid pace of humanneither induced change, atmospheric composition nor climate is currently in equilibrium. Thus, significant global change can be anticipated over the coming decades, no matter what course is taken in the future. The rate and magnitude of change, however, are subject to human control, which serves as the motivation for this report.

TABLE 2-1

Trace Gas Data

CO ₂ CARBON DIOXIDE	10 ¹² kg C
Atmospheric Burden	720
351 ppm in 1988 Not photochemically active	
Annual Trend	3.0
$1.1 \pm 0.2 \text{ ppm/yr} (0.4\%/\text{yr}) \text{ since } 1984$	
Annual Anthropogenic Sources	6-8
1. Fossil-fuel combustion 4.5%/yr since 1984	5.5
2. Land-use Modification	0.4 - 2.6
3. Biosphere climate feedback Enhanced aerobic decomposition of detrital material due to more favorable climate	?
Annual Anthropogenic Sinks	3-5
1. Ocean Ocean's capacity to absorb CO ₂ will be altered by changes in temperature, salinity, and biological activity of ocean.	<2
 Biosphere Enhanced photosynthetic uptake of CO₂ due to more favorable climate and/or due to CO₂ fertilization 	0.5-4

CH ₄	METHANE	10^9 kg CH_4
Atmosp	heric Burden	
167 Life	70 ppb in 1988 (global average) etime: 8 - 12 years	4600 - 4800
An n ual	Trend	
14	- 16 ppb/yr (0.8-1%/yr)	40 - 46
Annual	Sources	500 ±100
1.	Fossil fuel Coal mining Natural gas drilling, venting, processing, and transmission loss	15 - 45 25 - 50
2.	Biomass burning	50 - 100
3.	Natural wetlands	80 - 200
4.	Rice Paddies	60 - 170
5.	Animals mainly ruminants	65 - 100
6.	Termites Population unknown	10 - 100
7.	Oceans and freshwater lakes	5 - 45
8.	Landfills	20 - 70
9.	Methane hydrate destabilization	0 - 100 (future)
Annual	Sinks	495 ±145
1.	OH destruction	495 ±145
2.	Dry soils absorption by methane - oxidizing bacteria in dry soils	5 - 60

N ₂ O	NITROUS OXIDE	10 ⁹ kg N
Atmosp	heric Burden	1500
307 Lif	7 ppb in 1988 etime: 120 - 160 years	
Annual 0.7 0.2	Trend - 0.8 ppb/yr -0.3%/yr	3.5 ± 0.5
Ann ual	Sources	14 \pm 3 (inferred)
1.	Combustion of coal and oil	<1
2.	Land-use modification Biomass burning Forest clearings	<0.3 0.8 - 1.3
3.	Fertilized agricultural lands	0.2 - 2.4
4.	Contaminated aquifers	0.8 - 1.7
5.	Tropical and subtropical forests and woodlands	6 ±3
6.	Boreal and temperate forests	0.1 - 0.5
7.	Grasslands	<0.1
8.	Oceans	2 ± 1
Annual	Sinks	10.5 ±3

Stratospheric photolysis and reaction with $O(^{1}D)$

со	CARBON MONOXIDE	10 ⁹ kg CO
Atmo	spheric Burden	525
- (~ 110 ppb 150 - 200 ppb Northern Hemisphere, 75 ppb Southern Hemisphere)	
I	Lifetime: 0.2 year	
Annu	al Trend	4
1 0	- 6%/yr Northern Hemisphere - 1%/yr Southern Hemisphere	
Annu	al Sources	3300 ±1700
1	. Technological sources	640 ±200
2	. Biomass burning	1000 ± 600
3	CH ₄ oxidation	600 ±300
4	. Oxidation of natural hydrocarbons (isoprenes and terpenes)	900 ±500
5	Emission by plants	75 ±25
6	Production by soils	17 ±15
7	. Ocean	100 ±90
Annua	al Sinks	2500 ±750
1	. Soil uptake	390 ±140
2	. Photochemistry	2000 ±600
3	. Flux into stratosphere	110 ±30

NO _x	NITROGEN OXIDES	10 ⁹ kg N
$NO_x =$	NO + NO ₂ nitric nitrogen oxide dioxide	
$NO_y = 1$	$NO_{x} + HNO_{2} + HNO_{3} + HO_{2}NO_{2} + NO_{3} + 2N_{2}O_{5} + PAN$	+ Particulate Nitrate
Atmosph	eric Burden large variability; lifetime 1-2 days in summer	?
Mar	ine air 4 ppt (NO)	
	tinental air non-urban sites 2-12 ppb U.S. & European cities 70 - 150 ppb	
(100	$0 \text{ ppt} = 240 \text{ x } 10^9 \text{ kg N}$	
Annual I	Trend	?
Annual S	Sources Spatially and temporally concentrated sources	25 - 99
1.	Combustion of coal, oil and gas	14 - 28
2.	Biomass burning	4 - 24
3.	Lightning	2 - 20
4.	Oxidation of ammonia	1 - 10
5.	Emission from soils (mostly NO)	4 - 16
6.	Input from stratosphere (by reaction of $O(^{1}D)$ with $N_{2}O$)	~ 0.5
Sinks		24 - 64
1.	Wet deposition (precipitation scavenging) ocean continents	4 - 12 8 - 30
2.	Dry deposition	12 - 22

Chemical Formula	Name	Concentration (ppt)	Annual Trend	Global Prod. (10 ⁶ kg)	Sources	Sinks	Lifetime (years)
CCI ₃ F	CFC-11	226 (1986)	+4%	350 (1986) (CMA rep. co.'s only)	Rigid and flexible foam; Aerosol propellant	Removal in stratosphere	74 ⁺³¹ -17 (60)
CCl ₂ F ₂	CFC-12	392 (1986)	+4%	480 (1986) (CMA reporting co.'s plus USSR estimate)	Refrigerant; Rigid and flexible foam; Aerosol propellant	Removal in stratosphere	111 ⁺²²² -44 (120)
CHCIF ₂	HCFC-22	~80 (1985)	~ +7% (1986)	206 (1984) 163 (1981) 102 (1977)	Refrigerant; Production of teflon polymers (fluoropolymers)	Removal by OH in troposphere	15
CCl ₂ FCClF ₂ (C ₂ Cl ₃ F ₃)	CFC-113	30-70 (1986) (calibration uncertain)	+11%	138-141 (1984) 91 (1979) 79 (1978) 70 (1977)	Electronics solvent	Removal in stratosphere	90
CH ₃ CCl ₃	Methyl chloroform	125 (1986)	~5% (1986)	~580 (1985)	Industrial degreasing of metallic or metaplastic pieces; Cold cleaning; Solvent of adhesives, varnishes, and paints	Removal by OH in troposphere	6 ±1
CCl₄	Carbon tetra- chloride	75-100 (1986) (calibration uncertain)	+1%	~1000 (1985) atmospheric emissions 80-110	Chemical intermediate in CFC-11, -12 production; Declining use as: Solvent in chemical & pharmaceutical processes and as grain fumigant	Stratospheric photolysis	~ 40
CH3CI	Methyl chloride	~ 600 (1986)	?	(2000-5000 total, based on OH); 500 industrial	Burning Vegetation; Release from oceans	Removal by OH in troposphere	~ 1.5
CBrClF ₂	Halon 1211 (BCF)	~2 (1986) (calibration uncertain)	>10% (1985)	5-10 (est. from obs. of atm. increase)	High-tech fire extinguisher (portable)	Photolysis in stratosphere and upper troposphere	25

Chemical Formula	Name	Concentration (ppt)	Annual Trend	Global Prod. (10 ⁶ kg)	Sources	Sinks	Lifetime (years)
CBrF ₃ (CF ₃ Br)	Halon 1301	~2 (1986) (calibration uncertain)	>10%	7-8 (1984)	High-tech fire extinguisher (built-in systems)	Photolysis in stratosphere	110
CCIF ₃	CFC-13	~ 3.4 (1980)	~5% (avg. of 5 sites)		?	Removal in stratosphere	400
CCIF ₂ CCIF ₂	CFC-114	5 (1985)	?	13-14 (1985) Constant at 13 from 1979-84	Aerosol propellant; Refrigerant; Production of CFC-115	Removal in stratosphere	200
C ₂ ClF ₅	CFC-115	4 (1985)	?	?	?	Removal in stratosphere	400
C ₂ F ₆	CFC-116	~4 (1980)		?	?	Removal in mesosphere and above	> 500
СН ₃ Вг	Methyl bromide	15 (1985)	smali	?	Leaded motor fuel; Fumigation 50% natural (anthropogenic sources probably declining)	Removal by OH in troposphere	~ 1.5 (2.3)
CHBr,	Bromoform	~2 (1984) highly variable	?	?	Mainly natural (oceans)	Removal by OH in troposphere, photolysis	Short-lived
C₂H₄Br₂	Ethylene dibromide (EDB)	~1 (1984)	?	?	Evaporation of leaded gasoline; Fumigation; Anthropogenic sources probably declining	Removal by OH in troposphere	~1
СН³і	Methyl iodide	~1 (1981)		?		Removal by OH in troposphere	Very short-lived

Sources: Adapted from Seiler and Conrad, 1987; WMO, 1990.

ADDENDUM TO CHAPTER II: RADIATIVE FORCING DIFFERENCES AMONG THE GREENHOUSE GASES

Throughout this Report the relative contributions of greenhouse gases to climate change are measured based on changes in atmospheric concentrations of each gas; these concentration changes alter the radiative balance of the climate system. The radiative forcing implied by a change in the atmospheric concentration of a gas depends on several factors, including the absorptive strength of the gas within the infrared spectrum, its decay profile, and the relative concentrations of all gases in the atmosphere, among other factors. The scientific community has typically measured contributions to radiative forcing using estimated changes in atmospheric concentrations. For example, based on the work by Hansen et al. (1988), the relative contributions by greenhouse gas to radiative forcing during the 1980s are summarized in Figure 2-10a.

The relative contributions in Figure 2-10a are based on changes in atmospheric composition over the period. These changes are of primary scientific concern since they affect the radiative balance of the atmosphere and hence, the rate and magnitude of climate change. When discussing greenhouse gases in a policy context, however, it is useful to have some means of estimating the relative effects of emissions of each greenhouse gas on radiative forcing of the atmosphere over some future time horizon, without performing the complex and time-consuming task of calculating and integrating changes in atmospheric composition over the period. In short, the need is for an index that translates the level of emissions of various gases into a common metric in order to compare the climate forcing effects without directly calculating the changes in atmospheric concentrations.

A number of approaches, called Global Warming Potential (GWP) indices, have been developed over the past year. These indices account for direct effects due to growing concentrations of carbon dioxide (CO₂), methane (CH₄), chlorofluorocarbons (CFCs), and nitrous oxide (N₂O). They also estimate indirect effects on radiative forcing due to emissions which are not themselves greenhouse gases, but lead to chemical reactions that create or alter greenhouse gases. These emissions include carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOC), all of which contribute to formation of tropospheric ozone, which is a greenhouse gas.

In this study we follow the methodology used by the Intergovernmental Panel on Climate Change (IPCC, 1990). However, there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. In addition to the IPCC, there are several other noteworthy attempts to define a concept of global warming potential, including Lashof and Ahuja (1990), Rodhe (1990), Derwent (1990), WRI (1990), and Nordhaus (unpublished).

The concept of global warming potential developed by the IPCC is based on a comparison of the radiative forcing effect of the concurrent emission into the atmosphere of an equal quantity of CO_2 and another greenhouse gas. Each gas has a different instantaneous radiative forcing effect. In addition, the atmospheric concentration attributable to a specific quantity of each gas declines with time. In general, other greenhouse gases have a much stronger instantaneous radiative effect than does CO₂; however, CO₂ has a longer atmospheric lifetime and a slower decay rate than most other greenhouse gases. Atmospheric concentrations of certain greenhouse gases may decline due to atmospheric chemical processes, which in turn create other greenhouse gases or contribute to their creation or longevity. These indirect effects are included in the GWP of each gas.

Following this convention, the GWP is defined as the time-integrated commitment to climate forcing from the instantaneous release of 1 kilogram of a trace gas expressed relative to that from 1 kilogram of carbon dioxide.⁵ The magnitude of the GWP is, however, sensitive to the time horizon over which the analysis is conducted (i.e., the time period over which the integral is calculated). For example, Table 2-3 summarizes the GWPs of key greenhouse gases assuming 20-year, 100-year, FIGURE 2-10

CONTRIBUTION TO RADIATIVE FORCING



Sources: Hansen et al., 1988; IPCC, 1990.

Trace Gas	Lifetime (Years)	Glob (Integrat	Global Warming Potential (Integration Time Horizon, Years)		
		<u>20</u>	<u>100</u>	<u>500</u>	
Carbon Dioxide	а	1	1	1	
Methane	10	63	21	9	
Nitrous Oxide	150	270	290	190	
CFC-11	60	4500	3500	1500	
CFC-12	130	7100	7300	4500	
HCFC-22	15	4100	1500	510	
CFC-113	90	4500	4200	2100	
CCl₄	50	1900	1300	460	
CH ₂ CCl ₃	6	350	100	34	
CĔ₃Br	110	5800	5800	3200	
Ő	b	7	3	2	

TABLE 2-3 Global Warming Potential for Key Greenhouse Gases

^a Atmospheric retention of CO_2 is very complex. It is not destroyed like many other gases, but can be transferred to other reservoirs such as the oceans or biota and then return to the atmosphere. The IPCC used an approximate lifetime of 120 years by explicitly integrating the box diffusion model of Siegenthaler (1983).

^b Lifetime of CO was not provided, although its lifetime is generally no more than a few months.

Source: IPCC, 1990.

and 500-year time horizons. The assumed integration period defines the time period over which the radiative effects of the gas are measured. These GWPs indicate, for example, that 1 kilogram of methane emissions is estimated to have 21 times the impact on radiative forcing as 1 kilogram of carbon dioxide for a 100-year time horizon. If a 500year time horizon is assumed, however, methane is estimated to have only 9 times the impact on radiative forcing compared to an equivalent amount of carbon dioxide. The differences between the values for 100 years and 500 years incorporate the differences in atmospheric lifetime. Because methane is a much shorter-lived gas than carbon dioxide --10 years versus 120 years⁶ -- its relative contribution to global climate change will decrease (increase) over time as the time horizon increases (decreases).

For this discussion we will use the GWPs presented in Table 2-3 for a mid-level time horizon, i.e., 100 years, to convert all greenhouse gases to a CO_2 -equivalent basis so that the relative magnitudes of different quantities of different greenhouse gases can be readily compared. There is nothing particularly unique about this time horizon. Nevertheless, it is sufficiently long that many of the atmospheric processes currently thought to affect concentrations can be considered without excessively weighting longer-term impacts on atmospheric processes that are not well understood.

Using the GWPs presented in Table 2-3, we can estimate the relative contribution of each greenhouse gas to global warming for any set of greenhouse gas emission estimates. For example, in Figure 2-10b we present the contributions to global warming by greenhouse gas using the global emission estimates for each gas for the base year 1985 and the 100year GWPs. For purposes of comparison we also have included the contributions to global warming by gas for the 1980s based on estimates of the increase in atmospheric concentrations of each gas during the 1980s (Figure 2-10a; also presented in the Executive Summary and Figure 2-1 based on Hansen et al., 1988). Conceptually, the approaches used here are quite different. Hansen et al. (1988)

base their approach on the radiative forcing effects of estimated differences in atmospheric concentrations between 1980 and 1990. Since only changes in atmospheric concentrations are considered, Hansen's approach ignores any portion of anthropogenic emissions that maintains atmospheric concentrations at previous levels, even if those levels are elevated above pre-industrial concentrations. The use of GWPs measures the radiative forcing effects of emissions for a single year, in this case, 1985, over a 100-year time frame; this approach treats all anthropogenic emissions as contributing to radiative forcing. Differences occur for several other reasons, including:

• The atmospheric concentration changes in Hansen et al. (1988) include the "decay" of CH_4 , CO, and non-methane hydrocarbons (NMHC) to CO_2 in the atmosphere. The contribution of CO_2 concentrations during the 1980s will therefore be larger than the change due to CO_2 emissions.

• Assumptions about atmospheric lifetimes differ. For example, the IPCC assumed CFC-11 had a lifetime of 60 years; Hansen et al. (1988) assumed 75 years. For CFC-12 the IPCC assumed 130 years; Hansen et al. assumed 150 years.⁷ Additionally, atmospheric lifetime assumptions are only important to Hansen et al. to the extent they affect the atmospheric chemistry from 1980-90.

• The time period of the analyses differ. The GWPs are based on emission effects over a 100-year time frame, while Hansen et al. base their determination on the estimated changes in atmospheric composition over a 10-year period.

• The Hansen et al. pie chart (Figure 2-10a) includes the impacts for stratospheric water vapor and tropospheric ozone directly in the "Other" category; the pie chart using 100-year GWPs (Fig 2-10b) includes these effects in the calculations of the GWPs for the greenhouse gases, e.g., the GWP for CH_4 includes the effect that CH_4 has on the production of stratospheric water vapor and tropospheric ozone.

NOTES

1. peta = 10^{15} , giga = 10^9 , 1 ton = 10^6 grams. Thus, 1 petagram (Pg) = 1 gigaton (Gt).

2. A radical is an atom or group of atoms with at least one unpaired electron, making it highly reactive.

3. 1 Tg = 1 teragram = 10^{12} grams.

4. $1 \text{ Gg} = 1 \text{ gigagram} = 10^9 \text{ grams} = 10^6 \text{ kg.}$

5. The discussion here focuses on the use of Global Warming Potentials, where all gases are compared relative to carbon dioxide. This approach is used since, among other things, carbon dioxide is the largest contributor to radiative forcing. However, there is no reason why another gas could not be used as the common denominator, e.g., all gases could be expressed on a methane-equivalent basis.

6. The atmospheric lifetime of CO_2 is difficult to estimate due to the complex nature of the carbon cycle. Carbon dioxide is not destroyed like many other gases, but can be transferred to other reservoirs such as the oceans or biota and then return to the atmosphere. The IPCC used an approximate lifetime of 120 years by explicitly integrating results of the box diffusion model of Siegenthaler (1983).

7. Hansen et al. (1988) did not provide atmospheric lifetime assumptions for all of the greenhouse gases.

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CHAPTER III

CLIMATE CHANGE PROCESSES

FINDINGS

• Climate exhibits natural variability on all time scales, from seasons to millions of years. This variability is caused by a combination of changes in external factors, such as solar output, and internal dynamics and feedbacks, such as the redistribution of heat between the atmosphere and the oceans.

• The ultimate warming that can be expected for a given increase in greenhouse gas concentrations is uncertain due to our inadequate understanding of the feedback processes of the climate system. For the benchmark case of doubling carbon dioxide concentrations, the National Academy of Sciences has estimated that the equilibrium increase in global average temperature would most likely be in the range of 1.5-4.5°C. The Interim Report of the Intergovernmental Panel on Climate Change (IPCC) states:

> The evidence from the modelling studies, from observations and the sensitivity analyses indicate that the sensitivity of global mean surface temperature to doubling CO_2 is unlikely to lie outside the range 1.5 to $4.5^{\circ}C$... for the purpose of illustrating the IPCC Scenarios, a value of 2.5°C is considered to be the "best guess" in light of current knowledge (IPCC, 1990, p. 145).

The largest factor contributing to these ranges is uncertainty about how clouds will respond to climate change.

• There are varieties of geochemical and biogenic feedbacks that have generally not been quantified in estimating the temperature change that could occur for any given initial

increase in greenhouse gases. In particular, the potential of future global warming to increase emissions of carbon from northern latitude reservoirs in the form of both methane and carbon dioxide (CO_2) , to alter uptake of CO_2 by oceans, and a variety of other temperaturedependent phenomena indicate that the true sensitivity of the Earth's climate system to increased greenhouse gases could exceed 5.5°C for an initial doubling of CO_2 . There are biogenic and geochemical feedbacks that could decrease greenhouse gas concentrations -enhanced photosynthesis due to higher CO₂, for example. Although many of these feedback processes -- both those that might increase and those that might decrease greenhouse gas concentrations -- are poorly understood, it seems likely that, overall, they will act to increase, rather than decrease, greenhouse gas concentrations in a warmer world.

Uncertainties about ocean circulation and heat uptake, and about future internal climate oscillations and volcanic eruptions, make it difficult to predict the time-dependent response of climate to changes in greenhouse gas concentrations. Because the oceans delay the full global warming that would be associated with any increase in greenhouse gases, significant climatic change could continue for decades after the composition of the atmosphere were stabilized. The Earth is already committed to a total warming of about 0.7-1.5°C relative to pre-industrial times (assuming that the climate sensitivity to doubling CO_2 is 2-4°C). The Earth has warmed by 0.3-0.7°C during the last century, which is not inconsistent with expectations given the uncertain delay caused by ocean heat uptake. The temperature record over the last century, however, cannot now be used to confirm or refute specific model predictions.

INTRODUCTION

The increasing concentrations of greenhouse gases documented in the last chapter are expected to alter significantly the Earth's climate in the coming decades. The magnitude and timing of actual climatic change will be determined by future emissions (see CHAPTER VI), by changes in other climate forcings, and by the sensitivity of the climate system to perturbations. Weather and climate (the time-average of weather) are determined by complex interactions between the atmosphere, land surface, snow, sea ice, and oceans, involving radiative and convective exchange of energy within and among these As is readily apparent, this components. system exhibits considerable variability from day to day, month to month, and year to year.

Systematic diurnal (day-night) and seasonal variations are driven by changes in the distribution and amount of solar energy reaching the top of the Earth's atmosphere as the Earth rotates on its axis and orbits around the sun. Changes in the amount of energy emitted by the sun, changes in the Earth's orbit, changes in atmospheric composition (due to volcanic eruptions and human input of aerosols and greenhouse gases), and changes in the earth's surface (such as deforestation) can also affect the Earth's energy balance over the long term. Such factors are considered "external forcings" because they do not depend on the state of the climate system itself.

In contrast, much of the day-to-day and year-to-year variation results from the internal dynamics of the climate system. For example, the polar front may be unusually far south in North America during a given year, producing colder-than-normal weather in the northern Great Plains, but there can be warmer-thanaverage weather somewhere else, leaving the global average more or less unchanged. Similarly, upwelling of cold water off the Pacific Coast of South America may fail for several years. This irregularly recurring event, referred to as El Niño, leads to various regional weather anomalies, impacts like the collapse of the Peruvian anchovy fishery, and warmer global temperatures. In this case there is a temporary net release of heat from the ocean to the atmosphere, which is usually followed by a reversal, sometimes referred to as La Niña (Kerr, 1988). Such variations of the atmospheric and oceanic circulation can produce anomalous redistributions of energy in the climate system resulting in climate variations with amplitudes and time scales that may be comparable to climate changes expected from past increases in greenhouse gases (Lorenz, 1968; Hasselmann, 1976; Robock, 1978; Hansen et al., 1988).

In order to determine precisely the potential effects of the input of greenhouse gases on future climate, it would be necessary not only to be able to understand all the physics of the climate system and the effects of each potential cause of climate change, but also to be able to predict the future changes of these forcings. If we could do this, we could explain past climate change and separate the effects of greenhouse gases from the other factors that have acted during the past 100 years for which we have instrumental temperature records. We could also use theoretical climate models to calculate the future size and timing of climate changes due to greenhouse gases. Since our measurements of past climate are incomplete, our understanding of the climate system is incomplete, and some (not well known) portion of climate change is random and unpredictable, we can only estimate the impact of greenhouse gas buildup within a broad range of uncertainty.

To place in context the potential warming due to increasing greenhouse gas concentrations, in this chapter we discuss the magnitude and rate of past changes in climate and the various factors that influence climate. Feedback mechanisms that can amplify or lessen imposed climate changes are discussed The overall sensitivity of climate to next. changes in forcing is then considered, followed by a discussion of the time-dependent response of the Earth system. The focus is on global temperature as an indicator for the magnitude of climate change. Regional climate and the potential impacts of climate change are not discussed here, but are considered in the companion report Potential Effects of Global Climate Change on the United States (Smith and Tirpak, 1989).

CLIMATE CHANGE IN CONTEXT

The most detailed information on climate is, of course, from the modern instrumental record, but even this data set is quite sparse in the Southern Hemisphere and over the oceans. Wigley et al. (1986) reviewed a number of recent analyses, noting that independent groups (including Hansen et al., 1981 and Vinnikov et al., 1980; more recent publications are Hansen and Lebedeff, 1988 and Vinnikov et al., 1987), necessarily relying on the same basic data sources but using different data selection and averaging approaches, have obtained very similar results. Given the various uncertainties due to factors such as poor spatial coverage in some regions, changes in the number and location of stations, local temperature changes due to growth of urban areas, and changes in instrumentation, Wigley et al. conclude that the warming since 1900 has been in the range of 0.3-0.7°C. The most complete and up-todate global surface air temperature record available (Jones and Parker, 1990) is displayed in Figure 3-1a, which shows a global warming of about 0.3°C from 1900 to 1940, a cooling of about 0.1°C from 1940 to 1975, and a warming of about 0.2°C from 1975 to 1989. The six warmest years in the global record occurred during the 1980s: 1980, 1981, 1983, 1987, 1988, and 1989. The overall warming is similar in the land-air temperature record of the Northern and Southern Hemispheres (see Figures 3-1b,c), though the long-term trend is steadier in the Southern Hemisphere where the 1940-1975 cooling is less evident. While the gradual warming seen in Figure 3-1 during the past century is consistent with the increasing greenhouse gases during this period (see CHAPTER II), the pre-1940 warming, which is greater than expected from increases in greenhouse gas concentration during this period, the large interannual variations, and the relatively flat curve from 1940 to 1975 show that there are also other important causes of climate change. The differences between the two hemispheres also show that there are regional differences in the climate response to a global forcing (greenhouse gases), that important other forcings (such as large volcanic eruptions) are not global in their effects, or that internal climate variations produce regional differences. Data for the

United States, for example, show that it warmed by about half as much as the globe as a whole during the last century (Hansen et al., 1989). Because of past and potential future emissions of greenhouse gases (see below and CHAPTER VI), climate changes during the next century may be greater than the variations shown for the past 100 years.

Recent climate variations are put in a longer-term perspective in Figures 3-2 through 3-4. The amplitude of climate change over the last millennium (see Figure 3-2) is similar to what has been seen during the last century. The Medieval Warm Epoch (800-1200 AD) may have been restricted to the North Atlantic Basin (Wigley et al., 1986) and in any case appears to have been about as warm as the The Little Ice Age (1430-1850; present. Robock, 1979) appears to have been as cool as the early 20th century in parts of Europe. The peak of the most recent glaciation is generally given as 18 thousand years before the present (kyBP) (see Figures 3-3, 3-4) with globally averaged temperatures about 5°C cooler than today (Hansen et al., 1984) between 15 and 20 kyBP. Even over the 700,000-year period illustrated in Figure 3-4 the maximum global temperature swing appears to have been no greater than about 5°C, with the periods of greatest warmth being the present and the interglacial peaks, which occurred approximately every 100,000 years for the past million years. The temperature change shown in Figure 3-3 is for Antarctica and is substantially greater than what is believed to represent the globe as a whole. (Such highlatitude amplification of temperature increases is predicted for greenhouse-induced warming in the future.) The CO_2 variations are, in general, in step with the temperature variations deduced from deuterium variations in the same ice core (Jouzel et al., 1987), suggesting that CO₂ was important in amplifying the relatively weak orbital forcings during past climate variations (Genthon et al., 1987; see Orbital Parameters below). While it is difficult to assign a cause for these past changes, it is reasonable to conclude that, given current greenhouse gas concentrations, global temperatures will soon equal or exceed the maximum temperatures of the past million years.



Figure 3-1. (a) Global surface air temperature, 1856-1989, relative to the 1951-1980 average. The gradual warming during this period is consistent with the increasing greenhouse gases during this period, but the large interannual variations and the relatively flat curve from 1940 to 1975 show that there are also other important causes of climate change. (Source: Jones and Parker, 1990 -- Copyright © 1990 by the AAAS.)

(b,c) Land surface air temperatures, 1851-1987 for the Northern Hemisphere and 1857-1987 for the Southern Hemisphere. Note the larger interannual variability before 1900, when data coverage was much more sparse. (Source: Jones, 1988.)





Figure 3-2. Oxygen isotope (δ^{18} O) variations from ice cores in Greenland. This is an index of Northern Hemisphere temperature, with the maximum range equal to about 1°C. (Source: record of Dansgaard as given by Lamb, 1977.)



Figure 3-3. Carbon dioxide levels and temperatures over the last 160,000 years from Vostok 5 Ice Core in Antarctica. The temperature scale is for Antarctica; the corresponding amplitude of global temperature swings is thought to be about 5°C. (Source: Barnola et al., 1987. Reprinted by permission from *Nature*, Vol. 329, pp. 408-414. Copyright © 1987 Macmillan Journals Limited.)



Figure 3-4. Composite δ^{18} O record of Emiliani (1978) as given by Berger (1982). This comes from deep sea sediment cores and is an index of global temperature, with the temperature range from stage 1 (present) to stage 2 (18,000 years ago) equal to about 5°C.

CLIMATE FORCINGS

The patterns of climate variations discussed in the last section are the result of a combination of external forcings, internal feedbacks, and unforced internal fluctuations. The strictly external forcings are changes in solar output and variations in the Earth's orbital parameters, while changes in aerosols and greenhouse gas concentrations may be viewed as external forcings or internal feedbacks, depending on the time scale and processes considered. The sensitivity of the climate system is determined by the feedbacks that modify the extent to which climate must change to restore the overall energy balance of the Earth as external forcings change.

Solar Luminosity

The solar luminosity (or total energy output from the sun) has an obvious and direct influence on climate by determining the total energy reaching the top of the Earth's Theories of stellar evolution atmosphere. suggest that solar output was 25% lower early in Earth history, but geologic evidence and the fact that life was able to evolve on Earth show that the Earth was not an inhospitable icecovered planet. An important part of the explanation for this "faint young sun paradox" now appears to be that the CO_2 content of the atmosphere was many times higher than it is at present. The enhanced greenhouse effect from CO_2 was probably the main factor in counteracting the lower solar luminosity (see below). Geochemical models suggest that over millions of years CO_2 has acted as an internal feedback that has kept the Earth's climate in a habitable range (Walker et. al., 1981; Berner and Lasaga, 1988; see Figure 3-3).

Solar luminosity also varies by small but significant amounts over shorter time periods. Various attempts have been made to explain past climate variations by assuming a link between solar luminosity and observed parameters, such as sunspot activity, solar diameter, and the umbral-penumbral ratio (Wigley et al., 1986). Unfortunately, measurements with sufficient precision to detect insolation changes have only been available since 1979 -- too short a time period to be able to definitively confirm or refute the proposed relationships. These measurements show a decline in solar luminosity between 1980 and 1986; whereas the most recent data show a reversal of this trend (Willson and Hudson 1988; Willson et al., 1986). The luminosity data are positively correlated with sunspot number and suggest an 11-year cycle with an amplitude of 0.04% or 0.1 watts per square meter (W/m²) at the top of the atmosphere (Willson and Hudson, 1988).

Orbital Parameters

Cyclic changes in the Earth's orbital characteristics are now widely accepted as the dominant trigger behind the glacial/interglacial variations evident in Figure 3-3 and extending back to at least 1.7 million years before present (e.g., Wigley et al., 1986; COHMAP, 1988). While causing only small changes in the total radiation received by the Earth, the orbital changes (known as the Milankovitch cycles) significantly alter the latitudinal and seasonal distribution of insolation. For example, Northern Hemisphere summer insolation was about 8% greater 9 kyBP than it is now, but winter insolation was 8% lower. Changes of this type, in combination with internal feedbacks as discussed below, are presumed to have determined the pattern of glaciations and deglaciations revealed in the geologic record. Attempts have been made to compare model predictions with paleoclimatic There has been reasonably good data. agreement between the two, given specified ice sheet extent and sea surface temperatures (COHMAP, 1988; Hansen et al., 1984). To the extent that the Milankovitch explanation of ice ages is correct, one would expect the Earth to be heading toward a new ice age over the next 5000 years, but the very gradual changes in orbital forcings expected in this period will be overwhelmed if current trends in greenhouse gas concentrations continue (Wigley et al., 1986).

Volcanoes

Large volcanic eruptions can significantly increase the stratospheric aerosol concentration, increasing the planetary albedo and reducing surface temperatures by several tenths of one degree for several years (Hansen et al., 1978, 1988; Robock, 1978, 1979, 1981, 1984). Because of the thermal inertia of the climate system, discussed below, volcanoes can even be responsible for climate changes over decades, and in fact the warming shown in Figure 3-1 from 1920 to 1940 may be attributable to a period with very few volcanic eruptions (Robock, 1979). Since large eruptions occur fairly frequently and cannot now be predicted, this component of climate change will have to be considered when searching past climate for a greenhouse signal and when projecting future climate change.

Surface Properties

The Earth's radiative balance can also be changed by variations of surface properties. While interactions with the ocean, which covers 70% of the Earth's surface, are considered internal to the climate system and are discussed below, land surfaces also exert a strong influence on the climate. Human activities, such as deforestation, not only provide a source of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere, but also change the surface albedo and moisture flux into the atmosphere. Detailed land surface models, incorporating the effects of plants, are now being developed and incorporated into general circulation model (GCM) studies of climate change (Dickinson, 1984; Sellers et al., 1986).

The Role of Greenhouse Gases

The greenhouse effect does not increase the total energy received by the Earth, but it does alter the distribution of energy in the climate system by increasing the absorption of infrared (IR) radiation by the atmosphere. If the Earth had no atmosphere, its surface temperature would be strictly determined by the balance between solar radiation absorbed at the surface and emitted IR. The amount of IR emitted by any body is proportional to the fourth power of its absolute temperature, so that an increase in absorbed solar radiation (due to increased solar luminosity or decreased albedo, for example) would be balanced by a small increase in the surface temperature, increasing IR emissions until they are again equal to the absorbed solar radiation. The role of greenhouse gases can be understood by thinking about the atmosphere as a thin layer that absorbs some fraction of the IR emitted by the surface (analogous to the glass in a

greenhouse). The energy absorbed by the atmosphere is then re-emitted in all directions, and the downward half of this energy flux warms the surface (see Figure 3-5). Higher concentrations of greenhouse gases increase the IR absorption in the atmosphere, raising surface temperatures.

Changes in the atmosphere's radiative properties can result from external perturbations (such as anthropogenic emissions of CO_2) or from internal adjustments to climate change. The amount of water vapor, the dominant greenhouse gas, is directly determined by climate and contributes the largest positive feedback to climate change (Hansen et al., 1984; Dickinson, 1986). Similarly, clouds are an internal part of the climate system that strongly influence the Earth's radiative balance (Ramanathan et al., 1989). Changes in the concentrations of other greenhouse gases may be imposed by human activity or may result from changes in their sources and sinks induced by climate change. Such feedbacks are discussed below.

Internal Variations

As discussed in the introduction, even with no changes in external forcings, climate still exhibits variations due to internal rearrangements of energy within the atmosphere and between the atmosphere and the ocean. The total amplitude and time scales of these internal stochastic climate variations are not well known; these variations therefore pose an additional difficulty in interpreting the past record and projecting the level of future climate change.

PHYSICAL CLIMATE FEEDBACKS

Any imposed imbalance in the Earth's radiative budget, such as discussed above, will be translated into a changed climate through feedback mechanisms, which can act to amplify or decrease the initial imposed forcing. In this section, several of these mechanisms which are internal to the physical climate system are discussed. The next section describes several recently investigated mechanisms involving the planet's biology and chemistry.


FIGURE 3-5

Figure 3-5. (a) Highly simplified schematic of the global energy balance illustrating the mechanism by which increased greenhouse gas concentrations warm the Earth's surface. The atmosphere is treated as a thin layer that does not absorb solar radiation; the role of convective and latent heat transfer is also neglected. Doubling the concentration of CO_2 increases the absorption and emission of infrared radiation by the atmosphere, increasing the total energy absorbed at the surface. In the equilibrium depicted, total emissions to space remain unchanged.

(b) A more realistic schematic of the global energy balance for current conditions. (Source: adapted from MacCracken, 1985.)

By no means do we understand or even know about all the mechanisms involved in climate feedbacks. Figure 3-6 shows some of the physical climate feedbacks involved in changing surface temperature. Current stateof-the-art climate models attempt 10 incorporate most of the physical feedbacks that have been identified, but provide a very crude treatment for one of the most important -- changes in clouds -- because of inadequate understanding of cloud physics and because of the small spatial scale on which clouds form compared to the resolution of climate models (see Clouds below).

Water Vapor

When the climate warms, the atmosphere can hold more water vapor. The additional water vapor, which is a greenhouse gas, amplifies the initial warming, which in turn results in still more evaporation from the warmed surface. This positive feedback acts to approximately double imposed forcings.

Snow and Ice

When climate warms, snow and ice cover are reduced, exposing land or ocean with a lower albedo than the snow or ice. In addition, the albedo of the remaining snow and ice is reduced because of meltwater puddles and debris on the surface. This reduced albedo causes more energy to be absorbed at the surface, further enhancing the warming. This albedo feedback was originally thought to be the dominant positive feedback effect of snow and ice, but it now appears that the thermal inertia feedback of sea ice plays a more important role (Manabe and Stouffer, 1980; Robock, 1983). The albedo feedback requires that the sun be shining, and since the maximum ice and snow extent is in the winter, the feedback plays a small role in influencing the albedo except in the spring, when the snow and ice are present along with high insolation.

The thermal inertia feedback acts to increase the thermal inertia of the oceans when climate warms by melting sea ice, reducing its insulating effect and increasing the transfer of heat from the ocean to the atmosphere at high latitudes. This effect acts to reduce the seasonal cycle of surface temperature and is the prime reason for the enhancement of imposed climate change in the polar regions in the winter (Robock, 1983). If sea ice retained its current seasonal cycle, there would be no preferential latitude or time of year for climate change.

Clouds

Clouds respond directly and immediately to changes in climate and probably represent the most important uncertainty in determining the sensitivity of the climate system to the buildup of greenhouse gases. Fractional cloud cover, cloud altitude and cloud optical depth can all change when climate changes (Schlesinger, 1985). It has not been possible to determine the net effect of cloud feedbacks because all these properties of clouds can change simultaneously, because clouds affect long-wave radiation, short-wave radiation, and precipitation (which affects soil moisture and hence albedo, thermal inertia, and moisture flux of land), and because the net effect depends on the location of the cloud (in three dimensions), the underlying surface albedo, and the time of day and year of the changes. The current net effect of clouds is to cool the planet, but this does not imply that changes in clouds will decrease the impact of higher greenhouse gas concentrations (Ramanathan et al., 1989). Roeckner et al. (1987) and Somerville and Remer (1984) argue that the liquid water content of clouds will increase with warming, substantially altering their optical properties. A comparison of recent results with and without cloud optical property feedbacks shows that including this mechanism can increase or decrease total cloud feedback, depending on related changes in other cloud properties (Cess et al., 1989). Overall, a comparison of 14 GCMs found that the impact of cloud feedback ranged from a modest decrease in climate sensitivity (30%) to a large increase (150%) (Cess et al., 1989).

BIOGEOCHEMICAL CLIMATE FEEDBACKS

In addition to the climatic processes discussed above, a number of biogeochemical feedback processes will influence future concentrations of greenhouse gases and climate change. Increased greenhouse gas concentrations will alter not only the climate, but also biogeochemical processes that affect sources and sinks of radiatively important





Figure 3-6. Equilibrium temperature changes from doubling $CO_2(\Delta T_{2k})$ inferred from a review of the strength of individual feedback processes in various climate models. ΔT_0 is the temperature increase expected from doubling CO_2 with no feedbacks. The subscripts w, s, and c, refer to feedbacks due to water vapor and lapse rate, sea ice and surface albedo, and clouds, respectively. Each bar shows the estimated two-standard deviation range of equilibrium global warming with the indicated feedbacks included. (Source: adapted from Dickinson, 1986.)

Climatically important surface gases. properties, such as albedo and evapotranspiration, will also be modified by vegetation changes. The major biogeochemical feedback links, illustrated in Figure 3-7, can be categorized as follows: physical effects of climate change, changes in marine biology, and changes in terrestrial biology. Potential physical effects of climate change include release of methane hydrates and changes in ocean chemistry, circulation, and mixing. Changes in marine biology may alter the pumping of CO_2 from the ocean surface to deeper waters and the abundance of biogenic cloud condensation nuclei. Potential biological responses on land include changes in surface albedo, increased flux of CO_2 and CH_4 from soil organic matter to the atmosphere due to higher rates of microbial activity, increased sequestering of CO_2 by the biosphere due to CO_2 fertilization, and changes in moisture flux to the atmosphere.

Release of Methane Hydrates

Potentially the most important biogeochemical feedback is the release of CH_4 from near-shore ocean sediments. Methane hydrates are formed when a CH_4 molecule is included within a lattice of water molecules; the ratio can be as small as 1:6, that is, one methane molecule for every six water molecules (Bell, 1982). The hydrate structure is stable under temperature and pressure conditions that are typically found under a water column of a few hundred meters or more in the Arctic and closer to a thousand meters in warmer waters; the region where hydrates are found can start at the sea floor and extend up to a few hundred meters into the sediment, depending on the geothermal temperature gradient (Kvenvolden and Barnard, 1984). Estimates of the total quantity of CH₄ contained in hydrates range from $2x10^3$ to $5x10^6$ petagrams (Pg) (Kvenvolden, 1988). Given the climate change associated with a doubling of CO_2 , Bell (1982; as corrected by Revelle, 1983) estimated that there could be a release of ~120 teragrams (Tg) CH_4 per year from Arctic Ocean sediments, and Revelle (1983) calculated global emissions of ~ 640 Tg CH₄/yr from continental slope hydrates. These estimates, however, are highly uncertain both because the total quantity of hydrates potentially subject to

destabilization is not known and because bottom water may be insulated from surface temperature increases throughout much of the ocean (Kvenvolden, 1988). Nonetheless, a very strong positive feedback from this source cannot be excluded at this time.

Oceanic Change

The oceans are the dominant factor in the Earth's thermal inertia to climate change as well as the dominant sink for anthropogenic CO_2 emissions. The mixed layer (approximately the top 75 meters) alone contains about as much carbon (in the form of H_2CO_3 , HCO_3 , and $CO_3^{=}$) as does the atmosphere (see CHAPTER II). Furthermore, the ocean biota play an important role in carrying carbon (as organic debris) from the mixed layer to deeper portions of the ocean (see, e.g., Sarmiento and Toggweiler, 1984). Thus, changes in ocean chemistry, biology, mixing, and large-scale circulation have the potential to substantially alter the rate of CO_2 accumulation in the atmosphere and the rate of global warming.

Because the oceans are such an integral part of the climate system, significant changes in the oceans are likely to accompany a change For example, the oceans are in climate. responsible for about 50% of heat transport from the equator toward the poles (Dickinson, 1986), surface mixing is driven by winds, and deep circulation is driven by thermal and salinity gradients. The feedbacks involving the ocean can be divided into three categories: the direct effect of temperature on carbonate chemistry, reduced mixing due to increased stability of the thermocline, and the possibility large-scale reorganization of ocean of circulation and biological activity.¹

Ocean Chemistry

The most straightforward feedback is on ocean carbonate chemistry. As the ocean warms, the solubility of CO_2 decreases and the carbonate equilibrium shifts toward carbonic acid; these effects combine to increase the partial pressure of CO_2 (p CO_2) in the ocean by 4-5%/°C for a fixed alkalinity and total carbon content. Because the total carbon content would only have to decrease by about one-tenth this amount to restore p CO_2 to its

FIGURE 3-7



GREENHOUSE GAS FEEDBACK PROCESSES

Figure 3-7. Schematic diagram of biogeochemical feedback processes. Changes in trace gas concentrations produce climate change, which may affect ocean CO_2 uptake and the global distribution of natural ecosystems. Changes in ecosystem distribution affect surface albedo, evapotranspiration, the terrestrial component of the carbon cycle (both CO_2 and CH_4), and agriculture. Climate change can also directly affect these properties of the biosphere through the temperature and precipitation responses of given ecosystems. Global warming may also lead to methane emissions from hydrates and changes in energy use. Finally, changes in trace gas concentrations, particularly CO_2 , directly affect natural and agricultural ecosystems.

previous level, the impact of this feedback is to increase atmospheric CO_2 by about 1%/°C for a typical scenario (Lashof, 1989; see CHAPTER VI).

Ocean Mixing

As heat penetrates from the mixed layer of the ocean into the thermocline, the stratification of the ocean will increase and mixing can be expected to decrease, resulting in slower uptake of both CO_2 and heat. This feedback raises the surface temperature that can be expected in any given year for two reasons. First, the atmospheric CO_2 concentration will be higher because the oceans will take up less CO_2 . Second, the realized temperature will be closer to the equilibrium temperature due to reduced heat transport into the deep ocean (see THE RATE OF CLIMATE CHANGE below).

Ocean Biology and Circulation

A more speculative, but potentially more significant, feedback involves the possibility of large-scale changes in the circulation of the atmosphere-ocean system as suggested by Broecker (1987). This possibility is illustrated by the apparently very rapid changes in the CO_2 content of the atmosphere glacial-interglacial transitions as during revealed by ice-core measurements (e.g., Jouzel et al., 1987; see Figure 3-2). Only shifts in carbon cycling in the ocean are thought to be capable of producing such large, rapid, and sustained changes in atmospheric CO2. A number of papers have attempted to model the changes in ocean circulation and/or biological productivity required to account for the change in pCO_2 , emphasizing the importance of high-latitude processes (Kerr, 1988; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984; Knox and McElroy, 1984). Given that continuation of current trends could lead during the next century to a climate change of the same magnitude as that which occurred between glacial and interglacial periods, one must take seriously the possibility of sudden changes in ocean circulation. Should this happen, the rate of CO₂ uptake by the ocean could change substantially. The oceans could even become a CO₂ source rather than a sink -- significantly accelerating climate change. Such changes in

circulation could also cause abrupt changes in climate, a scenario that conflicts with the general assumption that the warming will be gradual (Broecker, 1987).

A different feedback involving ocean biology has been proposed by Charlson et al. (1987). It is also uncertain, but potentially significant. Dimethyl sulfide (DMS) emitted by marine phytoplankton may act as cloud condensation nuclei in remote marine environments, affecting cloud reflectivity and therefore climate (Charlson et al., 1987; Bates et al., 1987). Climate presumably affects biogenic DMS production but the relationship is complex and poorly understood at this time (Charlson et al., 1987). While this mechanism was originally proposed as a potential negative feedback consistent with the Gaia Hypothesis (Lovelock, 1988; Lovelock and Margulis, 1973), ice-core data indicate that aerosol levels were higher during the last glacial maximum, suggesting that biogenic DMS production may act instead as a positive feedback (Legrand et al., 1988). This is only one possible cloud optical property feedback (discussed above), and the net effect cannot be determined because other cloud properties (amount, elevation) would also change in a complex way.

Changes in Terrestrial Biota

The terrestrial biota interact with climate in a wide variety of important ways (see Figure 3-7). The most significant effects on climate may result from large-scale reorganization of terrestrial ecosystems as well as the direct effects of temperature and CO_2 increases on carbon storage.

Vegetation Albedo

Probably the most significant global feedback produced by the terrestrial biota, on a decades-to-centuries time scale, is due to changes in surface albedo (reflectivity) as a result of changes in the distribution of terrestrial ecosystems. Changes in moisture flux patterns may also be globally important if cloud properties are affected. Dickinson and Hanson (1984) analyzed this problem and found that the planetary albedo was 0.0022 higher at the glacial maximum due to differences in mean annual vegetation albedo, an increase of about 0.7% over the current albedo of 0.3. A similar result was obtained by Hansen et al. (1984) using a prescriptive scheme to relate vegetation type to climate in GCM simulations for current and glacial times. This feedback may be less important in the future than it was during the last deglaciation because of direct human effects on the surface, such as deforestation, and because the pattern of vegetation change will be different.

Carbon Storage

Other significant feedbacks are related to the role of the terrestrial biosphere as a source and sink for CO_2 and CH_4 . The carbon stored in live biomass and soils is roughly twice the amount in atmospheric CO_2 , and global net primary production (NPP) by terrestrial plants absorbs about 10% of the carbon held in the atmosphere each year. On average this is nearly balanced by decay of organic matter, about 0.5-1% of which is anaerobic and thus produces CH_4 rather than CO_2 . Small shifts in the balance between NPP and respiration, and/or changes in the fraction of NPP routed to CH_4 rather than CO_2 , could therefore have a substantial impact on the overall greenhouse forcing, because CH_4 has a much larger greenhouse effect than CO_2 per molecule. Both NPP and respiration rates are largely determined by climate, and NPP is directly affected by the CO₂ partial pressure of the atmosphere. Thus the potential for a substantial feedback exists.

Other Terrestrial Biotic Emissions

The biosphere also plays an important role in emissions of various other atmospheric trace gases that are likely to be influenced by climate change. For example, as much as half of nitrous oxide (N_2O) emissions are attributed to microbial processes in natural soils (Bolle et al., 1986). Emissions of N_2O tend to be episodic, depending strongly on the pattern of precipitation events in addition to temperature and soil properties (Sahrawat and Keeney, 1986). Thus, climate change could be accompanied by significant changes in N₂O emissions, although there is not sufficient understanding of the microbiology to predict these changes at present. The biosphere is also a key source of atmospheric non-methane

hydrocarbons (NMHCs), which play an important role in global tropospheric chemistry; the oxidation of NMHCs generates a substantial share of global carbon monoxide (CO) and therefore influences the concentration of the hydroxyl radical (OH) and the lifetime of CH_4 (Mooney et al., 1987; Thompson and Cicerone, 1986). As much as 0.5-1% of photosynthate is lost as isoprene and terpene (Mooney et al., 1987). Lamb et al. (1987) found that the volume of biogenic NMHC emissions in the United States is greater than anthropogenic emissions by about a factor of two. The ratio for the globe is much greater. Emissions, at least for isoprene and α -pinene are exponentially related to temperature (Lamb et al., 1987; Mooney et al., 1987). The first-order impact of climate change, then, would be to increase NMHC emissions, producing a positive feedback through the CO-OH-CH₄ link. The actual impact when changes in ecosystem distribution are considered is uncertain, however, as different species have very different emissions (Lamb et al., 1987).

Summary

Of the feedbacks that will come into play during the next century, the largest will almost certainly be the physical climate feedbacks discussed earlier (water vapor, clouds, ice cover, and ice and snow albedo). In comparison, each individual biogeochemical feedback discussed here is likely to be modest. Because feedback systems are non-linear, however, if the physical climate feedbacks approach the positive end of their ranges, then the overall sensitivity of the climate system would be substantially increased by even small additional feedbacks. If the physical feedbacks are weak in net, then the biogeochemical feedbacks may be less significant. Because both the physical and biogeochemical feedbacks are presently so poorly understood and because other feedbacks may be discovered, the overall equilibrium response of the climate system (discussed below) can only be specified with a fairly wide range.

The perturbations to global biogeochemical cycles reflected in the feedback processes discussed here are of great importance in their own right in addition to whatever warming they may produce. The

vegetation albedo feedback, for example, contributed only 0.3°C out of the 3.6°C global cooling in the ice-age analysis of Hansen et al. (1984), but this represented a massive change in terrestrial ecosystems. A better assessment of both the impact of climate change on biogeochemical cycles and the associated feedbacks is needed. Several aspects of the impact of climate change on biogeochemical processes are discussed in the companion report Potential Effects of Global Climate Change on the United States (Smith and Tirpak, 1989). A quantitative estimate of the impact of some of the feedbacks discussed here is presented in Chapter VI based on incorporating them in the Atmospheric Stabilization Framework developed for this study.

EQUILIBRIUM CLIMATE SENSITIVITY

When any forcing, such as an increase in the concentration of greenhouse gases, is applied to the climate system, the climate will start to change. Since both the imposed forcings and the climatic response are timedependent, and since the climate system has inertia due to the response times of the ocean, the exact relationship between the timing of the forcings and the timing of the response is In an attempt to simplify the complex. problem of understanding the sensitivity of the climate system to forcings, it has become a standard experiment to ask the question, "What would be the change in global average surface air temperature if the CO₂ concentration in the atmosphere were doubled from the pre-industrial level, all other climate forcings were held constant, and the climate became completely adjusted to the new radiative forcing?" This quantity is called the "equilibrium climate sensitivity to doubled CO_2 " and is indicated as ΔT_{2x} (see Box 3-1).

The actual path that the climate system would take to approach the equilibrium climate would be determined by the time scales of the forcings and the various elements of the climate system. This is called the "transient response" and is discussed in the next section. Because the climate system response always lags the forcing, there will always be a built-in unrealized warming that will occur in the future, even if there are no further increases in the forcing. Thus, there is certain to be some future climate response to greenhouse gases that were put into the atmosphere in the past, even if concentrations were stabilized starting today. Another way of saying this is that societal responses to the greenhouse problem that are undertaken now will be felt for decades in the future, and lack of action now will similarly bequeath climate change to future generations.

Analysis of past climate change, and model calculations of future climate change can both be used to determine ΔT_{2X} . Unfortunately, our knowledge of both past climate change and the responsible forcings are too poor to reliably determine ΔT_{2X} from past data. Wigley and Raper (1987) estimate that if all of the warming of the past 100 years was due to greenhouse gases, then ΔT_{2X} would be approximately 2°C. If however, one allows for other possible forcings, natural variability, uncertainties in ocean heat uptake the transient response, and and for uncertainties in pre-industrial greenhouse gas concentrations (see below; Hansen et al., 1985; Wigley and Schlesinger, 1985; Wigley et al., 1986; Wigley, 1989), then the climate record of the last 100 years is consistent with any ΔT_{2X} 0 and 6°C (Wigley, pers. between communication).

Due to the various problems with direct empirical approaches, mathematical models of the climate system are the primary tool for estimating climate sensitivity. While they have inherent errors, they can isolate the greenhouse forcing, and many theoretical calculations can be made to test the importance of various assumptions and various proposed feedback mechanisms. The simplest climate model is the zero-dimensional global average model described in Box 3-1. Models that are one-dimensional in the vertical, often called "radiative-convective" models, and that are one-dimensional in the horizontal, often called "energy-balance" models, are very useful for quickly and inexpensively testing various components of the climate system. In order to calculate the location of future climate change, however, and in order to incorporate all the important physical interactions, especially with atmospheric circulation, fully threedimensional GCMs are necessary. These sophisticated models solve simultaneous equations for the conservation of energy,

BOX 3-1. Simplified Modeling Framework

The concepts discussed in this chapter can be summarized in a simple zero-dimensional or one-box model of climate as discussed by Dickinson (1986):

(1)
$$C(d\Delta T/dt) + \lambda \Delta T = \Delta Q$$

where ΔQ is the climate forcing and could be due to changes in solar output, volcanoes, surface properties, stochastic processes, or greenhouse gases (as discussed in CLIMATE FORCINGS and BIOGEOCHEMICAL CLIMATE FEEDBACKS); ΔT is the change in tropospheric/mixed-layer temperature from the pre-industrial equilibrium climate; the factor λ , called the "feedback parameter" by Dickinson, gives the change in upward energy flux resulting from a change in surface temperature, ΔT , and is the net result of all the climate feedbacks (as discussed in the section on Climate Sensitivity); t is time; and C is the effective heat capacity of the Earth, which is determined by the rate of heat uptake by the ocean (C must be a function of time to account for the gradual penetration of heat into an increasing volume of the deep ocean and changing sea ice cover). In equilibrium the first term in (1) is zero, so the equilibrium climate sensitivity is simply given by

(2)
$$\Delta T = \Delta Q / \lambda.$$

For a doubling of CO₂, ΔQ is about 4.3 W/m², so the range 1.5-5.5°C of ΔT_{2x} discussed above corresponds to a range of 2.9-0.8 W m⁻² °C⁻¹ in λ . This conceptual model, with ΔQ calculated from changes in greenhouse gases and C replaced by a diffusive model of the ocean, is incorporated into the Integrating Framework used in the modeling exercises for this report (see CHAPTER VI and APPENDIX A).

momentum, mass, and the equation of state on grids with horizontal resolution ranging from 3 to 8 degrees of latitude by 3 to 10 degrees of longitude and with varying vertical resolution. The radiation schemes attempt to account for the radiatively significant gases, aerosols, and clouds. They generally use different schemes for computing cloud height, cover, and optical properties. The models also differ in their treatment of ground hydrology, sea ice, surface albedo, and diurnal and seasonal cycles (Schlesinger and Mitchell, 1985). Perhaps the most important differences lie in the treatment of oceans, ranging from prescribed sea surface temperatures, to "swamp" oceans with mixed layer thermal capacity but no heat transport, to mixed layers with specified heat transport, to full oceanic GCMs.

A series of reviews by the National Academy of Sciences (NAS, 1979, 1983, 1987) as well as the "State-of-the-Art" report of the Department of Energy (MacCracken and Luther, 1985) have concluded that the equilibrium sensitivity of climate to a $2xCO_2$ forcing (ΔT_{2X}) is probably in the range of 1.5 to 4.5°C. An independent review by Dickinson (1986) attempts to quantitatively combine the uncertainties indicated by the range of recent GCM results and concludes that the range should be broadened to 1.5-5.5°C. The GCM result of Wilson and Mitchell (1987) giving $\Delta T_{2X} = 5.2^{\circ}C$ was published after all of the reviews cited here. Dickinson's estimates of the contributions of the individual factors to climate sensitivity are shown in Figure 3-6. The largest positive feedback is from changes

in the amount and distribution of water vapor. Substantial positive feedback may also be contributed by changes in sea ice and surface albedo and clouds, although the uncertainty range includes the possibility that clouds contribute significant negative feedback. The differences in the strength of these feedbacks between models is the result of different parameterizations of the relevant processes as well as differences in the control $(1xCO_2)$ simulation (Cess and Potter, 1988). Even though the exact value of ΔT_{2X} is not known, we can study the potential impact of climate warming caused by greenhouse gases by choosing scenarios that span the range of theoretical calculations. Thus, we adopt 2-4°C as a putative one-standard deviation (1σ) confidence interval about the center of the range proposed by the National Academy of Sciences, and the range proposed by Dickinson (1.5-5.5°C) as 2σ bounds for subsequent modeling (see CHAPTER VI). When the biogeochemical feedbacks discussed above are also considered, a ΔT_{2X} as great as 8-10°C cannot be ruled out (Lashof, 1989).

THE RATE OF CLIMATE CHANGE

The Earth's surface does not immediately come to an equilibrium following an increase in radiative forcing. Excess radiation captured by the Earth heats the land surface, the ocean, and the atmosphere. The effective heat capacity of the oceanic part of the climate system, in particular, is enormous. The result is that the warming realized in any given year may be substantially less than the warming that would occur in equilibrium if greenhouse gas concentrations were fixed at their levels in that year. Hundreds of years would be required for the entire ocean to equilibrate with the atmosphere, but only the surface layer (about 100 m) is well mixed by winds and therefore tightly linked to climate in the short term. The heat capacity of the surface layer is about one-fortieth that of the entire ocean, and this layer by itself would equilibrate with a response time (the time required to reach 1 - 1/e, or 63%, of the equilibrium response) of 2-15 years, depending on the climate sensitivity and assumed mixed layer depth. The equilibration time is longer if the climate sensitivity is greater because the feedback processes that increase climate sensitivity respond to the realized changes in climate, not to the initial change in forcing (Hansen et al., 1985). When the transfer of heat from the mixed layer into the deep ocean is considered, it is impossible to characterize the oceanic response with a single time constant (Harvey and Schneider, 1985; Wigley and Schlesinger, 1985).

While the main features of ocean circulation and mixing, and therefore the rate of heat and carbon uptake, have been identified, they are not well defined or modeled on a global scale. The theory and modeling of ocean circulation are currently limited by the inadequacy of the database (Woods, 1985). The development of ocean general circulation models (OGCMs) lags significantly behind their atmospheric counterparts, mainly because it is difficult and expensive to obtain the necessary data with sufficient temporal and spatial coverage, because fewer scientists have addressed this problem and because a large amount of computer power is needed to resolve the necessary time and space scales. Due to these problems it may be a decade or more before OGCMs reach the state of development achieved by current atmospheric GCMs.

Lacking well-tested OGCMs, the main tools used so far to investigate ocean heat uptake have been highly parameterized models, very similar to those used for carbon (see CHAPTER II). These models are calibrated with data on the penetration of tracers such as tritium and carbon-14 (^{14}C) produced by atmospheric nuclear weapons tests during the 1950s and early '60s and/or with the steady-state profiles of various ocean parameters, such as natural ¹⁴C and temperature. The simplest models that yield a plausible time-dependence for heat (and carbon) uptake lump the entire ocean into two compartments: A well-mixed surface layer and a deep ocean compartment in which mixing is parameterized as a diffusive process (Box-Diffusion or BD model). This approach was introduced by Oeschger et al. (1975) for modeling carbon uptake and has been applied to ocean heat absorption by Hansen et al. (1985) and Wigley and Schlesinger (1985), among others. A more elaborate version of this model, which includes a representation of upwelling implicitly balanced by high-latitude bottom-water formation (Upwelling-Diffusion or UD model), has been used by Hoffert et al. (1980), Harvey and Schneider (1985), and Wigley and Raper (1987). The addition of an upwelling term allows the observed mean thermal structure of the ocean to be approximated (Hoffert et al., 1980), but given the highly parameterized nature of both of these models, there is no convincing reason to favor one approach over the other for modeling small perturbations to heat flows.

The response time, τ , of BD models is proportional to $\kappa (\Delta T_{2x})^2$, where κ is the diffusion constant used to characterize deep ocean mixing (Hansen et al., 1985; Wigley and Schlesinger, 1985). Data on the penetration of tracers into the ocean suggests that $\kappa = 1-2$ cm²/s (Hansen et al., 1985). Hoffert and Flannery (1985) have argued that mixing rates derived from tracers may be too high for heat because mixing rates are highest along constant density surfaces, which are nearly parallel to ocean isotherms. On the other hand, in a preliminary coupled GCM-OGCM run, Bryan and Manabe (1985) found that heat was taken up more rapidly than a passive tracer because of reduced upward heat convection. Using a range of 0.5-2 cm²/s for κ and the 1σ range for ΔT_{2x} given above (2-4°C) in the equation derived by Wigley and Schlesinger (with their recommended values for other parameters) yields $\tau = 6.95$ years.² Correspondingly, the warming expected by now, based on past increases in greenhouse gases and assuming no other climate forcings, is roughly 40-80% of the equilibrium warming (Wigley and Schlesinger, 1985). In other words, even if greenhouse gas concentrations could be fixed at today's levels, the Earth would still be subject to significant climate change that has yet to materialize. The large uncertainty surrounding ocean heat uptake, combined with uncertainty about potential climate forcings other than those from greenhouse gases, also implies that it is not possible to obtain a useful constraint on $\Delta T_{\gamma r}$ from the observed temperature record as discussed above (see also Hansen et al., 1985; Wigley and Schlesinger, 1985).

Experiments with UD models demonstrate the importance of the bottomwater formation process for the rate of ocean heat uptake. The impact of using an UD ocean model rather than a BD ocean model is

that the heat that diffuses into the thermocline is pushed back toward the mixed layer, which decreases the effective heat capacity of the ocean and the time constant for tropospheric temperature adjustment, assuming that the upwelling rate and the temperature at which bottom water is formed do not change. If the initial temperature of the downwelling water is assumed to warm as much as the mixed layer, however, then a UD model actually takes up more heat in the ocean than a BD model, leading to a larger disequilibrium between a given radiative forcing scenario and the expected realized warming. While there are reasons to think that the temperature of Antarctic bottom water will not increase as climate changes, the temperature of north Atlantic deep water could increase or decrease (Harvey and Schneider, 1985). Furthermore, there is no reason to assume that the rate of bottom-water formation will remain constant The tropospheric as climate changes. temperature could even overshoot equilibrium if the average bottom-water temperature cools as the surface temperature warms or if the upwelling rate increases with warming (Harvey and Schneider, 1985). One must also recognize the potential for sudden reorganizations of the ocean-atmosphere circulation system as suggested by Broecker (1987), which could lead to discontinuous, and perhaps unpredictable, changes in climate that cannot be included in the models used in this report.

Another major limitation of the BD and UD models generally used to analyze the climate transient problem is that they have limited or no spatial resolution (at best hemispheric, land-sea) and thus cannot consider spatial heterogeneity in either the magnitude or rate of climate change. Work at the NASA Goddard Institute for Space Studies (Hansen et al., 1988) has produced one of the few three-dimensional, time-dependent analyses of climate change that have been published to date. This study employed three simple, but reasonably realistic, scenarios of future greenhouse gas concentrations and volcanic eruptions. The results suggest that the areas where warming is initially most prominent relative to interannual variability are not necessarily those where the equilibrium warming is greatest. For example, low-latitude ocean regions warm quickly

because ocean heat uptake is limited by strong stratification in these regions. Warming is also prominent in high-latitude ocean areas where a large equilibrium warming is expected due to increased thermal inertia as sea ice melts. Global average temperatures are used in this report as an indicator of the rate and magnitude of global change but, as these results emphasize, it must be recognized that major variations among regions are a certainty.

CONCLUSION

The changing composition of the atmosphere will in turn drive significant changes in the Earth's climate. These changes may have already begun, but because of the uncertainties in temperature data sets and the complexity of the interaction between climate sensitivity and the transient response, definitive predictions are subject to a good deal of controversy at this time. Whether next year is warmer or cooler than this year, however, has no direct bearing on how the greenhouse effect should be viewed. Internal fluctuations or countervailing forcings may temporarily mask the warming due to increasing concentrations of greenhouse gases or make the climate warmer than expected solely from greenhouse warming. Therefore, to derive our estimates of the magnitude and rate of change that can be expected during the next century we must continue to rely on model calculations, which indicate that by early in the next century the Earth could be warmer than at any time during the last million years or more, and that the rate of change could be unprecedented in Earth history.

NOTES

1. The thermocline starts at the base of the mixed layer and extends to a depth of about 1000 m. It is characterized by a rapid decrease in temperature with increasing depth, which inhibits mixing in the water column because the colder deeper water is denser than the warmer overlying water.

2. It is important to note that the actual response does not correspond to exponential decay with a single time constant, so that while τ gives the time required for one e-folding and is a useful measure, it would not apply to subsequent e-foldings (the time constant would be substantially longer) and must be interpreted with care.

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CHAPTER IV

HUMAN ACTIVITIES AFFECTING TRACE GASES AND CLIMATE

FINDINGS

Various human activities affect the Earth's climate by altering the level of trace gases in the atmosphere. These activities include fossil-fuel consumption; industrial processes; land-use change, particularly deforestation; and agricultural practices such as waste burning, fertilizer use, rice production, and animal husbandry. Economic development and population growth are key factors affecting the level of each activity.

• Population levels and growth rates have increased tremendously over the last 200 years. Between 1650 and 1980, the global population doubling time shrank from 200 to 35 years. At the beginning of this century, global population was about 1.6 billion; in 1987, it reached 5 billion. By the early part of the next century total population is likely to reach 8 billion. The rate of population increase is most acute in the developing regions, particularly Africa and Asia where annual rates of growth exceed 2%.

• Fossil-fuel combustion emits carbon dioxide (CO_2) and other radiatively important gases and is the primary cause of the buildup of greenhouse gases in the atmosphere. Commercial energy consumption currently accounts for more than 5 of the 6-8 billion tons of carbon as CO_2 emitted to the atmosphere annually from anthropogenic sources (i.e., as a result of human activities). Between 1950 and 1986, annual global fossilfuel consumption grew 3.6-fold and annual CO_2 emissions grew 3.4-fold.

• Emissions of other trace gases due to fossil-fuel consumption are more uncertain. Approximately 0-2 million tons nitrogen as nitrous oxide, 20 million tons nitrogen as nitrogen oxides, and 180 million tons carbon as carbon monoxide are emitted annually from fossil-fuel combustion. Leaking and venting of natural gas contributes approximately 20-50 million tons methane (CH₄) annually to the atmosphere, and coal mining contributes approximately 25-45 million tons CH₄.

Three significant non-energy sources of greenhouse gases are associated with industrial activity: production and use of chlorofluorocarbons (CFCs), halons, and chlorocarbons; waste disposal in landfills; and cement manufacture. Production of CFC-11 and CFC-12 grew 4.7-fold between 1960 and 1985. Consumption of major CFCs and halons reached nearly one million tons in 1985. An international agreement (the Montreal Protocol), however, to reduce future production of certain CFCs and limit growth in the production of certain halons, came into force on January 1, 1989. The London Amendments, negotiated in June 1990, strengthen the Protocol by completely phasingout CFCs, halons, carbon tetrachloride, methyl chloroform, and encouraging limits on HCFCs. Anaerobic decay of organic wastes in landfills currently contributes approximately 30-70 million tons of CH_4 to the atmosphere Cement production, which has annually. increased sevenfold since the 1950s. contributed approximately 134 million tons carbon as CO_2 to the atmosphere in 1985.

Land-use change has resulted in . substantial emissions of greenhouse gases to the atmosphere. Since 1850, approximately 15% of the world's forests have been converted to agricultural and other land uses. Currently, deforestation contributes between one-tenth and one-third of the total anthropogenic CO₂ emissions to the atmosphere, i.e., between 0.4 and 2.6 billion tons of carbon. Between one-quarter and onehalf of the world's swamps and marshes also have been destroyed by man. Wetlands currently contribute approximately one-fifth of the total CH₄ emissions to the atmosphere; continued changes to wetlands could significantly alter the global CH_{4} budget. Biomass burning, in addition to contributing to atmospheric concentrations of CO_2 contributes approximately 10-20% of total annual CH_4 emissions, 5-15% of the nitrous oxide emissions, 10-35% of the nitrogen oxide emissions, and 20-40% of the carbon monoxide emissions.

Three agricultural activities directly result in major contributions to atmospheric emissions of greenhouse gases: animal husbandry, rice cultivation, and nitrogenous fertilizer use. Domestic animals, which produce CH_4 as a by-product of enteric fermentation, currently contribute approximately 65-85 million tons of CH₄ annually. Over the past several decades, domestic animal populations have grown by up to 2% annually. Methane is also produced by anaerobic decomposition of organic material in rice paddies. Currently, about one-fifth of annual CH_4 emissions, or between 60 and 170 million tons, comes from rice cultivation. Rice production has grown rapidly since the mid-1900s due to increases in crop acreage, double cropping, and higher yields. Between 1950 and 1984 rice production increased nearly threefold, and harvested area grew by about 70%. Use of nitrogenous fertilizers results in nitrous oxide emissions, either directly from

the soil, or indirectly from groundwater. Global use of organic and inorganic fertilizers has risen markedly, and nitrogen-based fertilizers increased their market share of total inorganic fertilizer consumption from 28% in 1950 to 64% in 1981. Nitrogenous fertilizer use may contribute between 0.14 and 2.4 million tons nitrogen as nitrous oxide per year to the atmosphere.

• In addition to the human activities that directly affect trace gas emissions, future concentrations of greenhouse gases will be influenced by feedback processes resulting from humans living in a world that has undergone climate change. Two potential feedbacks of increased temperatures, which may counteract each other to some extent, are increased energy demand for air conditioning in the summer, and decreased energy demand for heating in the winter.

INTRODUCTION

As discussed in Chapter III, the Earth's climate has been in a constant state of change throughout geologic time due to natural perturbations in the global geobiosphere. However, various human activities have the potential to cause future global warming over a relatively short amount of time. These activities, which affect the Earth's climate by altering the concentrations of trace gases in the atmosphere, include energy consumption, particularly fossil-fuel consumption; industrial processes (production and use of chlorofluorocarbons. halons. and chlorocarbons, landfilling of wastes, and cement manufacture); changes in land-use particularly deforestation patterns, and biomass burning; and agricultural practices (waste burning, animal husbandry, rice cultivation, and nitrogenous fertilizer use). Population growth is an important underlying factor affecting the level of growth in each activity.

This chapter describes how the human activities listed above contribute to atmospheric change, the current pattern of each activity, and how levels of each activity have changed since the early part of this century. Figure 4-1 illustrates the regional contributions to the increase in greenhouse forcing that occurred in the 1980s. Almost 50% of the forcing is attributable to activities in the United States, the USSR, and the European Economic Community (EEC). As background to the discussion of trace-gasproducing activities, we first provide an overview of population trends. This historical perspective is meant to serve as a framework for the discussion of possible future scenarios of trace gas emissions in Chapter VI.

HISTORICAL OVERVIEW OF POPULATION TRENDS

One of the major factors affecting trends in greenhouse gas emissions is the increase in human population. As population levels rise, increasing pressures are placed on the environment as the larger population strives to feed and clothe itself and achieve a higher standard of living. Without changes in the methods used to meet people's needs, higher population levels invariably lead to increased emissions of greenhouse gases.

Global Population Trends

Not only has global population grown rapidly over the past few centuries, but the rate of growth has also increased (see Figure 4-2). World population in the year 1 A.D., approximately 0.25 billion, doubled by 1650 (Wagner, 1971). By 1850 (i.e., 200 years later), global population had roughly doubled again to 1.1 billion. The global population doubling time has continued to decline -- 80 years later, in 1930, world population was 2 billion. By 1975 global population had reached 4 billion, and according to some estimates the population will double once again within 35 years (world population reached 5 billion in 1987). Despite recent declines in the world's annual population growth rate (IIED and WRI, 1987), world population is expected to continue to grow rapidly. Several studies estimate that world population will exceed 8 billion by 2025 (Zachariah and Vu, 1988; U.S. Bureau of the Census, 1987). Such rapid population growth can be expected to result in increasing pressure on the global environment, particularly as the burgeoning human population strives to improve its living standards through economic growth.

Population Trends by Region

The rapid population growth in recent decades has not occurred uniformly around the world (see Figure 4-2). Between 1950 and 1985, population in developed countries increased by 41%, compared to 117% in developing countries (IIED and WRI, 1987). Recent trends indicate these differences will continue: annual growth rates in the developed countries are generally less than 1%, while many developing countries continue to experience rates of growth between 2 and 3% (see Table 4-1). These higher growth rates in the 20th century in developing countries have been due primarily to the combined effects of declining death rates and continued high birth rates. Unfortunately, the countries that are experiencing the most explosive population growth rates are often the ones likely to suffer the most severe environmental stresses due to climate change and the ones least able to adapt to or accommodate these effects.

FIGURE 4-1





Figure 4-1. Estimated regional contribution to greenhouse forcing for the 1980s, based upon regional shares of current levels of human activities that contribute to greenhouse gas emissions. (Sources: U.S. EPA, 1988; United Nations, 1987; U.S. BOM, 1985; IRRI, 1986; FAO, 1986a, 1987; Bolle et al., 1986; Rotty, 1987; Lerner et al., 1988; Seiler, 1984; WMO, 1985; Hansen et al., 1988; Houghton et al., 1987; Matthews and Fung, 1987.)





Figure 4-2. Since about 1850, global population has grown at increasingly rapid rates. In 1850, the population doubling time was approximately 200 years; by 1975, the doubling time had declined to approximately 45 years. Most of the growth has occurred in the developing world, particularly Asia. (Sources: Matras, 1973; Hoffman, 1987.)

TABLE 4-1

Regional Demographic Indicators

Region	Total Fertility ^a 1980-85	Infant Mortality ^b 1980-85	Annual Population Growth Rate 1980-85 (percent)
			······································
North America	1.83	11	0.90
Europe	1.88	15	0.30
East Asia	2.34	36	1.22
Oceania	2.65	31	1.51
Caribbean	3.34	65	1.53
Southeastern Asia	4.11	73	2.05
Latin America	4.17	61	2.34
Southern Asia	4.72	115	2.14
Western Asia	5.22	81	2.79
Africa	6.34	112	2.92
World Average	3.52	60	1.67

^a The total fertility rate is the average number of children that a woman bears in a lifetime.

^b The infant mortality rate is the average number of infant deaths (deaths before the first birthday) per 1000 live births.

Source: Adapted from IIED and WRI, 1987.

Industrialized Countries .

Population growth rates in the industrialized countries are substantially lower than in the developing world. For example, while most developing countries contend with growth rates that will double their populations within 20-40 years, current growth rates in North America and Europe will lead to a doubling within about 100 years and 250 years, respectively (IIED and WRI, 1987). This trend toward lower growth rates is due to many complex economic and social factors, including the changing role of women in the labor force, the higher economic costs of child rearing, and the reduced need for children as a labor pool.

Developing Countries

The highest rates of population growth are in the developing countries: from 1950 to 1985, developing countries increased their share of the world's population from 66.8% to 75.6% (IIED and WRI, 1987). During this time Asia's population grew from 1.3 to 2.7 billion, Africa's from 224 to 555 million, and Latin America from 165 to 405 million. Key trends are summarized below.

Africa. Africa currently has the highest fertility rates and population growth rates in Its growth rate has increased the world. recently: between 1955 and 1985, Africa's average annual growth rate increased from 2.3% to 2.9%. The total fertility rate (i.e., average number of children that a woman bears in a lifetime) is six or higher in 38 African countries, most of which have experienced declining infant mortality rates (infant deaths per thousand live births) over the past 20 years (IIED and WRI, 1987). For example, in Kenya, where the total fertility rate is 7.8, the infant mortality rate fell from 112 to 91 between 1965 and 1985. Between 1965 and 1985, the crude birth rate (births per thousand population) for Kenya grew by 4.7%, while the crude death rate fell by 37.7%. The average annual growth rate reached 4.1% in the 1980s (World Bank, 1987). The United Nations expects the African population to continue to grow rapidly, with the average annual growth rate increasing to 3% in 1990 (United Nations, 1986).

From 1850 to 1950, Asia Asia. experienced the largest increase in population in the world (Ehrlich and Ehrlich, 1972). Rates of growth have continued at high levels -- annual growth rates since 1960 have exceeded 2%. These rates are likely to remain high in several Asian countries in future years (United Nations, 1986). For example, China currently is the most populous country in the world, with 22% of the world's total population (Ignatius, 1988). Although its strong population policy of one child per family helped to halve the 2% annual growth rates of the 1960s, growth rates have recently turned upward, approaching 1.5% annually. This trend of growth could lead to population levels in China in excess of 1.7 billion by 2025.

India's population has also been rapidly expanding. It is the second most populous country in the world (United Nations, 1986), with 765 million people as of 1985. India's rate of growth has been relatively high this century, although it has declined in recent years; in 1960 its annual rate of growth was 2.3%, but has since dropped to 1.7% (IIED and WRI, 1987). Despite this recent decline, its population is expected to grow for many years; for example, the United Nations estimates that India's population will be over 1.2 billion by 2025 (United Nations, 1986).

Latin America. Latin America currently has one of the highest population growth rates in the world: from 1980 to 1985, the annual rate of growth averaged 2.3% for the region (IIED and WRI, 1987), although these rates of growth varied substantially between countries. Argentina, Chile, and Uruguay have the lowest growth within Latin America, while countries such as Bolivia, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Paraguay, and Venezuela have annual population growth rates that exceed 2.5%. Fertility rates have been declining throughout the region due to industrialization, urbanization, rising incomes, and official population policies, although one source estimates that Latin America's share of world population will nonetheless increase from 8.4 to 9.5% between 1985 and 2025 (IIED and WRI, 1987). The two population projection sources used in this report (U.S. Bureau of the Census, 1987; Zachariah and Vu, 1988; see CHAPTER VI) project that by

2025, Latin America's share of world population will grow to 9.1% and 8.7%, respectively.

ENERGY CONSUMPTION

The major human activity affecting trace gas emissions is the consumption of energy, particularly energy from carbon-based fossil fuels. As discussed in Chapter II, global carbon dioxide (CO_2) emissions from anthropogenic sources currently range from 6 to 8 petagrams (Pg) of carbon (C) annually, with commercial energy consumption accounting for approximately 65-85% of this total.1 Non-commercial (biomass) energy consumption accounts for approximately 7%. Energy consumption and production also produce substantial amounts of other greenhouse gases, including carbon monoxide (CO), methane (CH₄), nitrogen oxides (NO_x, i.e., nitric oxide [NO] and nitrogen dioxide $[NO_2]$), and nitrous oxide (N_2O) .

This section explores the role of energy consumption in climate change. We first discuss the world's increasing reliance on fossil fuels, the roles that fossil-fuel production (e.g., coal mining and oil drilling) and fossil-fuel combustion play in the emission of trace gases to the atmosphere, and the implications of the continuation of current energy consumption patterns on future global warming.

History of Fossil-Fuel Use

Prior to the discovery and development of fossil fuels (coal, oil, and natural gas), people relied on readily-available energy resources such as wood and other forms of biomass (i.e., living matter), as well as water and wind, to satisfy their basic energy needs. Since the beginning of the 19th century, fossil fuels have played an increasingly important role in the world economy, particularly for developed countries, by providing the energy required for industrial development, residential and commercial heating, cooling, lighting, and transportation services. Fossil fuels now provide about 85% of the world's total energy requirements. This dependence on fossil fuels is greatest in industrialized countries, where over 95% of all energy needs are provided by fossil fuels, compared with about 55% in developing countries (Hall et al., 1982).³

Global consumption of fossil fuels has increased rapidly over the past century as human populations and their economic activities have grown. Since 1950, global primary energy consumption has increased nearly fourfold (see Figure 4-3), with energy consumption per capita approximately doubling. In 1985, 42% of global energy demand was supplied by liquid fossil fuels (primarily petroleum); solid fuels (coal) supplied 31%, natural gas, 22%, and other fuels combined accounted for 5% of the These relative proportions market share.⁴ have changed considerably since 1950, when coal supplied 59% of total commercial energy requirements, liquids, 30%, natural gas, 9%, and other fuels, 2%.

The increase in fossil-fuel consumption over the last century has caused a substantial increase in the amount of CO_2 emitted to the atmosphere. Carbon dioxide emissions from fossil fuels grew from less than 0.1 Pg C annually in the mid-nineteenth century, to about 5.4 Pg C in 1986 (see Figure 4-4).⁵ This rate of increase is about 3.6% per year and is the major reason why atmospheric CO_2 concentrations increased from about 290 ppm in 1860 to about 348 ppm as of 1987 (Rotty, 1987). Currently fossil-fuel combustion also contributes approximately 0-2 teragrams of nitrogen (Tg N) as N₂O, 20 Tg N as NO_x and 180 Tg C as CO to the atmosphere each year.

In recent decades there has also been a significant shift in global energy-use patterns. In 1950, countries belonging to the Organization for Economic Cooperation and Development (OECD) consumed about threefourths of all commercial energy supplies, the centrally-planned economies of Europe and Asia, 19%, and developing countries, 6% (United Nations, 1976, 1983).6 **Bv** 1985 OECD countries consumed just over one-half of all commercial energy globally, while the Asian centrally-planned European and economies and the developing countries had increased their relative shares to 32% and 15%, respectively (see Figure 4-5). Between 1950 and 1985, commercial energy use per capita in the OECD grew from 93 to 189 gigajoules per capita (GJ/cap) (103%), in centrally-planned economies from 16 to 59 GJ/cap (269%), and in the developing countries from 3 to 18 GJ/cap (500%).⁷ The



FIGURE 4-3

Figure 4-3. Global demand for fossil fuels has more than tripled since 1950. Today, about 85% of the world's energy needs are met by fossil fuels. (Sources: United Nations, 1976, 1982, 1983, 1987.)



Figure 4-4. Carbon dioxide emissions from fossil-fuel consumption have grown from less than 0.1 Pg C in the mid-1850s to approximately 5.4 Pg C in 1986. This is the major reason why the atmospheric concentration of CO_2 increased from approximately 290 ppm in 1860 to approximately 348 ppm in 1987. (Sources: Rotty and Masters, 1985; Rotty, 1987, pers. communication.)







Figure 4-5. Primary energy use by region. Between 1950 and 1985, the share of global energy demand for the OECD declined, while that for the centrally-planned and developing economies increased. (Sources: United Nations, 1982, 1987.)

proportion of energy consumed by the OECD is expected to decline further as the developing world continues to experience more rapid population growth and economic development and, thus, significantly expands its energy requirements (see CHAPTER VI).

Current Energy-Use Patterns and Greenhouse Gas Emissions

The allocation of energy consumption among end-use sectors varies considerably from one region to the next. Figure 4-6 summarizes 1985 end-use energy demand (for both commercial and non-commercial, or biomass, fuels) by sector for the OECD countries, the centrally-planned economies of Asia and Europe (including China and the USSR), and the developing countries. Whereas the OECD split is approximately one-third industrial, one-third transportation, and one-third residential/commercial, centrallyplanned economies of Asia and Europe consume more than 50% of their energy in the industrial sector.

These energy consumption patterns partly reflect the basic differences in the structure of economic activity at the current stage of each region's economic development. The centrally-planned economies and the developing countries devote a greater share of their energy requirements to the industrial sector because they are at a stage of economic development where energy-intensive basic industries account for a large share of total while infrastructure in the output, transportation and commercial sectors has not been extensively developed. In the OECD, transportation consumes a larger share of total energy compared with other regions, primarily because of the large number of automobiles in the OECD. For example, in the U.S. there are 550 cars and light trucks/1000 people, compared with 60 cars and light trucks/1000 people in the USSR, and 6 cars and light trucks/1000 people in China. Also, biomass is very important to the residential energy requirements of the developing economies compared with those of industrialized countries; the industrial sector is the major consumer of fossil fuels in most developing countries.

Emissions by Sector

The differences among regions in terms of the share of energy consumed by each sector and the types of applications for which the energy within each sector is used can have a major impact on the amount and types of greenhouse gases emitted. This section discusses how emissions of greenhouse gases vary as a result of differences in type of fossil energy consumed and combustion technology used.

Electric Utility Sector. Energy is increasingly desired in the form of electricity. The amount of greenhouse gases produced from electricity generation is a function of the type of primary energy used to produce the electricity and the production technology. For example, nuclear, hydroelectric, or solar primary energy sources emit little or no greenhouse gases, while fossil fuels generate substantial quantities of CO_2 , as well as other gases (see Table 4-2). The amount of greenhouse gas emissions varies according to the type of fossil fuel used because of inherent differences in the chemical structure of the Additionally, the level of emissions fuels. varies as a function of production efficiency. For example:

Coal-fired powerplants produce about two to three times as much CO_2 as natural gas-fired units per unit of electricity generated (330 kg CO₂/GJ for a pulverized coal wallfired unit compared with 120 kg CO_2/GJ for a combined cycle gas-fired unit). Oil-fired units produce more CO_2 than natural gas units produce, but less O_2 than coal-fired units produce. Within fuel types the emission levels may vary. For example, when natural gas is used as the fuel, combined cycle units produce about 40% lower CO_2 emissions than simple cycle units (see CHAPTER V) because of the greater generating efficiency obtained through the use of these technologies. Similarly, coalfired fluidized bed units produce less NO_x emissions than do coal-fired cyclone units because the higher operating temperatures typical of cyclone-units are more conducive to NO, formation.

FIGURE 4-6



Figure 4-6. End-use energy demand by sector for three global regions. While energy demand in the OECD countries is split almost equally among the three sectors, over 50% of the energy in the centrally-planned countries is consumed by the industrial sector, and almost 50% of the energy in the developing countries is consumed by the residential/commercial sector. (Sources: Sathaye et al., 1988; Mintzer, 1988.)

TABLE 4-2

Emission Rate Differences by Sector

Efficiency Source NO_x CO CO CH₄ (%) N₂O Electric Utility (g/GJ delivered electricity) 42.0 120,300 70 Gas Turbine Comb. Cycle 13 20 110 191,400 20 Gas Turbine Simp. Cycle 26.4 30 **Residual Oil Boilers** 32.4 230,000 43 2.2 44 Coal - F. Bed Comb. Cycle 35.0 290,000 NA 1.8 40 45 Coal - PC Wall Fired 31.3 330,000 42 2.0 330,000 42 2.0 45 Coal - PC Cyclone 31.3 222 51 Coal - Integrated Gas 27.3 253,600 NA Industrial (g/GJ delivered steam for boilers; energy output for others) Boilers Coal-Fired 80 130,000 110 2.9 18 **Residual Oil-Fired** 85 88,000 17 3.3 16 Natural Gas-Fired 85 57,000 18 1.5 3.5 Kilns - Coal 65-75 300,000-350,000 75 2 1 Dryer - Natural Gas 30-65 75,000-170,000 10 1 NA 30-65 100,000-240,000 15 NA Dryer - Oil 1 30-65 155,000-340,000 170 Dryer - Coal 1 NA Residential/Commercial (g/GJ energy output) [150,000] 17,600 70 Wood Stoves 50 NA 50 198,000 3,400 Coal Stoves NA NA Distillate Oil Furnaces 75 111,000 17 7 NA Gas Heaters 70 101,000 13 1 NA Wood Boilers 67.5 [138,000] 280 21 6 2.7 Gas Boilers 80.9 61.800 10.6 1.4 Residual Oil Boilers 84.9 86.000 19 1.8 14 Coal Boilers 75.9 135,000 244 13 16 Transportation (g/GJ energy input) Rail NA 69,900 570 13 NA Jet Aircraft NA 72,800 120 2 NA 70.000 320 20 NA NA Ships 54,900 10,400 36 0.5 Light Duty Gasoline Vehicle NA 2 Light Duty Diesel Vehicle NA 73,750 340 20 7

(grams per gigajoule)*

400

640

590

690

1,400

2,600

760

390

180

71

500

52

160

215

190

170

65

61 47

53

183 295

1,640

290

830

400

300

140

All emission rates are based on total molecular weight.

NA = Not Available

N. Gas Vehicle

Light Duty Compressed

 $[] = No Net CO_2$ if based on sustainable yield

Source: Radian Corporation, 1990; except N₂O data, which is based on unpublished EPA data. N₂O emission coefficients are highly uncertain and currently undergoing further testing and review.

50,200

4

120

NA

Industrial Sector. The industrial sector includes mining, construction, and manufacturing, which are some of the most energy-intensive economic activities. Energy consumption in this sector can be subdivided into four categories:

• Boilers -- Boilers produce steam for many different purposes, including machine drive, on-site electricity production, highpressure cleaning, and process requirements. Virtually any fuel can be consumed to produce steam (e.g., fossil fuels, biomass, hazardous wastes, by-product wastes, etc.). In the U.S., boilers consume about 30% of all industrial energy.

• Process Heat -- Many industrial processes that do not use steam require the use of some form of heat during production. Examples of process heat applications include ovens, furnaces, dryers, melters, and kilns. The degree of flexibility in fuel choice a consumer may have depends on the process heat application -- some applications may use technologies or production processes that require a particular fuel.⁸ Process heat applications consume about 40% of the energy in the U.S. industrial sector.

• Feedstocks -- Fuels may be used as a raw material for the production process. Examples of such applications include the conversion of metallurgical coal to coke for use in the manufacture of steel, natural gas for fertilizer production, and petroleum for asphalt. It is usually very difficult to switch to alternative fuels with these applications. In the U.S., feedstocks consume about 15% of industrial energy.

• Other -- This category consists primarily of industrial activities requiring electricity, e.g., motors and lighting. These applications account for 15% of all energy consumed by U.S. industry.

The amount of greenhouse gas emissions generated from industrial energy consumption is a function of fuel type and the process in which it is consumed (see Table 4-2 for emissions from selected industrial applications).

Residential and Commercial Sectors. In the residential and commercial sectors the

main end-use applications for energy are heating, cooling, cooking, and lighting. The form and amount of energy used to meet these needs varies, as summarized in Table 4-3 for the U.S. and South/Southeast Asia. Ĭn developing countries, most of the energy in these two sectors is consumed for cooking purposes, with consumers relying on biomass or kerosene for fuel. In industrialized countries, however, space heating and water heating consume the most energy, which is supplied primarily by fossil fuels and, to some extent, electricity; gas and electricity are the primary energy forms for cooking in industrialized countries. Because of the wide variety of end-use applications, types of energy consumed, and conversion efficiencies in the residential and commercial sectors it is difficult to generalize about emission trends in these sectors; for illustrative purposes, emission coefficients for several major applications in industrialized countries are listed in Table 4-2.

Transportation Sector. As consumers become wealthier, the absolute quantity and share of energy used in the transportation sector increases. For example, as discussed earlier, in many developing countries, such as China, the transportation sector consumes a much smaller portion of the country's energy requirements than the portion consumed by this sector in industrialized countries, such as the United States. Energy requirements in the transportation sector are typically met with fossil fuels, particularly petroleum-based products such as gasoline, diesel, or jet fuel. For example, in 1985 countries belonging to the OECD met 91% of their transportation energy requirements with oil-derived products, 8% with electricity, and the remaining 1% with natural gas and coal (OECD, 1987). As countries become wealthier, increased use of petroleum to meet transportation needs can significantly increase greenhouse gas emissions to the atmosphere (see Table 4-2).

The amount and type of greenhouse gases emitted can also be affected by the transportation technology. For example, gasoline vehicles produce about 25% less CO_2 on an energy input basis than do diesel vehicles, while producing substantially more CO. However, the CO is eventually oxidized to CO_2 , so the CO_2 emissions attributable to gasoline vehicles are comparable to those of

TABLE 4-3

End-Use Energy Consumption Patterns for the Residential/Commercial Sectors

		Type of Energy		
End-Use	Biomass	Fossil Fuels	Electricity	Total
South/Southeast Asia				
Heating Cooling Cooking Lighting	0 0 75 0	$\begin{array}{c} 16 \\ 0 \\ 3 \\ 1 \end{array}$	NA NA NA <u>NA</u>	NA NA NA NA
TOTAL	75%	20%	5%	100%
United States				
Heating Cooling Cooking Lighting Other	<1 0 0 0	59 0 7 0 0	8 6 3 7 10	67 6 10 7 10
TOTAL	<1%	66%	34%	100%

(% of total energy)

Sources: Sathaye et al., 1989; Mintzer, 1988; EIA, 1987; Leon Schipper, pers. communication.

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diesel vehicles. Also, the efficiencies of diesel engines are generally greater than those of gasoline engines for a similar vehicle, implying that diesel vehicles would actually have lower effective CO_2 emissions per mile travelled. Similarly, vehicles powered with compressed natural gas would emit CO_2 and CO at lower levels than would either gasoline or diesel vehicles, although CH_4 emissions might be higher.

Fuel Production and Conversion

Significant quantities of greenhouse gases are emitted during the production of energy and its conversion to end-use energy forms. Several major components of these fuel production and conversion processes are discussed below.

Natural Gas Flaring, Venting, and Leaking. During the production of oil and natural gas, some portion of natural gas, which is mostly methane, is typically vented to the atmosphere (as CH_4) or flared (thereby producing CO_2) rather than produced for commercial use. Venting typically occurs natural gas drilling and well during maintenance operations to avoid pressure buildup, to test well drawdown, and during required maintenance at existing production wells. Flaring is most common in conjunction with oil production when no market can be found for the natural gas associated with oil reservoirs. In some circumstances, the gas may be vented rather than flared. The amount of natural gas flared and vented is highly uncertain. On average, it is estimated to be about 2-3% of global natural gas production, although in some regions virtually all of the natural gas may be vented or flared, while in other regions (like the U.S.) the total amount flared or vented is less than 0.5% of total production (EIA, 1986).⁹ Currently, approximately 50 Tg of CO_2 are released to the atmosphere from flaring of natural gas (Rotty, 1987).¹⁰

Leaks of natural gas also occur during the refining, transmission, and distribution of the gas. These leaks may occur at the refinery as the gas is cleaned for market, from the pipeline system during transportation to the end user, or during liquefaction and regasification if liquified natural gas (LNG) is produced. About 20-50 Tg of CH_4 is released to the atmosphere each year from leaking and venting of natural gas (Crutzen, 1987; Cicerone and Oremland, 1988).

Coal Mining. As coal forms, CH₄ produced by the decomposition of organic material becomes trapped in the coal seam. This CH_{4} is released to the atmosphere during coal extraction operations. The amount of CH₄ released by coal mining varies depending on factors such as depth of the coal seam, quality of the coal, and characteristics of the geologic strata surrounding the seam. The amount of CH_{4} emitted as a result of coal mining is highly uncertain, with estimates ranging from 25 to 45 Tg per year (Cicerone and Oremland, 1988). If coal mining operations intensify, the quantity of methane released as an indirect result of mining is expected to increase at a comparable rate.

Synthetic Fuel Production. As conventional petroleum resources are depleted, some of the demand for liquid (oil and natural gas liquids) and gaseous (natural gas) fuels may be met by synthetic fuels. Although there is currently little synthetic fuel produced in the world, processes have been developed to convert relatively abundant solid energy resources such as coal, oil shale, and tar sands to liquid or gaseous products that could be consumed in the same end-use applications as conventional oil and gas.

Significant amounts of energy are typically required to produce synthetic fuels. The conversion process produces greenhouse gas emissions, particularly CO_2 , so that the net emissions per unit of energy for synthetic fuels are greater than those for conventional fossil fuels. For example, the CO_2 emissions from production and consumption of synthetic liquid fuels from coal are about 1.8 times the amount from conventional liquid fuels from crude oil (Marland, 1982). Table 4-4 lists emission rates for both conventional fossil fuels and synthetic fuels produced from coal and shale oil.

Future Trends

As shown in Figure 4-4, the quantity of CO_2 emitted to the atmosphere as a result of the combustion of fossil fuels has increased dramatically in the last century. This increase in fossil-fuel-produced CO_2 emissions is the

TABLE 4-4

• • • • • • • • • • • • • • • • • • •		
Fuel	(kg C/10 ⁵ J)	Notes
Conventional Fossil Fuels (rates	for consumption)	
Natural Gas	13.5-14.2	
		Differences are partly attributable to
Liquid Fuels from Crude Oil	18.2-20.6	product mix, i.e., gasoline versus fuel
•		oil and gasoline
Bituminous Coal	23.7-23.9	
Synthetic Fuels (rates for produc	tion and consumption)	
Syndictic Fuels (lates for produc	and consumption)	
Shale Oil	104.3	High temperature, 10 gal/ton shale
	66.4	High temperature, 25 gal/ton shale
	47.6	Modified in situ, 28 gal/ton shale
	28.4	Low temperature retorting
Liquids from Coal	51.3	Gasoline from methanol using Mobil
		MTG process
	41.8	Sasol-type technology, Eastern coal
	39.9	FHP process
	38.6	Exxon-Donor Solvent, Eastern coal
	37.2	H-coal
	31.9	Generic 75% thermal efficiency
	30.5	SRC-II, liquid and gas products
Lich Dtu Cos from Cost	40.7	I urgi
righ Blu Gas from Coal	40.7	Luigi
	40.1	riygas
	36.2	Generic 66% inermal emciency
	32.7	Via synthesis gas with by-product credits

Carbon Dioxide Emission Rates for Conventional and Synthetic Fuels

Source: Marland, 1982.

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main factor that has led to an increase in atmospheric CO_2 concentrations -- from about 280 parts per million by volume (ppm) in preindustrial periods to about 350 ppm today. As discussed in Chapter II, future CO_2 concentrations will depend on many factors, but most important will be the rate of growth in energy demand and the type of energy that is consumed in order to satisfy this demand.

The Fossil-Fuel Supply

Higher levels of energy demand will produce higher levels of greenhouse gas emissions if the demand is satisfied with fossil fuels. As indicated above, fossil fuels currently supply a majority of the world's energy needs, and it seems likely that fossil fuels will continue to play a key role in the world's energy supply picture for decades to come. However, supplies of fossil fuels are not unlimited. Resource and reserve estimates for coal, oil, and gas are listed in Table 4-5. A resource is any mineral supply; a reserve is a mineral supply that is known with a high amount of geologic certainty. A reserve may or may not be presently economical to extract; if not, it is likely to become economical in the future. The estimates of the lifetimes of fossilfuel reserves are based on 1985 rates of production. The lifetime estimates of fossilfuel resources are based on linear and exponential extrapolations of recent energy (described below). Despite demand uncertainties about the size of the resource base and the rate at which the resource base may be depleted, it is clear from a technical standpoint that the consumption of fossil fuels could continue for a very long time. As will be discussed in Chapter VI, if the world continues to rely on fossil fuels to meet the majority of its energy needs, the amount of carbon emitted to the atmosphere may be many times greater than current levels.

Future Energy Demand

The future rate of energy demand depends on many variables, including the rate of population growth, the rate of economic growth, energy prices, the types of energy services demanded by consumers, the type and efficiency of technology used, and the type and amount of energy supplies available (see CHAPTER VI). Two hypothetical cases based

on crude extrapolations illustrate potential upper and lower bounds on future energy demand (see Figure 4-7) and the lifetime of fossil-fuel resources (see Table 4-5). For example, from 1950 to 1973, the average annual growth rate in energy demand was If this rate of growth were 5.2%. exponentially extrapolated to 2050, global energy demand would be about 254 terawatts (TW) (or equivalently about 8000 exajoules [EJ]), almost 30 times the 1985 level.¹¹ This amount of energy demand could lead to an increase in annual CO₂ emissions from the current 5.2 Pg C to about 140 Pg C in 2050, assuming that this demand is met by consumption of fossil fuels. Cumulative energy demand for 1985 through 2050 based on this extrapolation represents over five times the amount of fossil fuels in proven reserves and about 45% of the resource estimate. On the other hand, the average annual growth rate in energy demand from 1973 to 1985 was much lower: about 2.2%. If this rate were linearly extrapolated to 2050, global energy demand would be about 23 TW (720 EJ) -almost 150% greater than the demand in 1985 -- which could increase annual CO₂ emissions from fossil fuels to nearly 13 Pg C. Cumulative energy demand for 1985 through 2050 based on the linear extrapolation represents about 115% of proven fossil-fuel reserves, or nearly 10% of estimated resources.

INDUSTRIAL PROCESSES

There are three significant non-energy sources of greenhouse gases associated with industrial activity: the use of chlorofluorocarbons (CFCs), halons, and (collectively, halocarbons); chlorocarbons cement manufacture; and waste disposal in The use of CFCs, halons, and landfills. chlorocarbons, which are man-made chemicals with a variety of applications, results in their release to the atmosphere. Certain uses, such as aerosol propellants and solvents, result in instantaneous release (when the product is used), while others, such as foam-blowing agents and refrigerants, result in a delayed release. Cement manufacture results in CO₂ emissions, and waste disposal in landfills results in CO_2 and CH_4 emissions, although only the CH_4 emissions are significant in terms of the total global source.

TABLE 4-5

Estimates of Global Fossil-Fuel Resources^a

(Exajoules)

	Geological Resources (exajoules)	Reserves (exajoules)	Reserves/ Resources (%)	Reserves Lifetime ^b (Years)	Resource Lifetime (Years)	
					Linear Extrapolation	Exponential Extrapolation
Coal	315,800	20,400	6	229	524	103
Oil	12,800	4,300	34	41	69	39
Gas	10,100	3,700 ^c	37	61	86	44

^a Resources estimates, as of 1985, are from the World Energy Conference (1980), adjusted for global production from 1979-85. Reserve estimates are from EIA (1986); oil and gas estimates as of January 1, 1986; and coal estimates as of 1981.

^b Based on 1985 rates of production.

^c Includes estimates for the Middle East and USSR.

Sources: World Energy Conference, 1980; United Nations, 1983, 1987; EIA, 1986.
FIGURE 4-7



Figure 4-7. Two hypothetical cases of future energy demand. The upper case is based on an exponential extrapolation of the average annual growth rate in energy demand between 1950 and 1973, a period of rapid growth in demand. The lower case is based on a linear extrapolation of the average annual growth rate in energy demand between 1973 and 1985, when the growth rate was much lower. These two cases illustrate potential upper and lower bounds on future energy demand. (Sources for historical data: United Nations, 1976, 1982, 1983, 1987.)

Chlorofluorocarbons, Halons, and Chlorocarbons

Historical Development and Uses

Chlorofluorocarbons are man-made chemicals containing chlorine, fluorine, and carbon, hence the name CFCs (HCFCs contain hydrogen as well). Table 4-6 lists the major CFCs with their chemical formulae. CFCs were developed in the late 1920s in the United States as a substitute for the toxic, flammable, refrigerator coolants in use at that time. The chemicals, which are noncorrosive, nontoxic, nonflammable, and highly stable in the lower atmosphere, provided the refrigerator industry with a safe, efficient coolant that soon proved to have numerous other uses as well. Commercial development of CFCs began in 1931. During World War II, CFCs were used as propellants in pesticides against malariacarrying mosquitos. Since then, CFCs have been used as aerosol propellants in a wide range of substances, from hairsprays to spray paints. In the 1950s, industries began using CFCs as blowing agents for plastic foam and foam insulation products. Chillers, used for cooling large commercial and industrial buildings, as well as cold storage units for produce and other perishable goods, became feasible at this time with the use of CFCs. Mobile air conditioners (in automobiles, trucks, and buses) currently constitute the largest single use of CFCs in the United States. CFCs are also used in gas sterilization of medical equipment and instruments, solvent cleaning of manufactured parts, especially electronic components and metal parts, and miscellaneous other processes and products such as liquid food freezing.

Halons, or bromofluorocarbons, are man-made chemicals containing carbon, fluorine, and chlorine and/or bromine (see Table 4-6 for the chemical formulae of the major halons in use today). These chemicals were developed in the 1970s, and are used primarily as fire extinguishants. Halon 1211 is used almost exclusively for portable (i.e., wheeled or handheld) fire extinguishers, particularly for situations where human exposure to the chemical is possible, such as in airplanes. Halon 1301 is used exclusively for total flooding fire extinguishing systems such as those used to protect computer centers, document rooms, libraries, and military installations. A summary of the end-use applications for the major CFC and halon compounds is shown in Table 4-6.

Chlorocarbons, man-made chemicals containing chlorine and carbon (see Table 4-6), are used primarily as solvents and chemical intermediates. The primary chlorocarbons are carbon tetrachloride and methyl chloroform. In the United States, carbon tetrachloride was once used extensively as a solvent and grain fumigant, but because of its toxicity, only small amounts of it are used in such applications today. Its primary use in the United States is in the manufacture of CFC-11 and CFC-12, a process which consumes or destroys almost all of the carbon tetrachloride, resulting in very small emissions. However, carbon tetrachloride is believed to be used as a solvent in developing countries, resulting in considerable emissions. Methyl chloroform is used worldwide as a cleaning solvent in two applications: 1) vapor degreasing (the solvent is heated and the item to be cleaned is suspended in the vapor); and 2) cold cleaning (the part to be cleaned is submerged in a tank of solvent). Small amounts are also used in adhesives, aerosols, and coatings.

Production of CFCs, halons, and chlorocarbons has grown steadily as new uses have developed. Production of the two largest CFC compounds, CFC-11 and CFC-12, increased rapidly in the 1960s and early 1970s (see Figure 4-8). Production peaked in 1974 at 812.5 gigagrams (Gg) and then declined due to a ban on most aerosol use in the United States, Canada, and Sweden in the late 1970s.¹² However, non-aerosol use has continued to grow, with 1985 production of 703.2 Gg. Globally, major CFC and halon consumption reached nearly one Tg in 1985 (see Table 4-7). Global production of carbon tetrachloride and methyl chloroform in 1985 was estimated at nearly 1029 Gg and 545 Gg, respectively (Hammitt et al., 1987).

Most CFC and halon consumption occurs in the United States and other industrialized nations. Of the 703.2 Gg of CFC-11 and CFC-12 produced in 1985, about 70% was consumed by the U.S., the EEC, and Japan (see Figure 4-9). Although CFC use is concentrated in the industrialized world,

TABLE 4-6

Major Halocarbons: Statistics and Uses

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Chemical	1986 Atmospheric Concentration (parts per trillion by volume)	Atmospheric Lifetime (Years)	Current Annual Atmospheric Concentration Growth Rates (%/yr)	Major Uses
Chlorofluorocarbons				······
CFC-11 (CCl ₃ F)	226	75^{+31}_{-17}	4	Aerosols, Foams
CFC-12 (CCl ₂ F ₂)	392	111 ⁺²²² - 44	4	Aerosols, Foams, Refrigeration
HCFC-22 (CHCIF ₂)	80 (1985)	15	7	Refrigeration, Fluoropolymer production
CFC-113 (C ₂ Cl ₃ F ₃)	30-70	90	11	Solvents
Halons (Bromofluorocarbo	ns)			
Halon 1211 (CBrClF ₂)	~2	25	>10	Fire extinguisher
Halon 1301 (CBrF ₃)	~2	110	>10	Fire extinguisher
Chlorocarbons				
Carbon tetrachloride (CCl ₄)	75-100	~40	1	Production of CFC-11 and CFC-12
Methyl chloroform (CH ₃ CCl ₃)	125	6±1	~5	Solvents

Sources: U.S. EPA, 1988; Hammitt et al., 1987; Wuebbles, 1983; WMO, 1985.



Figure 4-8. While non-aerosol production of CFC-11 and CFC-12 has grown fairly steadily since 1960, aerosol production declined in the 1970s and then leveled off in the 1980s due to a ban on most aerosol use of CFCs in the United States, Canada, and Sweden. (Source: U.S. EPA, 1987.)

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FIGURE 4-8

TABLE 4-7

Estimated 1985 World Use of Potential Ozone-Depleting Substances

(gigagrams)

Chemical	World	United States	Reporting Countries	Other Communist Countries
CFC-11	341.5	75.0	225.0	41.5
CFC-12	443.7	135.0	230.0	78.7
CFC-113	163.2	73.2	85.0	5.0
Halon 1301	10.8	5.4	5.4	0.0
Halon 1211	10.8	2.7	8.1	0.0
Carbon tetrachloride	1029.0	280.0	590 .0	159.0
Methyl chloroform	544.6	270.0	186.7	87.0

Source: Hammitt et al., 1986.

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FIGURE 4-9

Figure 4-9. The EEC, the United States, and Japan accounted for almost 70% of the 1985 global production of CFC-11 and CFC-12. (Source: U.S. EPA, 1988.)

consumption has also increased recently in developing countries.

The Montreal Protocol

Concern over the effect on the Earth's atmosphere of CFCs and related anthropogenically-produced compounds containing chlorine, bromine, and nitrogen began in the 1970s. Because of their stability (i.e., their long lifetimes; see Table 4-6), CFCs are transported to the stratosphere where they contribute to the destruction of ozone. Since the early 1970s, improved understanding of this process, accumulation of data indicating growing atmospheric concentrations of CFCs, and observed depletion of stratospheric ozone, particularly in the Antarctic, have fueled international action on this issue.

International negotiations to protect the stratosphere began in 1981 under the auspices United Nations of the Environment Programme (UNEP). These negotiations culminated in September 1987 in Montreal, Canada, where a Diplomatic Conference was held, resulting in an international agreement ("The Montreal Protocol on Substances That Deplete the Ozone Layer," or the Montreal Protocol) to begin reducing the use of CFCs and halons (chlorocarbons were not included). The Montreal Protocol came into force on January 1, 1989, and has been ratified by 68 countries, representing just over 90% of current world production of these chemicals (as of February 1, 1991). As a result of this historic agreement, the very high growth rates in atmospheric CFC concentrations projected in earlier studies (e.g., Ramanathan et al., 1985) are not likely to occur. Nevertheless, because of the long atmospheric lifetimes of CFCs, their concentrations could continue to increase for several decades (see CHAPTER In June 1990 the Protocol was **VI**). strengthened by the London Amendments calling for a complete phase-out of CFCs, halons, carbon tetrachloride and methyl chloroform and a non-binding resolution to phase out HCFCs.

Landfill Waste Disposal

Humans have generated solid wastes since they first appeared on Earth, although disposal of these wastes did not become a major problem until the rise of synthetic

materials (e.g., plastics) and densely-populated urban areas. The environment can usually assimilate the smaller amounts of wastes produced by rural, sparsely-settled communities. However, because urban populations produce such high volumes of waste, due to both the sheer concentration of individuals contributing to the waste stream and the high use of heavily-packaged products, urban waste disposal has become a formidable task.

Approximately 80% of the municipal solid wastes collected in urban areas around the world is deposited in landfills or open dumps (Bingemer and Crutzen, 1987). Sanitary landfilling (compaction of wastes, followed by daily capping with a layer of clean earth), which became common in the United States after World War II, is used primarily in urban centers in industrialized countries. Open pit dumping is the most common "managed" disposal method in developing countries (30-50% of the solid wastes generated in cities of developing countries is not collected [Cointreau, 1982]). Most landfills and many open dumps develop anaerobic conditions, resulting in decay of organic carbon to CH_4 and CO_2 . The amount of CH₄ resulting from anaerobic decay of organic municipal and industrial wastes in landfills is currently about 30-70 Tg per year (Bingemer and Crutzen, 1987), approximately 10% of the total annual CH_4 source.¹³

The primary variable affecting gas generation in landfills is the composition of the refuse. Wastes high in organic material (e.g., food wastes, agricultural wastes, paper products) decompose readily, while inorganics are relatively unaffected by the decomposition process. While agriculture is the largest single source of solid wastes in the U.S. (Berry and Horton, 1974), most of these wastes are not Increasing urbanization and landfilled. demand for "convenience" items, which encourages marketing of single-serving and heavily-packaged products, have resulted in increasingly greater proportions of plastics, glass, metals, and paper products in the waste Other factors influencing gas stream. generation include inclusion of sewage sludge (which enhances gas generation), oxygen concentration, moisture content, pH, and available nutrients.

Disposal of municipal solid waste in industrial nations increased by 5% per year during the 1960s and by 2% per year in the 1970s (CEQ, 1982). Currently, per capita waste production in industrialized countries is considerably larger than in developing countries (see Table 4-8), and the largest contribution of landfill CH_4 comes from the industrialized world (Bingemer and Crutzen, 1987). Although current rates of waste disposal in landfills have begun to level off in many industrialized countries, associated CH₄ emissions are probably still growing because the total quantity of waste in place is still increasing. In the developing world, with its high population growth rates and increasing urbanization, municipal solid waste disposal is projected to double by the year 2000 (Kresse and Ringeltaube, 1982), so CH_4 production from waste dumps and/or sanitary landfills can be expected to increase rapidly in developing countries.

Cement Manufacture

Cement manufacture produces CO_2 , as well as numerous other exhaust gases. As demand for cement has grown over the last century, CO_2 emissions associated with this industry have also increased. Between 1950 and 1985, CO_2 emissions from cement manufacture grew from 18 to 134 Tg C/yr (see Figure 4-10). In recent years CO_2 emissions from cement production have grown at a faster rate than those from fossil-fuel combustion: in the early 1950s CO_2 emitted as a result of cement manufacture was approximately 1% of the amount emitted from the consumption of fossil fuels; by the early 1980s this fraction had increased to 2.5% (Rotty, 1987).

The CO₂ emissions resulting from cement manufacture occur during the production of clinker (round, marble-sized particles), a material produced midway through the process. After the raw materials (cement rock, limestone, clay, and shale) are quarried and crushed, they are ground and blended to a mixture that is approximately 80% limestone by weight. The mixture is then fed into a kiln for firing, where it is exposed to progressively higher temperatures that cause heating, then drying, calcining, and sintering. Finally, the feed is heated to the point of fusion (approximately 1595°C), and clinker is produced. It is during the calcination process, which occurs at approximately 900 to 1000°C, that the limestone (CaCO₃) is converted to lime (CaO) and CO₂, and the CO₂ is released. For every million tons (Tg) of cement produced, approximately 0.137 Tg C as CO₂ is emitted from calcining (Rotty, 1987).¹⁴ An additional 0.165 Tg C is emitted per million tons of cement produced from fossil fuel used for kiln firing and electricity generation. This CO₂ is accounted for as part of industrial energy-use emissions.

World cement production has increased at an average annual rate of approximately 6% since the 1950s, from 133 million tons in 1950 to 972 million tons in 1985 (U.S. BOM, 1949-1986). Cement production growth rates in individual countries have varied during this period (see Figure 4-11) due to economic fluctuations in cement's primary market, i.e., the construction industry, and competitive shifts internationally among the primary cement-producing countries. For example, in United States produced 1951 the approximately 28% of the global total, while by 1985 its share had shrunk to 7%.¹⁵ During the same time, the production shares for the USSR grew from 8% to 13%, for China, from less than 1% to 15%, and for Japan, from 4% to 8%. Although many national markets, except the United States', experienced low levels of demand during the 1980s, global cement production is expected to continue to grow faster than GNP for some time.

LAND-USE CHANGE

Over the past few centuries, man has significantly changed the surface of the Earth. Forests have been cleared, wetlands have been drained, and agricultural lands have been expanded. All of these activities have resulted in considerable changes in trace gas emissions to the atmosphere. Deforestation results in a net release of carbon from both the biota and the soils (unless the land is reforested) as these organic carbon pools burn or are decomposed. Biomass burning, due to shifting agriculture, burning of savanna, use of industrial wood and fuelwood, and burning of agricultural wastes, is a source of CO₂, as well as CH₄, N₂O, and NO_x. ¹⁶ Destruction of wetlands, from either filling or dredging, can alter the atmospheric CH₄ budget, since

TABLE 4-8

Refuse Generation Rates in Selected Cities

City	Per Capita Waste Generation Rate (kg per day)					
Industrial Cities						
New York. United States	1.80					
Singapore	0.87					
Hong Kong	0.85					
Hamburg, West Germany	0.85					
Rome, Italy	0.69					
Developing Cities						
Jakarta, Indonesia	0.60					
Lahore, Pakistan	0.60					
Tunis, Tunisia	0.56					
Bandung, Indonesia	0.55					
Medellin, Colombia	0.54					
Surabaya, Indonesia	0.52					
Calcutta, India	0.51					
Cairo, Egypt	0.50					
Karachi, Pakistan	0.50					
Manila, Philippines	0.50					
Kanpur, India	0.50					
Kano, Nigeria	0.46					

Source: Cointreau, 1982.



FIGURE 4-10

Figure 4-10. Carbon dioxide emissions from cement production grew from 18 to 134 Tg between 1950 and 1985, an average annual rate of growth of about 6%. (Sources: Rotty, 1987; U.S. BOM, 1949-1986, selected years.)





Figure 4-11. World cement production grew at an average annual rate of about 6% between 1950 and 1985. Growth has been particularly rapid in China, the U.S.S.R., and Japan. (Source: U.S. BOM, 1949-1986, selected years.)

anaerobic decomposition in wetlands produces methane.

Deforestation

Estimates of net emissions of CO_2 to the atmosphere due to changes in land use (deforestation, reforestation, logging, and changes in agricultural area) in 1980 range from 0.4 to 2.6 Pg C (Houghton et al., 1987; Detwiler and Hall, 1988), which accounts for approximately 10-30% of annual anthropogenic CO_2 emissions to the atmosphere. Deforestation in the tropics accounted for almost all of the flux; the carbon budget of temperate and boreal regions of the world has been approximately in balance in recent years. Of the net release of carbon from tropical deforestation, 55% was produced by only six countries in 1980: Brazil, Indonesia, Columbia, the lvory Coast, Thailand, and Laos (see Figure 4-12).

The world's forest and woodland areas have been reduced 15% since 1850, primarily to accommodate the expansion of cultivated lands (IIED and WRI, 1987). The largest changes in forest area during this period have occurred in Africa, Asia, and Latin America. Europe is the only region that has experienced a net increase in forest area over this time interval. Forest area began to increase in Europe in the 1950s and in North America in the 1960s (see Table 4-9). However, recent data from the Food and Agriculture Organization of the United Nations (FAO) and the U.S. Forest Service indicates that net deforestation may be occurring in the United States -- although there are discrepancies between the two data sets. The FAO data indicates that between 1980 and 1985 the area of U.S. forest and woodlands decreased by approximately 3.8 million hectares (Mha) per year, or 1.4% per year (FAO, 1986b).¹⁷ The U.S. Forest Service (Alig, 1989) estimates that between 1977 and 1987 the area of U.S. forests decreased by approximately 0.41 Mha per year, or 0.14% per year.

Currently, it is estimated that approximately 11.3 Mha of tropical forests are lost each year, while only 1.1 Mha are reforested per year (FAO, 1985). Most of the tropical deforestation is due to transfer of forest land to agricultural use, through shifting agriculture and conversion to pasture. FAO

has estimated a demand for an additional 113-150 Mha of cultivated land for the 20-year period between 1980 and 2000 to meet food production needs (FAO, 1981). Most of this land will have to come from areas that were once forested; however, there is a large potential to use land currently under shifting cultivation by adapting low-input agricultural techniques (see CHAPTER V). Fuelwood use also contributes to deforestation, particularly in Africa where fuelwood is a major source of residential energy. Sixty-three percent of the total energy consumption of developing African countries, 17% in the Asian countries, and 16% in the Latin American countries, is through fuelwood burning. In the Sudan, Senegal, and Niger, fuelwood provides 94%, 95%, and 99%, respectively, of household energy consumption (Anderson and Fishwick, 1984). Rapidly increasing populations, particularly in developing nations, will result in increasing demands on forest lands to meet growing agricultural and energy needs.

Biomass Burning

Biomass burning, in addition to contributing to the atmospheric CO_2 budget, contributes approximately 10-20% of total annual CH_4 emissions, 5-15% of the N₂O emissions, 10-35% of the NO, emissions, and 20-40% of the CO emissions (Crutzen et al., 1979; WMO, 1985; Logan, 1983; Stevens and Engelkemeir, 1988; and Andreae et al., 1988). These estimates are for instantaneous emissions from combustion. Recent research has shown that biomass burning also results in longer-term (at least up to 6 months after the burn) emissions of NO and N₂O due to enhancement of biogenic soil emissions (Anderson et al., 1988). Estimates of emissions of trace gases due to biomass burning are very uncertain for two reasons: 1) data on amounts and types of biomass burned are scarce, and 2) emissions per unit of biomass burned are highly variable.

Activities associated with biomass burning include agriculture, colonization, wildfires and prescribed fires, and burning of industrial wood and fuelwood. Currently, agricultural burning, due to shifting agriculture, savanna burning, and burning of agricultural wastes, is estimated to account for over 70% of the biomass burned annually (see FIGURE 4-12



Figure 4-12. Tropical deforestation accounts for approximately 10-30% of the annual anthropogenic CO_2 emissions to the atmosphere. Over half of the 1980 CO_2 emissions from deforestation was produced by six countries: Brazil, Indonesia, Colombia, the Ivory Coast, Thailand, and Laos. (Source: Houghton et al., 1987.)

TABLE 4-9

Land Use: 1850-1980^a

															Percentage Change
	<u>Area (million hectares)</u> 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 15				1980	1850 to 1980									
ALL TEN REGIONS															
Forests and Woodlands	5,919	5,8 9 8	5.869	5,833	5,793	5,749	5,69 6	5,634	5,553	5,455	5,345	5.219	5,103	5,007	-15
Grassland and Pasture	6.350	6,340	6,329	6,315	6,301	6,284	6,269	6,260	6,255	6,266	6,293	6,310	6,308	6,299	-1
		209	008	629	/12		842	913		1,085	1,169	1.278	1,396	1,501	179
Tropical Africa															
Grassland and Pasture	1,336	1,333	1,329	1,323	1,315	1,396	1,293	1,275	1,251	1,222	1,188	1,146	1,106	1,074	-20
Croplands	57	58	1,004 61	64	68	73	1,081 80	1,091	101	1,114	1,130	1,147	1,157	222	288
North Africa and Middle Fast		·····-													
Forests and Woodlands	34	34	33	32	31	30	28	27	24	21	18	17	15	14	-60
Grassland and Pasture	1,119	1,119	1,118	1,117	1,116	1,115	1,113	1,112	1,108	1,103	1,097	1,085	1,073	1,060	-5
Croplands	27	28	30	32	35	37	40	43	49	57	66	79	93	107	294
North America															
Forests and Woodlands	971	968	965	96 2	959	954	949	944	941	940	939	939	941	942	-3
Grassland and Pasture	571	559	547	535	522	504	486	468	454	450	446	446	447	447	-22
Croplands	50	65	80	95	110	133	156	179	196	201	206	205	204	203	309
Latin America															
Forests and Woodlands	1,420	1,417	1,414	1,408	1,401	1,394	1,383	1,369	1,348	1,316	1,273	1,225	1,186	1,151	-19
Croplands	021 18	023	023 21	24	28	33	39	45	57	72	87	104	123	147	677
													125		
China Forests and Woodlands	96	93	Q 1	89	86	84	82	79	76	73	69	64	59	58	-39
Grassland and Pasture	799	799	798	796	797	797	797	796	796	794	793	789	784	778	-3
Croplands	75	78	81	84	86	89	91	95	96	103	108	117	127	134	79
South Asia															
Forests and Woodlands	317	315	311	307	303	299	294	289	279	265	251	235	210	180	-43
Grassland and Pasture	189	189	189	189	189	189	190	190	190	190	190	190	189	187	-1
Croplands	71	73		81	85	89	93		108	122	1.36	153	1/8	210	196
Southeast Asia						2.40	240	2.47	246	244	242	2.40			-
Forests and Woodlands	252	252	122	251	250	249	248	247	246	244	242	240	238	235	-1
Croplands	123	123	8	10	12	15	18	21	25	30	35	40	47	55	670
Furana															
Forests and Woodlands	169	158	157	157	156	156	155	155	155	154	154	156	161	167	4
Grassland and Pasture	150	147	145	144	143	142	141	139	138	137	136	136	137	138	-8
Croplands	132	1 36	140	142	143	145	146	147	149	150	152	151	145	137	4
USSR						_									
Forests and Woodlands	1, 067	1,060	1,052	1,040	1,027	1,014	1,001	98 7	973	96 1	952	945	940	941	-12
Grassland and Pasture	1,078	1,081	1,083	1,081	1,079	1,078	1,076	1,074	1,072	1,070	1,070	1,069	1,065	1,065	-1
Croplands	94	98	103	118	132	147	162	178	194	208	216	225	233	233	147
Pacific Developed Countries															
Forests and Woodlands	267	267	266	265	264	263	262	261	260	259	258	252	247	246	-8
Grassland and Pasture	638	638	638	637	635	634	632	630 10	629 22	627	625	617	609 54	608 608	-5 841
Cropiands	0	0	/	У	12	14	1/	19	22	24		42	00	56	0+1

^a These three categories refer to aggregate data from eleven categories of natural land cover. Land areas covered by snow, ice, rock, or desert are the only categories not included here.

Source: IIED and WRI, 1987.

Table 4-10). Biomass burning is a particularly important source of trace gas emissions in the tropics, where forest exploitation is unsurpassed. Continued rapid population growth and exploitation of forests may substantially increase emissions from biomass burning in the future.

Wetland Loss

Annual global emissions of CH₄ from freshwater wetlands are estimated to be 110 Tg, approximately 25% of the total annual source of 400 to 600 Tg (Matthews and Fung, 1987). Of the approximately 530 Mha producing this CH_4 , 39% is forested bog, 17% is nonforested bog, 21% is forested swamp, 19% is nonforested swamp, and 4% is alluvial formations.¹⁸ The bulk of the bog acreage is located between 40°N and 70°N, while swamps predominate between 10°N and 30°S. Alluvial formations are concentrated between 10°N and 40°S (see Figure 4-13). Coastal saltwater and brackish-water environments produce minor amounts of CH₄ in comparison, probably due to the inhibitory effects of dissolved sulfate (SO_4) in the interstitial water of salt-marsh sediments (DeLaune et al., 1983; Bartlett et al., 1985).

The latitudinal distribution of wetland CH_4 emissions is estimated to be very similar to the latitudinal distribution of freshwater wetland area. About 50% of the emissions originate between 50°N and 70°N, and about 25% between 20°N and 30°S. The source of the high-latitude emissions is organic-rich bogs, while most of the low-latitude emissions come from swamps (see Figure 4-13).

Between 25 and 50% of the world's original swamps and marshes have been eliminated by human activities (IIED and WRI, 1987). For centuries people have drained and filled marshes and swamps to create dry land for agricultural and urban development. Wetland areas have been converted to open water by dredging and installation of flood-control levees, and have been used as disposal sites for dredge materials and solid wastes. Peat mining and pollution from agricultural and industrial runoff have also contributed to the destruction

of wetlands. By 1970, more than half of the original wetland acreage in the United States had been destroyed (IIED and WRI, 1987). Between the mid-1950s and mid-1970s, there was a net loss of wetlands in the United States of approximately 4.6 Mha, 97% of which occurred in inland freshwater areas (OTA, 1984). Agricultural conversions were responsible for 80% of this freshwater wetland loss.¹⁹ Wetland loss has also been extensive in Europe and the Asia-Pacific region. For example, approximately 40% of the coastal wetlands of Brittany, France, have been lost in the last 20 years, and 8100 ha of wetlands on the east coast of England have been converted to agricultural use since the 1950s. Largescale wetland losses have not been as prevalent in the developing world, but rising populations will result in increasing demands for agricultural expansion. There is already pressure to develop two large wetland systems in Africa, the Okavango Swamps of Botswana and the Sudd Swamps of southern Sudan, for agricultural use (IIED and WRI, 1987).

AGRICULTURAL ACTIVITIES

Three agricultural activities contribute directly to atmospheric emissions of greenhouse gases: enteric fermentation in domestic animals, rice cultivation, and use of nitrogenous fertilizer.²⁰ Global demand for food and agricultural products has more than doubled since 1950, fueled by rising populations and incomes. Agricultural advancements during the post-war years, such Revolution," brought as the "Green improvements in soil management and disease control, new high-yielding varieties of crops, increased application of commercial fertilizers, and increased use of machinery. Between 1950 and 1986, world grain production increased from 624 to 1661 million tons and average yield more than doubled, from 1.1 to 2.3 tons per ha (Wolf, 1987). Over this same time interval, growth of various domestic animal populations ranged from 20 to 150% (Crutzen et al., 1986) and fertilizer consumption grew approximately 750% (Herdt and Stangel, 1984). According to projections by the Food and Agriculture Organization of the United Nations, by the year 2000, a world population of about 6 billion will require an agricultural

TABLE 4-10

Summary Data on Area and Biomass Burned

Activity	Burned and/or Cleared Area (million ha)	Burned Biomass (100 Tg dry matter)
Burning due to shifting agriculture	21-62 (41)*	9-25 (17)
Deforestation due to population increase and colonization	8.8-15.1 (12.0)	5.5-8.8 (7.2)
Burning of savanna and brushland	(600)	4.8-19 (11.9)
Wildfires in temperate and boreal forests	4.0-6.5 (5.4)	1.9-3.2 (2.6)
Prescribed fires in temperate forests	2.0-3.0 (2.5)	0.1-0.2 (0.2)
Burning of industrial wood and fuelwood		10-11 (10.5)
Burning of agricultural wastes		17-21 (19)
TOTAL	630-690 (660)	48-88 (68)

* Data in parentheses represent average values.

Source: Crutzen et al., 1979.

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Figure 4-13. Estimated latitudinal distribution of wetland area (top) and associated methane emissions (bottom). Forested and non-forested bogs located between 40° and 70°N account for approximately 50% of the current CH_4 emissions from wetlands. (Source: Matthews and Fung, 1987.)

output approximately 50 to 60% greater than that required in 1980 (FAO, 1981).

Enteric Fermentation In Domestic Animals

Methane is produced as a by-product of enteric fermentation in herbivores, a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream. Both ruminant animals (e.g., cattle, dairy cows, sheep, buffalo, and goats) and some nonruminant animals (e.g., pigs and horses) produce CH_4 . The highest CH_4 losses are reported for ruminants (approximately 4-9% of total energy intake), which are able to digest cellulose due to the presence of specific microorganisms in their digestive tracts. The amount of CH_4 that is released from both ruminant and non-ruminant animals depends on the type, age, and weight of the animal, the quality and quantity of feed, and the energy expenditure of the animal.

Of the annual global source of 400-600 Тg CH₄, domestic animals contribute approximately 65-85 Tg (Crutzen et al., 1986; Lerner et al., 1988). Domestic animals that produce the bulk of the CH₄ are (in decreasing order of amount produced) cattle, dairy cows, buffalo, goats, sheep, camels, pigs, Currently, approximately 57% and horses. comes from cattle, and 19% from dairy cows. Domestic animals in six countries, India, the USSR, Brazil, the U.S., China, and Argentina, produce over 50% of the methane by enteric fermentation (Lerner et al., 1988).

The domestic animal population has increased considerably during the last century. Between the early 1940s and 1960s, increases in global bovine and sheep populations averaged 2% per year. Since the 1960s, the rates of increase have slowed somewhat, to 1.2% and 0.6% per year, respectively (see Figure 4-14). The annual increases in global populations of pigs, buffalo, goats, and camels since the 1960s have been comparable: 1.4%, 1%, 1.2%, and 0.5%, respectively. The horse population declined about 0.25% per year. For comparison, the average annual increase in global human population since the 1960s has been about 1.8%.

Rice Cultivation

Anaerobic decomposition of organic material in flooded rice fields produces methane, which escapes to the atmosphere by ebullition (bubbling) up through the water column, diffusion across the water/air interface, and transport through the rice plants. Research suggests that the amount of CH_4 released to the atmosphere is a function of rice species, number and duration of harvests, temperature, irrigation practices, and fertilizer use (Holzapfel-Pschorn and Seiler, 1986; Seiler et al., 1984; Cicerone et al., 1983).

Rice cultivation has grown tremendously since the mid-1900s, due both to increases in crop acreage and yields.²¹ Between 1950 and 1984, rough rice production grew from 163 to 470 million tons, nearly a 200% increase.²² During the same time, harvested rice paddy area increased approximately 40%, from 103 to 148 Mha, and average global yields doubled, from 1.6 to 3.2 tons per ha (IRRI, 1986).²³ Average yields higher than 5 tons per ha have already been obtained in parts of the developed world (FAO, 1986a). The increase in rice production has been due both to the "Green Revolution" of the 1960s, which resulted in the development and dissemination of high-yield varieties of rice and an increase in fertilizer use, and to a significant expansion of land area under cultivation. Methane emissions are probably primarily a function of area under cultivation, rather than yield, although yield could influence emissions, particularly if, in order to increase yield, more organic matter is incorporated into the paddy soil.

Over 90% of global rice acreage and production occurs in Asia. Five Asian countries, China, India, Indonesia, Bangladesh, and Thailand, account for 75% of global production and 73% of the harvested area (IRRI, 1986; see Figures 4-15 and 4-16). Rice fields contribute 60-170 Tg of methane per year to the atmosphere, or approximately 20% of the global flux (Cicerone and Oremland, 1988). This estimate is highly uncertain because there have been no comprehensive rice-paddy flux measurements in the major rice-producing countries in Asia.



Figure 4-14. Global domestic animal populations have grown by about 0.5 to 2.0% per year during the last century. Currently, domestic animals account for about 15% of the annual anthropogenic CH_4 emissions. Note: The cattle population figures include dairy cows. (Sources: Crutzen et al., 1986; FAO, 1971, 1982, 1986a.)

FIGURE 4-14



FIGURE 4-15







Figure 4-16. Distribution of the total harvested rice paddy area of 148 Mha. Five Asian countries, India, China, Bangladesh, Indonesia, and Thailand, accounted for 73% of the 1984 rice acreage harvested. (Source: IRRI, 1986.)

Use of Nitrogenous Fertilizer

Nitrous oxide is released through microbial processes in soils, both through denitrification and nitrification. Nitrogenous fertilizer application enhances N_2O flux rates, since some of the applied fixed N is converted to N_2O and released to the atmosphere. The amount of N_2O released depends on rainfall, temperature, the type of fertilizer applied, mode of application, and soil conditions.

Nitrogen is currently the most abundant commercial fertilizer nutrient consumed worldwide. Its dominance in the fertilizer markets has increased steadily over the last few decades, from 28% of total nutrients (nitrogen, phosphorus, and potassium) in 1950 to 64% in 1981 (Herdt and Stangel, 1984). Approximately 70.5 million tons N was consumed worldwide in 1984/1985 in the form of nitrogenous fertilizers (FAO, 1987). Α preliminary estimate suggests that this produced N₂O emissions of 0.14-2.4 Tg N of the global source of approximately 8-22 Tg N per year (Fung et al., 1988), although this estimate is highly uncertain. Experiments to determine the fraction of fertilizer nitrogen lost to the atmosphere as nitrous oxide have shown a wide range of results (see Table 4-11 and CHAPTER II). Anhydrous ammonia, which requires sophisticated equipment for application (it is injected under pressure into the soil), is used exclusively in the United States. It comprises about 38% of the U.S. nitrogenous fertilizer consumption. Urea, which is usually broadcast as pellets by hand, comprises about 69% and 58% of nitrogenous fertilizer consumption in Asia and South America, respectively.

Asia, Western Europe, Eastern Europe, and North America consume the major share nitrogenous fertilizers world's of the (collectively, about 85%). China, the Soviet Union, and the United States together account for approximately one-half of the world's fertilizer consumption. The twelve largest nitrogen fertilizer consumers, all of which consume more than one million tons N annually, are (in decreasing order): China, the United States, the Soviet Union, India, France, the United Kingdom, West Germany, Canada, Indonesia, Poland, Mexico, and Italy (see Figure 4-17). Together, these twelve countries account for approximately 74% of the annual nitrogenous fertilizer consumption.

Although developed nations will probably increase their consumption of commercial fertilizer over the next few decades, most of the increased demand will occur in developing nations. The World Bank estimates that over 90 million tons N will be consumed in 1997/98, a 30% increase over consumption in 1986/87. Almost 50% of the growth between 1986/87 and 1997/98 is expected to occur in the developing nations (World Bank, 1988).

IMPACT OF CLIMATE CHANGE ON ANTHROPOGENIC EMISSIONS

Climate change will affect human activity in a myriad of ways, and thus influence anthropogenic emissions of greenhouse gases BIOGEOCHEMICAL CLIMATE (see FEEDBACKS in CHAPTER III). The impact of climate change on land-use patterns and agricultural practices could be particularly significant in influencing the trace gas emissions from these sources. For example, increases in the frequency and severity of droughts in farm belt regions will increase irrigation needs and associated energy requirements, resulting in increased energy emissions. However, the magnitude (or even the direction) of such changes have not been examined to date. More information is available regarding the impact of climate change on electric utilities (Linder et al., 1987). A brief discussion of this subject is presented here as an illustration of some ways in which climate change can, in turn, influence trace gas emissions.

Linder and Inglis (1989) estimate that annual electricity consumption increases by 0.5 to 2.7%/°C for utilities in the United States, depending on the local climate and the fraction of buildings with electrical heating and air-conditioning equipment. If climate change leads to increases in ownership levels of this equipment, then substantially greater sensitivities are possible (Linder et al., 1987). Currently, 37% of total CO₂ emissions from

TABLE 4-11

Nitrous Oxide Emissions by Fertilizer Type

Percent of Nitrogenous Fertilizer Evolved as N ₂ O					
0.5 to 6.84					
0.04 to 1.71					
0.025 to 0.1					
0.067 to 0.5					
0.001 to 0.50					

Source: Eichner, 1988; Galbally, 1985.



Figure 4-17. Distribution of the total nitrogenous fertilizer consumption of 70.5 million tons N. China, the United States, and the Soviet Union together accounted for just over 50% of the 1984/1985 global fertilizer consumption. Currently, 5-35% of the total anthropogenic N_2O emissions is attributed to nitrogenous fertilizer consumption. (Source: FAO, 1987.)

Chapter IV: Human Activities

fossil fuels are produced by electric utilities, and this share is expected to increase in the future (see CHAPTER VI). Applying the U.S. average sensitivity of 1.0%/°C obtained by Linder and Inglis (1989) to the rest of the world implies a feedback on CO₂ emissions of 0.4%/°C. This feedback would be offset to an extent that has not been estimated by lower fuel use for heating, but as the penetration of air conditioning rises in developing countries this feedback could increase.

Climate change may affect the electricity industry from the supply side as well. When steam is produced to generate electricity in a powerplant, either water (usually from a nearby reservoir or river) or air is used as a coolant to condense the steam back into water and start the process over again. Higher atmospheric temperatures will result in warming of these coolants, and reduction in the efficiency of the powerplants. This effect is not likely to be as significant as others, however, since seasonal temperature changes are already much greater than the warming predicted for the next century (Linder et al., 1987).

More immediate and acute effects of climate change on electric utilities are likely to occur due to reduced availability of water. The drought of the summer of 1988 resulted in such low river levels in the U.S. Midwest that some electric plants were forced to reduce generation due to lack of cooling water. More frequent and severe droughts would also result in reduced hydropower for generation of electricity. (This change would also affect barge shipping, since many rivers would become unnavigable, and result in increased trace gas emissions from truck and rail transport.)

Sea-level rise and lowered stream flows resulting from climate change would also have adverse effects on electric utilities. Salinities in rivers and estuaries would increase, and stream chemistry could change, possibly causing the water to become too corrosive to be used as a coolant. A few powerplants in the United States use salt water for cooling purposes, so the technology to adapt to more saline coolants does exist, although the conversion process is costly.

These feedback mechanisms are likely to have a smaller influence on future warming than the biogeochemical feedbacks discussed in Chapter III. The impact of climate change on anthropogenic trace gas emissions may nevertheless prove to be important and should be investigated further.

NOTES

1. Anthropogenic sources of trace gases are those resulting from human activities, e.g., combustion of fossil fuels. These sources are distinguished from natural sources, since emissions from anthropogenic sources result in unbalanced trace gas budgets and accumulation of gases in the atmosphere.

2. Throughout the report these gases are often referred to as greenhouse gases, although strictly speaking, CO and NO_x are not greenhouse gases since they do not directly affect radiative forcing (see CHAPTER II). However, these two gases indirectly affect greenhouse forcing due to their chemical interactions with other gases in the troposphere. As a result, for simplicity, we shall refer to them as greenhouse gases.

3. In some developing countries, the dependence on biomass can approach 95% of total energy requirements.

4. Non-commercial biomass estimates are not included in these figures.

5. In 1986 CO₂ emissions from fossil fuels were approximately 5370 million metric tons C, or 5.37 Pg C. 1 billion metric tons = 1 gigaton = $1 Pg = 10^{15}$ grams.

6. The OECD countries include Australia, Austria, Belgium, Canada, Denmark, Finland, France, the German Federal Republic, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. 7. $1 \text{ GJ} = 1 \text{ gigajoule} = 10^9 \text{ joules}$. 1055 joules = 1 Btu.

8. For example, some food production processes use natural gas because its relatively clean-burning characteristic allows it to be used when product contamination may be an issue. Similarly, melters in the glass industry are often designed to burn natural gas because of the flame characteristics of this fuel. Use of other fuels would tend to produce an inferior product and likely require the redesign of equipment.

9. U.S. regulations strictly govern the flaring and venting of natural gas. In other parts of the world, however, insufficient data exists to determine whether the natural gas is flared or vented, although safety precautions would strongly encourage flaring rather than venting.

10. 1 Tg = 1 teragram = million metric tons = 10^{12} grams.

11. TW = Terawatt-years per year = 10^{12} watt-years per year; 1 TW = 31.53 EJ; 1 EJ = 1 Exajoule = 10^{18} joules; 1055 joules = 1 Btu.

12. 1 Gg = 10^9 grams = 10^6 kg.

13. This estimate does not include methane from anaerobic decomposition of agricultural wastes, which could be a significant quantity. The total amount of carbon in agricultural wastes in the United States alone is already 2.5 times larger than the 113 million metric tons of waste carbon that are generated and dumped in landfills worldwide (Bingemer and Crutzen, 1987).

14. 1 ton = 1 metric ton = 1000 kg.

15. The U.S. is currently a net importer of cement; the volume of its imports has grown, representing only a small percentage of consumption in the early 1980s but as much as 18% in 1986 (ITA, 1987).

16. Shifting agriculture is the practice of clearing and planting a new area, farming it until productivity declines, and then moving on to a new plot to start the cycle over again. If the land is allowed to reforest for a long

enough period of time, there are no net CO_2 emissions.

17. 1 ha = 1 hectare = 2.471 acres.

18. Bogs are peat or organic-rich systems, usually associated with waterlogging and seasonal freeze-thaw cycles; swamps are loworganic formations occurring most commonly in the tropics, and alluvial formations are loworganic riverine formations.

19. For example, drainage of prairie potholes in Iowa to provide new farmland has resulted in the reduction of Iowa's original wetlands by over 98%, from 930,000 ha when settlement began, to 10,715 ha today.

20. Emissions due to energy requirements in agriculture, such as energy use for irrigation equipment and other farm machinery, are accounted for as part of industrial energy use emissions.

21. Rice statistics are for rice grown in flooded fields, i.e., they do not include upland rice, since methane emissions result only from flooded rice fields.

22. Rough rice, also called paddy rice, is rice with the hull, or husk, attached. The hull contributes about 20% of the weight of rough rice. The kernel remaining after the hull is removed is brown rice. Milling of brown rice, which removes the bran, followed by polishing, results in white rice.

23. Harvested area is the area under cultivation multiplied by the number of crops per year. For example, 1 ha that is triple-cropped is counted as 3 ha of harvested area.

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CHAPTER V

TECHNICAL OPTIONS FOR REDUCING GREENHOUSE GAS EMISSIONS

FINDINGS

• A number of technical changes which could reduce sources of greenhouse emissions are believed likely to be feasible at reasonable economic costs. No single technology or small set of technical options offers "a solution" to greenhouse gas emissions. Only by aggregating the effects of many technical opportunities over a long time can significant reductions in greenhouse gas emissions be achieved. This chapter highlights options that appear to be "relatively cost-effective." Detailed analysis necessary to quantify total costs of the measures has not been conducted.

• Improvements in end-use energy efficiency provide the best option for reducing carbon dioxide (CO₂) emissions over the next few decades. Reductions in energy use would also reduce emissions of methane (CH₄), nitrous oxide (N₂O), nitrogen oxides (NO_x), and carbon monoxide (CO). Examples of potential efficiency improvements are:

-- Transportation -- 50 mile per gallon automobiles are technically feasible with currently-available technology. Further improvements could increase fuel efficiency to more than 80 miles per gallon. What effects these changes would have on size, safety, performance, cost, and other desirable product characteristics need to be carefully considered. In addition, major improvements in the fuel efficiency of diesel trucks, rail transport, and aircraft are possible.

-- Residential and Commercial -- By 2025 accelerated improvements in building shells, lighting, space conditioning, and appliances could reduce energy consumption per square foot by 75% below current levels for residences, and by 50% for commercial buildings. The rate at which such improvements would find market acceptance both in increases in the building stock and in retrofitting or replacing the existing building stock is dependent on a number of complex economic factors, including the costs of such improvements, and therefore is quite uncertain.

Industrial Energy -- Advanced -industrial processes for energy-intensive basic materials, recycling of used basic materials steel, aluminum, and (i.e., glass), cogeneration, and improved electric motors could reduce industrial energy use significantly. This is especially important for most developing countries and Eastern Europe, where industrial energy is currently the largest share of total energy use and rapid growth is expected.

Reforestation may offer one of the most cost-effective technical options for reducing CO_2 and other gases. At some point, the costs of reforestation are likely to rise rapidly, as the costs of reforesting poorer lands rise or as the costs of bringing lands into forestry from other uses with high economic yields increases. The world-wide cost curve for reforestation opportunities is not well understood. Preliminary estimates of the feasibility of large-scale reforestation suggest that with aggressive reforestation programs the current deforestation trend might be reversed and that a significant net increase in forest biomass is possible. An effective program could include programs to increase forest biomass -- by replanting marginal agricultural lands, improving management of existing forests, building tree plantations, and increasing urban planting -- as well as programs to reduce demand for wood where resources are currently stressed. This, according to some estimates, could convert world forest management practices from a net source to a net sink for 0.7 petagrams of carbon/year, or more, by the year 2025.

• Elimination of chlorofluorocarbons (CFCs) and related compounds over the next decade appears technically feasible and costeffective. Substitutes or process changes now available or under development have been identified to reduce or eliminate almost all applications of CFCs and halons. Key examples are: -- Worldwide replacement of CFCs as an **aerosol propellent** with substitutes already in use in the U.S., Canada, and Sweden.

-- Replacement of CFC-12 with substitutes (such as HFC-134a or other hydrochlorofluorocarbons) in **mobile air** conditioners.

-- Replacement of CFC solvent use with aqueous cleaning in the electronics industry.

-- Replacement of CFC-blown foam insulation with other materials or use of alternative blowing agents.

• Several actions may be possible to reduce greenhouse gas emissions from agriculture. The magnitudes of the agricultural sources, as well as the potential effects of control measures, are difficult to quantify. Further detailed research and data collection will be required in order to produce credible estimates. Major agricultural activities of interest are:

-- Methane emissions from livestock might be reduced through increases in productivity of livestock systems and use of methanogenesis inhibitors for beef cattle.

-- Methane emissions from rice production may be reduced somewhat through productivity increases and removal of crop residues. In the long term, improvements in varieties of rice, soil amendments, and water management practices could decrease CH_4 emissions.

-- Biomass burning associated with agricultural practices produces N_2O , CO, and CH_4 . Changing those practices, for example, practicing sustainable agriculture or utilizing crop residues, is technically feasible and could substantially reduce emissions.

-- N_2O emissions from fertilizer use could probably be reduced through better placement of the fertilizer, nitrification inhibitors, and fertilizer coatings, which may also reduce farming costs and agricultural runoff problems. • Near-term reductions in greenhouse gas emissions from electricity generation are possible through:

Efficiency -*improvements* Improved fossil electricity generation technology, such as advanced combustion turbines and cogeneration, can increase the efficiency of using these fuels by up to 25%. More efficient transmission and distribution, availability or capacity improvements at existing non-fossil powerplants (i.e., nuclear, hydro), and changes in electric utility system operation (i.e., dispatching, wheeling across regions or even internationally) can reduce CO_2 emissions by a few percent per kwh of electricity delivered. The rate at which such efficiency improvements are likely to be implemented is uncertain. Electric generation facilities are long-lived, and the economic factors entering into decisions to replace existing facilities are complex.

Fuel switching -- Use of more natural gas to displace coal as a fuel for generating electricity could reduce CO_2 emissions by a substantial amount in the near term. The potential of this option is largely dependent on availability and cost of natural gas in the future. Wood, municipal waste, wind, etc., could play a somewhat larger role than they currently play in the near term.

• Alternative fuels that do not emit significant amounts of greenhouse gases could make an important contribution to reducing these emissions in the medium term and could virtually eliminate many categories of emissions over the long term. For widespread use of alternative fuels, important engineering, economic, environmental, and social issues must be resolved.

- Hydroelectric power is already making a significant contribution to global energy production. There appears to be a significant potential to expand this contribution, although environmental and social impacts of large-scale projects must be considered carefully. How great the potential for expansion, after taking into account the economic costs and benefits of available hydropower sites and the limitations due to environmental and social impacts, is unknown.

Biomass energy is currently being extensively utilized, particularly in developing countries. Current and emerging technologies could vasily improve the efficiency of that use. More advanced technologies, especially for conversion of biomass to gaseous and liquid electricity fuels and could become economically competitive within a decade. Measures to increase biological productivity are also under study. These advances would allow biomass to provide a much larger share of global energy services over the long term, particularly in developing countries. There are certain environmental and social issues associated with large-scale biomass use; these involve, for example, land use, competition with food production, and particulate and organic emissions.

Solar energy offers a large range Direct use of solar thermal of options. energy, either passively or in active systems, is already commercially available for water and space heating applications in many regions. These applications could be expanded considerably in the near to medium term. Solar thermal concentrating technologies are widely being tested for power generation or industrial process heat and are already competitive in some locations. Solar photovoltaic cells are economically competitive for remote some power generation needs, especially in developing countries. If current research and testing succeeds in lowering the cost in the next decade, solar electricity generation and/or photolysis could play a major role in meeting energy needs in the next century.

-- Geothermal energy resources are extensive and widely distributed. Systems are commercially available for electricity generation, and over 7 gigawatts of capacity are currently in operation worldwide. Technologies are improving and being demonstrated rapidly. It may be possible to expand this energy source significantly in the future.

-- Wind energy systems are currently commercial in some applications and locations. In recent years engineering advances have resulted in reductions in cost and improvements in performance. Assuming this trend continues, wind energy can play a larger role in future energy production.

-- Nuclear fission is a technology that is currently widely used and increasing its contribution to global energy supply due to the completion of powerplants ordered during the 1970s. High cost and concerns about safety, nuclear weapons proliferation, and radioactive waste disposal have brought new orders to a halt in most countries. It is technically feasible to expand the contribution of this energy source beyond what is currently projected in the future, if these problems are resolved.

Emission controls Control -technologies are currently available and in use in some countries that reduce CO and NO, emitted from automotive and industrial sources and NO_x produced by power generation at relatively low cost. Other technologies, which remove larger fractions of these pollutants but at higher cost, are also available. Emerging control technologies and combustion technologies with inherently lower NO_x emissions are being tested and could reduce NO_x emissions drastically at a lower cost. In a few very limited situations (i.e., combined with enhanced oil recovery), CO₂ recovery from powerplant flue gases may be economic.

• Methane emissions from coal seams, natural gas production, and landfills can be reduced. The current emissions from coal production and landfills are projected to grow in the future. Natural gas (primarily methane) is sometimes vented and often flared in conjunction with oil production. Technologies exist for economically recovering this methane and using it for energy production, thereby partially augmenting natural gas supply.

• Aggressive research programs may be the most important policy option for the long run. Resolution of several key technical issues could vastly expand the economically attractive options for reducing greenhouse gas emissions in the next century. Some important examples are: -- Improved characterization of sources and control options in several areas would allow better policy and research planning decisions to be made. Since sources of N_2O and CH_4 are poorly understood at present, field measurement and data collection work are needed to increase our understanding of the potential role that reductions in these emissions could play in an overall climate stabilization strategy. Detailed cost analysis is also needed for most of the technical reduction options identified to support policy decisions in the future.

-- Solar photovoltaic technology has been improving rapidly over the last decade. Continuing or accelerating this progress could bring this technology into widespread commercial viability early in the next century.

-- Biomass conversion technologies that could make substantially greater contributions currently exist. Commercial demonstrations of some existing technologies, additional research on advanced biomass conversion technologies, and improvements in biomass productivity could greatly expand the role of biomass energy.

Nuclear fission does not currently appear viable in many countries because of concerns about safety, waste disposal, proliferation, and cost. Research is underway in several countries to develop and demonstrate "second generation" fission technologies, which reduce cost and safety concerns. The establishment of waste disposal plans acceptable to society is also an area of intense study in several countries already committed to nuclear fission. Satisfactory resolution of these problems could expand the role of nuclear fission in future decades.

-- Energy storage technology could play a crucial role in integrating intermittent technologies such as solar and wind into energy supply systems. A number of promising concepts are currently under study. Accelerating research and testing to reduce cost and to improve performance of storage technologies for electrical energy could greatly expand the potential roles of some alternative energy sources.

Hydrogen energy systems offer a long-term potential for reducing or eliminating CO_2 emissions, if the hydrogen is produced from non-fossil energy inputs. Hydrogen is not a primary energy source but rather an "energy carrier," an intermediate form like electricity. As an energy carrier, it can help resolve some of the energy storage issues with renewables and substitute in some existing fossil-fuel applications. Research needs include improved conversion processes using solar, hydroelectric, nuclear, wind, or other renewable energy inputs. Additional concerns include transmission and storage and also applications to transportation, space heating, industrial processes, and other end uses.

Research in energy efficiency could be helpful in accelerating the rate of improvement and ensuring continued improvements over the longer term. Industrial technology, for example, could be developed to the extent that developing countries and Eastern Europe could substantially increase their standards of living without producing the enormous increases in CO_2 emissions that accompanied this development in the OECD. Further research to improve efficiency of automobiles and other vehicles could make a significant long-term contribution. Also potentially effective would be a major cooperative research effort to adapt advanced technologies that are being developed in the OECD to the particular constraints and needs of the rapidly industrializing areas.

-- Agricultural research to identify and develop alternative rice production systems, which reduce the production of methane, could play a significant role in a long-term solution to the greenhouse problem. Similarly, improvements in productivity and other technological options for reducing methane emissions from domestic animals (cattle, sheep, etc.) are possible. Concentrated research in these areas could make a major long-term contribution toward reducing greenhouse emissions.

INTRODUCTION

This chapter describes a wide variety of alternative technologies and other means by which greenhouse gas emissions from manmade sources could be reduced. It builds on the discussion in the previous chapter describing major sources of greenhouse gas emissions in some detail. The catalogue of technical options presented here provides a background for the development of scenarios that are presented in Chapter VI to illustrate the effects of possible combinations of emission reduction options over time. Α range of policy actions that might be taken to implement various technical measures for reducing emissions are described in Chapters VII and VIII, which address domestic and international policy, respectively.

The preceding chapters discuss the diverse sources and economic activities responsible for greenhouse gas emissions. It should not be surprising, therefore, to find that there is an equally diverse array of methods for reducing greenhouse gas emissions. The primary means of accomplishing this goal is the development and use of technologies that reduce energy requirements (i.e., improve energy efficiency), use less carbon-intensive fuels, or replace or reduce emissions of other greenhouse gases. In addition to this technological approach, there are also several areas in which management strategies are the means of greenhouse emissions. reducing gas particularly with respect to the buildup of gases resulting from some agricultural practices and the use of forest resources.

In general, technical options presented in this chapter assume that the level of consumer services remains constant. For example, technical options are presented that could dramatically reduce the energy consumed per square meter of residential buildings. It is assumed, however, that the number of square meters of residential space per capita would not change as a result of implementation of any technical measures. Obviously, policies could be implemented that encouraged smaller homes, smaller or fewer cars, less consumption of greenhouse gasintensive goods, etc. Such policies could be effective in reducing emissions, but involve

potentially difficult tradeoffs with standards of living or lifestyles. It is not the intent of this report to argue for or against such tradeoffs. Rather, the focus of this report is on identifying those emissions reduction measures that could be implemented with minimal impact on lifestyles. This appears to be a logical first step in the policy evaluation process.

The Role of Long-Term and Short-Term Options

In the time frames considered in this report, long-term options become critical. In order to stabilize or reduce the concentrations of greenhouse gases, new sources of energy supply and dramatic improvements in efficiency will be necessary. However, there is also much that could be done to reduce greenhouse gas emissions over the next decade by improving energy efficiency, making greater use of natural gas, reducing use of chlorofluorocarbons (CFCs), promoting reforestation and other applications of available technologies and techniques.

While the current generation of technical measures will not be sufficient to stabilize global greenhouse gas emissions several decades hence, efforts to adopt such technologies are exceedingly valuable for several reasons. First, reducing the rate of growth in global emissions now would make it easier to stabilize concentrations in the future because of the long atmospheric lifetimes of greenhouse gases. Second, shortterm strategies are often intermediate steps toward long-term strategies; for example, currently-available implementation of efficiency improvements will encourage the development of future efficiency improvements. Finally, the incentives necessary for longer-term strategies, such as emission fees on carbon-intensive fuels, will generally be consistent with short-term strategies.

Over the long term, the most important options are advanced, non-fossil energy technologies, combined with major breakthroughs in end-use technology that would drastically reduce energy requirements. Also, changes in agricultural and forest management technologies could become
important. In addition to the incentives that may flow out of short-term strategies, it is important in the short term to promote research and development by governments, and the identification and advancement of promising long-term technologies by the private sector.

The Economics of Control Options

For several reasons, this report does not attempt either a detailed comparison of the economic cost of specific emission reduction options or an assessment of the aggregate cost of entire emission reduction For one thing, the analysis scenarios. presented in this report is, of necessity, global and very long-term. It is very difficult, if not impossible, to produce credible estimates of global costs of policy scenarios. Similarly, it is of questionable value to project costs of alternative policy actions or particular technologies more than a hundred years into the future. A primary focus of this chapter is to identify techniques that appear promising today but are not yet widely accepted in today's markets. As discussed above, the need to foster new technological developments is necessary because of the long-term nature of the problem. The future costs of currently technologies emerging are inherently unknowable now.

It is more appropriate to begin serious cost analyses on a country-by-country basis and over a time horizon of a few decades. A number of such cost studies are underway now in the United States Environmental Protection Agency (U.S. EPA) and other U.S. agencies as well as in other countries. Even when limited to individual countries and shorter time horizons, however, many difficulties remain in evaluating costs of alternatives. For example, the cost of some options is difficult to evaluate partly because the absence of a market for reducing the risks of climate change has meant relatively little effort toward research and development.

The recent rapid development of substitutes for CFCs demonstrates the importance of creating a market incentive to improve technology and reduce costs. Until it became apparent that environmental regulation would create a market for CFC substitutes, industry reported that there were few feasible options at any price. Now, an intensely competitive race to commercialize substitutes is underway around the world at costs orders of magnitude below estimates from just a few years ago.

Similarly, current prices may not accurately reflect costs since climate change is a potential major cost not currently reflected in the cost of goods and services. As discussed in Chapter VII, it may be desirable to incorporate the risk of climate change into markets through the imposition of carbon fees or other policies, in which case currently more expensive options may become more competitive.

A detailed economic analysis of options discussed in this report has not been attempted for all of the reasons discussed above. It is worth noting, however, that anecdotal information and partial analyses cited in this chapter indicate many of the near-term reduction options are economically justified, or nearly so today, even based on current prices. This is particularly true for measures to improve energy efficiency, where substantial opportunities for cost saving investments exist despite recent progress. Chapter VII discusses these opportunities as well as some of the current constraints to their implementation.

Worldwide Emissions and Control Techniques

Figure 5-1 shows the contribution to global warming, by trace gas and by sector. Figure 5-1a identifies the "greenhouse gases" and illustrates their estimated percentage contributions to the greenhouse effect in the All of these gases are produced 1980s. through a diverse range of human activities, which we have classified into five broad categories. Energy-related activities have been broken down into two categories: "applications" of energy, that is, energy services, or "end uses," and the production of energy, or energy supply. Other emissionsproducing activities are related to industry, which include the use of CFCs, forestry (particularly deforestation), and agriculture. Often a single broad category of activity -fossil energy consumption, deforestation, for example -- contributes to several of the gases





of concern. Figure 5-1b shows the proportions that the major categories of human activity contribute to global warming.

As the modeling results in the next chapter make clear, the U.S. is likely to for a declining share of future account greenhouse gas emissions. Stabilizing concentrations will require control options applicable to the needs of other countries, particularly developing countries with very different resources. The special conditions in the Soviet Union and Eastern Europe may also require somewhat different technical approaches. Some technologies, such as more efficient lighting, are relevant to virtually all parts of the world, but other needs vary considerably. This chapter therefore discusses improved cookstoves, strategies for arresting tropical deforestation, and other options of particular relevance to developing countries. It also identifies special needs in the USSR and Eastern Europe such as improvements in existing district heating systems and the industrial infrastructure. Table 5-1 illustrates some of the promising options for various regions under near-term and long-term time horizons.

Organization of this Chapter

Because of the enormous amount of information presented in this chapter (in truth, a separate chapter could be devoted to each major source category discussed here), we have departed somewhat from the format used throughout the rest of this Report to Congress and divided the remainder of this chapter into five parts.

The first two parts discuss energyrelated activities. The single most important determinant of greenhouse gas emissions is the level of energy demand and the combination of sources used to supply that Energy use causes, in different energy. proportions, emissions of five important gases: carbon dioxide (CO_2) , carbon monoxide (CO), methane (CH_{4}) , nitrous oxides $(N_{2}O)$, and nitrogen oxides (NO_x). Energy use is integrally linked with virtually all forms of economic and recreational activity within In developing industrialized countries. countries, current biomass energy use contributes to greenhouse gas emissions, and potential increases in commercial energy use could be the largest source of increasing greenhouse gas emissions in the future.

Thus, evaluation of the options for reducing greenhouse gas emissions from energy use must begin with a systematic analysis of all aspects of energy use. Although there are "end-of-pipe" control options for removing some of the relevant emissions from energy use, while leaving the basic process intact, the potential impact of such approaches is very small relative to the magnitude of the overall problem. Given the dominance of fossil fuels as a source of greenhouse gas emissions, technologies to reduce use of fossil fuels must play a central role in any effort to stabilize concentrations. Accordingly, a major focus for policies to reduce emissions, discussed in Chapters VII and VIII, must be to promote demand-side measures that reduce total energy demand and supply-side measures that promote less carbon-intensive fuels. Technologies to achieve these goals are a major focus of this chapter.

PART ONE: ENERGY SERVICES reviews the basic applications for which energy is ultimately used and the greenhouse opportunities for reducing emissions at the point of end use. PART **ENERGY SUPPLY** reviews energy TWO: supply, conversion activities, and related opportunities for reducing emissions. This includes improvements in efficiency in energy conversion and distribution and the potential for increasing supplies of non-fossil energy Also discussed are reductions in sources. emissions of CH_A from coal mining and natural gas production and distribution.

PART THREE: INDUSTRY discusses technical options for controlling emissions from industrial activities. Non-energy industrial activities contribute to greenhouse warming in three significant ways. First and foremost, industrial activities are the source of all CFC emissions. As discussed in Chapters IV and VIII, an international process is already underway to reduce global emissions of CFCs because of their role in depleting the stratospheric ozone layer. This

TABLE 5-1

Key Technical Options By Region and Time Horizon

Region	Near Term (by 2010)
OECD	Energy Efficiency autos, lighting, space heating CFC Controls Reforestation Technology Development
Developing Countries	Energy Efficiency industrial processes, transport Low-Carbon Energy hydroelectricity, biomass, natural gas Reversing Deforestation
Eastern Europe	Energy Efficiency industrial processes, space heating, transport Natural Gas Non-fossil electricity
All Regions	Long Term
	Alternative Fuels biomass, solar, nuclear, hydrogen Agriculture rice production, animals Forest Plantations

chapter discusses the technical potential for reducing CFCs beyond the level required under the current protocol.

A second source of industry-related emissions are landfills, which produce emissions of CH_4 . This source category represents a small portion of total methane emissions, but emissions from this source could increase rapidly in the future. Finally, production of cement produces CO_2 as a process emission (in addition to CO_2 produced by energy consumption). This again is a small component of total CO_2 emissions currently, but the percentage contribution from cement production has been growing rapidly in recent years.

PART FOUR: FORESTRY examines current forest management practices (resulting in a net annual loss of biomass), which account for a significant share of emissions of CO₂ and CO as well as some portions of other gases. It should be noted that the importance of forestry is greater than its percentage contribution to global warming as implied in Figure 5-1. Forests are the only category that, over time, can be shifted from a source to a major sink for carbon. It is technically possible, though by no means simple, to reverse the long-term trend of global deforestation and to begin increasing the amount of forested lands. There are several components to reforestation strategies that need to be considered. For example, reductions in demand for forest products (e.g., fuelwood) in some areas may be necessary to relieve the pressures that have caused deforestation in recent years.

PART FIVE: AGRICULTURE examines the technical options for reducing emissions resulting from agricultural activities, which are an important source of CH_4 , N_2O_2 , NO_x, and CO. The principal activities of interest rice production, enteric are fermentation in domestic animals (primarily cattle, sheep, etc.), fertilizer use, and biomass It is apparent that considerable burning. flexibility exists, particularly over the long term, to alter agricultural practices in the specific categories that constitute the large emitters, but the technical potential is difficult to quantify.

In general, most of the research and analysis of agriculture to date has focused on opportunities for improving productivity. Productivity improvements should automatically lead to some reductions in greenhouse gas emissions per unit of output; however, this relationship is not well quantified. Additional options for reducing emissions, beyond productivity changes, can be envisioned for each of the specific categories mentioned, though, again, very little work has been done as yet to quantify the potential effects and costs of such options.

Limitations

In this review the information presented, although somewhat detailed, can only begin to illustrate potential technical options that currently appear most promising. The analysis also highlights the uncertainties and need for further study of many options. In some cases, the impact of specific technologies cannot be estimated at present, for example, technologies for reducing emissions from agricultural sources. In general, however, there are fewer uncertainties about how to achieve emission reductions than there are about the rate of warming, change in climate, and the ultimate effects of an increase in greenhouse gas concentrations. While some currently emerging technologies may not fulfill current expectations, the options are sufficiently diverse that we can encourage the development and use of technologies that are relatively less intensive sources of greenhouse gas emissions if we so choose.

The source of most of the uncertainties discussed in this chapter is the difficulty of predicting future technological developments. Many of the options that may have the greatest impact on the buildup of greenhouse gases, such as the development of new engine technology for cars, new designs for nuclear plants, and the use of hydrogen as a substitute for liquid fuels, are long-term possibilities that require substantial further research. It is important to recognize several key limitations:

• The discussion cannot deal exhaustively with the tremendous range of

technical options that have been identified in the areas of energy efficiency improvements, fuel substitution, industrial emissions reductions, forest management, and agriculture.

. Because of the limited information available, but even more so because of the extensive scope of this study (in terms of emissions-producing activities as well as the global diversity of emissions), it was not possible to provide detailed quantification of expected emissions reductions and costs for many of the technical options discussed.

• Much data development and detailed analytical work remains to be done. A more detailed technical assessment of U.S. emission reduction options and costs, also mandated by Congress, is now underway and will be completed in 1990 by the U.S. Department of Energy and U.S. EPA.

• Estimates of the potential performance of technical options, as discussed in this chapter, are often based on engineering design calculations, prototype performance, laboratory results, etc. Actual achievable performance may be less, in practice, since mass production often requires some engineering compromises relative to laboratory or prototype specifications. Also, performance of technology under conditions of day-to-day use often deteriorates somewhat from design or new product performance. On the other hand, currently unforeseen developments may improve performance beyond levels estimated today.

This chapter identifies and . attempts where possible to quantify technical potentials for reductions in greenhouse gas Even where technical options emissions. appear economically attractive on a life-cycle basis, there are generally institutional, behavioral, and policy constraints that currently operate to limit their market penetration. The portion of identified technical potential that can be achieved in practice is largely a function of the availability and effectiveness of policy options, as discussed in Chapters VII and VIII.

PART ONE: ENERGY SERVICES

The services that energy provides (also often referred to as end uses), such as lighting and fuel-driven locomotion, are an integral part of human society and, at the same time, constitute the largest category of greenhouse gas emissions. While the production and conversion of primary energy (e.g., coal, oil, gas) is the immediate source of a large portion of energy-related greenhouse gas emissions, it is the application of this energy to provide specific services that justifies this production and conversion. Thus, minimizing the energy required to provide various services or using non-fossil fuels in specific end-use applications can reduce productionand conversion-related emissions as well.

For convenience, energy services are classified as belonging to one of three major transportation, residential/ sectors: commercial. and industrial (including agriculture). Each of these sectors uses energy in distinctly different ways and offers different opportunities for reducing energy use and/or shifting to alternative fuels. Figure 5-2 shows the relative contributions of the three sectors to global energy use as of 1985. Figure 5-2a shows the secondary energy actually consumed at end-use points. Figure 5-2b shows the energy use by sector in primary energy production equivalent terms; that is, the production, conversion, and transmission losses are ascribed to the enduse sectors based on the characteristics of the Figure 5-2c shows the energy they use. proportions that the equivalent primary energy use for these three categories contributes to global greenhouse emissions in the 1980s. The differences are due to the variations in greenhouse gas emissions from the different primary energy sources.

There are two time horizons that are useful in discussing technical options for energy services. Near-term options refer to technologies currently available or expected to be commercially available by the year 2010. These are the options about which information is available; such information could provide a basis for near-term policy action. Long-term options are those that are not expected to be available until after 2010 and, in some cases, well after.

An attempt is made to hypothesize about potential technological developments over the longer term and to discuss the role research could play in accelerating the availability of advanced options. Some of these technologies are speculative and require additional research. They are included in the analysis because they have the potential to play major roles in the long run.

In discussing global energy-use patterns, it is important to distinguish between modern and traditional energy forms, particularly in order to understand energy use in developing countries. For this discussion, the terms modern or commercial energy are used to describe all fuels and energy forms that are priced and sold in energy markets (or, in the case of centrally-planned economies. accounted for and valued in national economic planning). In this category are virtually all of the fossil fuels, which are the major source of greenhouse gases, as well as electricity from all sources. Readily available energy statistics, which pertain almost exclusively to modern energy, accurately represent energy-use patterns in industrialized countries.

For developing countries, however, traditional energy accounts for a substantial fraction of the total energy used. This type of energy includes fuels such as firewood, agricultural waste, and animal waste that are gathered and used informally, usually without being priced and sold in commercial energy markets.

Technical options, especially in the near term, vary substantially from region to region and often among individual countries. For each of the sectors discussed in this part (transportation, residential/commercial, and industrial), we look first at near-term options,





for industrialized countries, developing countries, and the USSR and Eastern Europe, then briefly discuss the long-term options.

The industrial market economies, the members of the Organization for Economic Cooperation and Development (OECD), have many similarities in terms of economic activities and resources, and hence are discussed as a group. Energy use in these countries is relatively high but not expected to grow rapidly; rising incomes are being devoted increasingly to products that do not require significant energy inputs.

The developing countries are vastly different from industrialized countries both in current levels and types of economic activities and available resources. Energy use in the developing countries will grow significantly in the future, but there is great uncertainty about the rate of growth.

The USSR and Eastern Europe share with most developing countries a much greater emphasis on government intervention in economic planning and industrial activities than occurs in OECD countries. On the other hand, these countries have massive and, in many ways, technologically sophisticated industrial infrastructures that are in some ways more similar to those of the OECD countries than they are to the industrial infrastructures of most developing countries. Energy use in Eastern European countries (and associated greenhouse gas emissions) has been growing rapidly and is expected to grow in the future. While less is known about the technical potential to reduce emissions in these countries, it is generally believed that very substantial improvements can be made in energy efficiency.

TRANSPORTATION SECTOR

Transportation currently consumes approximately 27% of global modern energy use. Virtually all of the energy used in transportation is derived from oil. In 1985 in OECD countries, energy used for transportation accounted for about 23% of all energy consumed (27% in the U.S.), expressed as primary energy equivalents. As a share of secondary energy consumption, transportation accounted for about 34% in the OECD, approximately 97% of which was oil (U.S. DOE, 1987b).

In industrialized countries it is likely that the private automobile will continue to be the primary means of transportation in the near future. Fortunately, there are near-term opportunities for improving the efficiency of this mode of transportation. Near-term improvements in efficiency of freight transport and aircraft will also be cost-effective over the next few decades. A few industrialized countries (e.g., Canada, New Zealand) are also pushing ahead with major alternative fuels programs in the near term.

Over the longer term, additional reductions in energy consumption may come from shifting to more efficient modes of transportation and substitutes for transportation (e.g., advanced communication technologies). Also, increasing the use of non-fossil-based fuels in the transportation sector is essential in order to greatly reduce or eliminate greenhouse gas emissions (see **PART TWO: ENERGY SUPPLY**).

In developing countries and the USSR and Eastern Europe, transportation currently accounts for a smaller percentage of total energy use. (In some African countries, however, the percentage is much higher.) However, in the future, as economies expand and incomes rise in these regions, the potential exists for explosive growth in transportation energy use.

Near-Term Technical Potential in the Transportation Sector

With aggressive programs to improve transportation energy efficiency across the board in industrialized countries, it appears that significant overall reductions could be made over time. By 2010 in the OECD, improvements in the efficiency of light-duty vehicles and freight transport could reduce energy use in the transportation sector by about 7 exajoules (EJ) from expected levels. If the same efficient technologies were transferred to developing countries and the USSR and Eastern Europe, even larger reductions below expected levels could be achieved because of the rapid expansion of vehicle stock in those areas. This suggests

that the technical potential may exist to reduce energy use 25 EJ worldwide by 2010. Furthermore, it appears that there are alternative fuel options that could be implemented during this time period, which could reduce the greenhouse gases emitted unit of energy consumed per in transportation. The overall potential of these options has not been quantified. Near-term options in the various regions are discussed below.

Near-Term Technical Options: Industrialized Countries

Within the transportation sector, technical options to reduce greenhouse gas emissions include improvements in fuel efficiency, alternative fuel use, stricter and more universal emissions control, improvements in urban planning, and greater use of mass transit.

Increase Fuel Efficiency

Light-duty vehicles, mainly passenger cars, account for the bulk (about 63%) of current transportation energy use (see Figure 5-3). Other major contributors are freight transport vehicles (diesel trucks, ships, and railroads), accounting for about 25%, and aircraft, primarily those used in passenger travel, accounting for 12% of transportation energy.

Light-Duty Vehicles. In the past decade, a great deal of attention has been devoted to options for improving the efficiency of lightduty vehicles. Consequently, a number of very promising approaches have been identified and well-documented (see Bleviss, 1988; Goldemberg et al., 1988, for more extensive discussions of the technical options for improving the fuel efficiency of light-duty These efficiency improvements vehicles). must be considered in the context of several societal and consumer concerns related to light vehicles, such as urban air quality, safety, comfort, and performance. These other goals also affect the patterns of vehicle technology development.

Although average fuel efficiency for new cars in the industrialized countries is between 25 and 33 miles per gallon (mpg), or 7.7-10 liters $(\ell)/100$ kilometers (km) (IEA, 1987), several vehicles that are roughly twice as efficient are commercially available: the Honda Civic and the Chevrolet Geo Metro both average greater than 50 mpg (5 $\ell/100$ km).

It is important to note that all of the new-car fuel economy figures for the U.S. are nominal values based on a standardized U.S. Environmental Protection Agency (U.S. EPA) test procedure. Estimates for other countries are aiso generally based on similar standardized tests. In the U.S., it has been established that this procedure produces estimates that are approximately 15% higher than the actual on-road performance of these In addition, it has been new vehicles. suggested (Geller, 1989) that this differential is increasing and likely to continue to increase in the future because a larger share of total vehicles will be operated in urban areas where congestion and other factors may adversely affect fuel economy.

Moreover, these mpg estimates apply to automobiles only. In the U.S., though not in most other OECD countries, there has been a recent trend toward the use of lighter duty trucks -- pickups, vans, etc. -- as passenger vehicles. In general, new light trucks are significantly less fuel efficient than new automobiles. In addition, in recent years in the U.S. there has been a trend toward keeping old cars on the road longer (Watkins, 1989). All of these factors could reduce the projected impact of improvements in newautomobile fuel economy, discussed below. These issues have not been addressed in detail and deserve greater attention in future analysis.

As indicated in Table 5-2, there are larger prototype vehicles currently being tested that are substantially more efficient. It is important to note that these are considered "concept vehicles" by the industry. Such vehicles are often designed to demonstrate the maximum potential of certain technologies without regard to mass production cost, feasibility, and emissions requirements. In addition, desired product attributes such as driveability, comfort, and power may also be reduced in order to increase fuel economy in these vehicles. It is inappropriate, therefore,





Source: OECD, 1987.

TABLE 5-2

High Fuel Economy Prototype Vehicles

Company	General Motors	British Leyland	Volkswagen	Volkswagen	Volvo	Renault	Renault	Peugeot	Peugeot	Ford	Toyota
Model	TPC (Gasoline)	ECV-3 (Diesel)	AUTO 2000 (Diesel)	VW-E80 (Diesel)	LCP2000 (Diesel)	EVE+ (Diesel)	VESTA2 (Gasoline)	VERA+ (Diesel)	ECO 2000 (Gasoline)	(Diesel)	AXV . (Diesel)
Number of Passengers	2	4-5	4-5	4	2-4	4-5	2-4	4-5	4	4-5	4-5
Aerody- namic Drag Coefficient	.31	.2425	.25	.35	.2528	.225	.186	.22	.21	.40	.26
Curb Weight (lb)	1 040	1460	1716	1540	1555	1880	1047	17 40	990	1875	1430- Target
Maximum Power (hp)	38	72	53	51	52,88	50	27	50	28	40	56
Fuel economy (mpg)	61 City 74 Hwy	41 City 52 Hwy	63 City 71 Hwy	74 City 99 Hwy	63 City 81 Hwy	63 City 81 Hwy	78 City 107 Hwy	55 City 87 Hwy	70 City 77 Hwy	57 City 92 Hwy	89 City 110 Hwy

Source: Bleviss, 1988.

to assume that fuel economy levels achieved by prototypes could be readily achieved by production vehicles in the near term. On the other hand, the prototypes do illustrate that a wide range of technologies exist to improve on today's fuel economy levels.

Box 5-1 outlines several examples of the many automobile fuel-efficiency improvements already possible with current

technology. Research is proceeding rapidly undoubtedly and will yield further opportunities for improved fuel efficiency in the next decade. It is clear that opportunities exist for major reductions in light-duty fuel use by the end of this century. This is particularly true for the United States, which is still behind most other industrialized countries in the average fuel efficiency of new cars sold (see Table 5-3), partly because of

BOX 5-1. Technologies for Automotive Fuel Efficiency

- Weight Reductions -- Many of the most efficient cars substitute non-traditional materials for steel to achieve weight reductions, which contributes to their superior operating efficiency. Much greater weight reduction appears possible by substitution of high-strength steels, aluminum, plastics, ceramics, and composite materials (Bleviss, 1988).
- Aerodynamic and Drag Improvements -- In 1979 the average "coefficient of drag" (C_D) for the U.S. was 0.48, and for Europe, 0.44. Currently, some production models such as the Ford Sable and Taurus, Subaru XT Coupe OL-10, and Peugeot 405 achieve a C_D of 0.3 or less. An experimental prototype, the Ford Probe V, has achieved a C_D of 0.137 (Bleviss, 1988). Incorporating some of the prototype design features could reduce drag for production vehicles significantly over the next decade. Rolling resistance is being reduced with advanced radial tires. General Motors has recently introduced a "fourth generation" radial tire that reduces rolling resistance by 10-12% from the previous generation. An Austrian company has developed a more advanced tire concept, a liquid-injectionmolded (LIM) polyurethane tire. Preliminary tests indicate improvements in rolling resistance as well as tread mileage (Bleviss, 1988).

Engine and Drive Train Improvements -- Several researchers have identified a number of improvements to conventional light-vehicle propulsion systems and transmissions that could dramatically increase efficiency (see Bleviss, 1988; von Hippel and Levi, 1983; Gray, 1983; OTA, 1982). One interesting example is the use of continuously variable transmissions (CVT), which eliminate some of the energy losses during shifting and allow the engine to be operated closer to full load at varying speeds. Another possible innovation is an engine-off feature with energy storage capability during idle and coast. In addition, advanced engine designs currently in prototype could be much more fuel efficient than current technology. One example is the adiabatic diesel engine shown in Box 5-2.

TABLE 5-3

Actual Fuel Efficiency for New-Passenger Cars (Gasoline consumption in liters per 100 kilometers)

								Projections/Targets		
	1973	1978	1 97 9	1980	1982	1983	1984	1985	1990	2000
Australia	NA	11.8	11.2	10.1	9.8	9.5	9.5	· · · · · · · · · · · · · · · · · · ·	8.5 ^a	
Canada	NA	11.5	11.5	10.3	8.5	8.5	8.4	8.2	7.4	6.8 ^b
Denmark	9.0 ^c	NA	NA	8. 6	NA	7.3	7.0	7.1		
Germany	10.3	9.6	9.4	9.0	8.3	8.0	7.7	7.5		
Italv ^d	8.4	8.3	8.3	8.1	8.3	8.0	NA	7.8	7.4	
Japan	10.4	8.8	8.6	8.3	7.7	7.8	7.8	7.8		
Netherlands	NA	9.2	8.9	8.8	8.5	NA		9.1	8.6	7.8
Sweden	NA	9.3	9.2	9.0	8.6	8.6	8.5	8.5		
United Kingdom	11.0	9.1	9.0	8.7	8.1	7.9	8.8	7.6		
United States	16.6	11.8	11.6	10.0	8.9	9.0	8.9	8.7	8.8	8.2

^a 1987 target.

^b 1995.

^c 1975.

^d The figures for Italy represent average efficiency of the total car fleet.

Source: IEA, 1987a.

the preference for larger cars in the U.S. If light trucks were included in these averages, the U.S. would be even further behind most other OECD countries.

Despite the fact that improvements have been identified, it is not clear whether, and at what rate, new technology will be into automobile incorporated designs. Clearly, opportunities for dramatic efficiency improvements exist, but costs associated with these opportunities must be considered. Several years ago, the U.S. Office of Technology Assessment (OTA) conducted a detailed analysis of the potential for and cost of future improvements in the fuel efficiency of new automobiles. The study, which was based on extensive interviews with automobile manufacturers and other fuel-efficiency experts found that it was technically feasible to achieve average new-car fuel efficiency in the range of 50-70 mpg $(3.4-4.7 \ \ell/100 \ \text{km})$ by 2000. It also found that "the consumer costs of fuel efficiency range from values that are easily competitive with today's gasoline prices to values that are considerably higher" (OTA, 1982).

OTA found that the projected cost of efficiency improvements varied considerably, depending on the actual performance of potential design changes, whether production techniques to hold down variable cost increases are successfully developed, and the value consumers place on future fuel savings. Under optimistic assumptions, OTA estimated the cost of fuel efficiency measures to be as low as \$60-\$130 per car during the 1985-2000 time period. Under alternative assumptions, the cost of efficiency improvements could be as high as \$800-\$2,300 per car.

Von Hippel and Levi (1983) conducted a computer analysis of the cost of introducing a number of specific measures that would improve fuel efficiency, beginning with the 1981 Volkswagen Rabbit diesel. A package of specific improvements that would improve the fuel economy from 5.2 to 3.3 $\ell/100$ km (45 to 71 mpg) was estimated to cost about \$500 per car.

Goldemberg et al. (1988) and Bleviss (1988), however, suggest that cost estimates

toward the lower end of the OTA range are more likely for several reasons. First, the efficiency improvements would yield a number the consumer. other benefits to of Alternative materials, for example, could also reduce maintenance costs. There is also some anecdotal evidence that, contrary to popular expectations, use of more plastics and plastic composites may in some cases increase passenger safety (Bleviss, 1988). In other cases, alternative materials may reduce safety. The inclusion of the engine-off feature may prolong engine life. If the value of these other benefits is deducted from the cost of fuel-efficiency improvements, more rapid improvements may be cost-effective.

A second reason for lower cost estimates is that the cost of individual improvements may not be additive. Some costs may be offset by the savings from combining measures and integrating a number of related changes into ongoing production process changes. Vehicle manufacturers periodically make major investments in design changes, incorporating style concerns as well as engineering improvements. Chrysler recently conducted a study comparing the costs of producing a conventional steel vehicle and an alternative made principally of composite plastics. Although the composite material is more costly, its use allows a dramatic reduction in the number of parts and hence, assembly costs. The study concluded that the number of parts might be reduced by as much as 75%, and that the overall production costs for the composite vehicle would be only 40% of those for the corresponding steel vehicle (Automotive News, 1986).

On the other hand, automobile manufacturers have expressed the view that further fuel efficiency improvements may be more difficult and costly to achieve than estimates from the early 1980s suggest (Plotkin, 1989). Concerns raised by the manufacturers include the following:

• Most of the cost-effective efficiency measures that are acceptable to consumers have been implemented in the last decade.

• Performance of actual production models incorporating design changes for efficiency have fallen short of engineering calculations.

• There are major technical uncertainties and marketability problems associated with many of the fuel-efficiency technologies (e.g., advanced diesels, two-stroke engines).

• Real trade-offs do exist between further fuel-efficiency improvements and environmental standards (particularly for nitrogen oxide $[NO_x]$ emissions) and safety standards.

Other recent research on potential fuel economy improvements has also emphasized the difficulties of achieving cost-effective improvements in the near term. For example, in diFiglio et al. (1989), several constraints on vehicle efficiency improvements were noted, including that auto manufacturers require several years to retool existing production lines, decisions on production are essentially locked in already for the next several years, and the technical acceptability of many efficiency improvements has not been demonstrated on many models. Also. consumer purchasing decisions are affected by including vehicle many factors. size. acceleration. braking, maneuverability. Nevertheless, diFiglio et al. comfort, etc. that some efficiency pointed out improvements are cost-effective, even if vehicle size, performance, and ride quality are held constant to current (1987) levels. They noted that new-car fuel efficiency could be increased 17% (to 31.6 mpg) by 1995 at a net savings to the consumer (i.e., including fuel savings using a 10% discount rate over four years). Additional improvements to surpass 36 mpg would be cost-effective over the life of the vehicle by 2000 (also see Plotkin 1989).

Fuel Efficiency Tradeoffs. The governments of many industrialized countries regulate light-duty vehicles to reduce emissions of a number of air pollutants. In addition, consumers value performance attributes other than fuel efficiency, as well as comfort, safety, and cost in their choice of automobiles. To the extent that proposed fuel-efficiency improvements or alternative fuels involve tradeoffs against these other goals, or *are perceived* to require such sacrifices, they may be more difficult to implement.

Safety is a major concern long associated with light-duty vehicles. Some industrialized countries regulate the manufacture, sale, and maintenance of vehicles to improve safety. In the 1970s and 1980s, U.S. safety standards significantly improved vehicle safety. Some evidence exists of a correlation between size and weight reductions and increases in injury and fatality for currently available vehicles (OTA, 1982). Clearly, effects on safety must be considered in the evaluation of technical alternatives for improving fuel efficiency.

Weight reductions to improve efficiency may in fact reduce the structural strength of vehicles, thus making them less safe. It is not true, however, that the use of lighter materials necessarily reduces safety. Early attempts in the 1970s to improve fuel efficiency often involved simple weight reductions throughout a vehicle with corresponding declines in crashworthiness. In recent years manufacturers have employed other methods to achieve weight reductions, including the use of lighter, composite materials and changes in body designs that maintain or enhance structural integrity. These types of improvements are reflected in U.S. government crash tests where some smaller vehicles have consistently shown superior crash performance to other vehicles weighing as much as 50% more (Bleviss, 1988). In contrast, some comparatively heavy vehicles have the lowest crashworthiness ratings among available models. These crash tests, however, do not accurately reflect safety concerns in crashes between vehicles of different weights.

Weight reductions, aerodynamic design and engine improvements could also stimulate increased use of composites, plastic, and other new materials. Ultimately, these materials might present new solid waste disposal problems as the cars are eventually scrapped. This area should be evaluated in more detail in the future.

Emissions are another major concern associated with automobiles. Vehicles emit several pollutants -- particulates, volatile organic compounds (VOCs), carbon monoxide (CO), and nitrogen oxides (NO_x) -- which contribute directly to urban air quality problems and indirectly to climate change. Some options for increasing fuel efficiency (and thus reducing greenhouse gas emissions) have the potential to worsen local air pollution problems. For example, diesel engines are more fuel efficient than gasolinepowered automobiles, but diesel engines tend to produce greater emissions of particulates of (many which аге cancer-causing compounds) per mile travelled.

The design of vehicle emission standards can be another complicating factor. In most industrialized countries pollutant emission requirements for vehicles are applied on a grams-per-mile (or kilometer) basis. One concern about this approach is that it mav not encourage development of technologies that would simultaneously improve fuel efficiency and reduce emissions of urban air pollutants, even though such technological options exist (Bleviss, 1988). In addition, as fuel efficiency improves, the marginal cost of driving would decline, assuming fuel prices remain constant, which might induce vehicle operators to drive more than they otherwise would. If this effect is significant, it would offset some of the expected reductions in greenhouse gas emissions and could also result in a net increase in emissions of conventional urban air pollutants.

Conversely, some of the options for reducing emissions of pollutants can lead to increases in emissions of greenhouse gases. As noted above, switching to methanol fuels could increase greenhouse gas emissions if the methanol is derived from coal. Similarly, use of electric cars might result in net increases in greenhouse gas emissions if the electricity were generated from fossil fuels, although recent evidence indicates that electric cars would likely achieve a net reduction in emissions.

There are potential solutions to all of the problems illustrated. For example, new diesel cars are much cleaner than earlier models. Mercedes Benz and Volkswagen have now developed emission control devices that make it possible for their diesel cars to meet the strict California particulate standard of 0.2 grams/mile (Bleviss, 1988). In addition. emission standards could be modified (e.g., to grams per gallon in conjunction with higher efficiency standards, or direct regulation of carbon dioxide $[CO_2]$ emissions) to encourage fuel-efficiency improvements that would also benefit local air quality. Over the long term, it is important that options like methanolfueled and electric vehicles are promoted in conjunction with non-fossil (or at least low carbon) energy inputs.

Many consumers are concerned about sacrificing size, comfort, οг driving performance to achieve major improvements in fuel economy. On the other hand, many consumers may also be concerned about the environmental impacts of their consumption patterns, and willing to alter those patterns, if informed of the environmental implications. Nonetheless, analysts have demonstrated possible design changes that would reduce fuel consumption while retaining the size and performance of a large automobile (e.g., Forster, 1983).

Some of the prototype high-efficiency vehicles have already demonstrated that size and acceleration do not necessarily have to be sacrificed. The Volvo LCP 2000, with an average fuel efficiency of 65 mpg $(3.9 \ \ell/100$ km), accelerates from 0 to 60 miles per hour in 11 seconds -- compared with 13.1 seconds for the average acceleration of the U.S. newcar fleet (1986 models, which averaged only 28 mpg [8.4 $\ell/100$ km]). Likewise, a recently developed lightweight prototype car, by Toyota, is designed to seat five to six passengers while achieving 80 mpg (2.9 $\ell/100$ km) under urban driving conditions (Bleviss, 1988).

In summary, it appears technologically feasible to achieve average new-car fuel efficiency of at least 40 mpg $(3.8 \ l/100 \text{ km})$ in the U.S. by 2000. A new fleet average of 50 mpg $(4.7 \ l/100 \text{ km})$ would be technically feasible with continuing technical innovation, size reductions, and vehicle turnover. This would require a strong commitment by government and industry, but the reductions in energy use, and greenhouse gas emissions, from this improvement would be significant. However, a new car fleet average of 40 mpg by the year 2000 could require size, performance, and safety reductions. The length of the development period and the degree of technical change requiredto achieve a new fleet 50 mpg average without compromising safety and other desired product characteristics are highly uncertain.

The U.S. Department of Energy (U.S. DOE, 1987c) has projected that automobile vehicle miles travelled (VMT) in the U.S. will increase over 50% by the year 2010 (from 1,315 to 2,032 billion miles). In calculating future transportation energy use, the report also projects that automobiles will average about 27 mpg (8.7 *l*/100 km) in 2010 (overall average of all operating vehicles, not new-car average). If automobiles averaged 50 mpg $(4.7 \ \ell/100 \text{ km})$, the energy consumed would be reduced by over 45%, or more than 30 billion gallons of gasoline (3.8 EJ^1) in 2010 -- more than a 40% decline from the 1985 consumption level (as opposed to the 7% increase projected by U.S. DOE). То achieve these results, it would be necessary for automobiles to perform at the specified on-road fuel efficiency over the life of the vehicle. Currently, there is a widening gap between nominal test values and on-road performance as well as considerable degradation in fuel efficiency over the life of an automobile. These factors require further study and could limit the expected energy savings from fuel economy programs.

In addition, the current trend in the U.S. toward the use of light-duty trucks for personal transportation could offset some of the efficiency gains if it continues in the future. Efficiency improvements in light-duty trucks and/or programs to discourage personal use of these vehicles could produce significant energy savings in the U.S. The recent trend toward slower turnover of older vehicles could also offset efficiency improvements if it continues. Conversely, programs to stimulate more road turnover and scrappage of older vehicles could improve efficiency gains. Decreasing fuel use in the U.S. could also support many important national goals such as reducing international trade deficits and

improving energy security. Improvements of this magnitude could be made for the OECD as a whole and would undoubtedly also spill over to the non-OECD countries that produce vehicles for sale in the OECD and/or import vehicles or technology from the OECD. Most light-duty vehicles currently in production are derived from designs that originated in the OECD (Bleviss, 1988).

Freight Transport Vehicles. Diesel trucks use about 14% of the oil consumed for transportation in OECD countries (von Hippel and Levi, 1983). Improvements in efficiency in this sector could, therefore, have a noticeable effect on total energy use. Current prototype vehicles could reduce energy use per ton-mile in the U.S. by as much as 40% for truck transport (Automotive News, 1983). Goldemberg et al. (1988) have estimated that further improvements on the order of 50% or better could be achieved with existing technology and at reasonable cost. Box 5-2 describes one of the most promising advanced diesel technologies. OECD truck fuel use for 1985 totaled about 5.3 EJ. A 50% improvement in fuel efficiency over the next several decades seems feasible if aggressively pursued. As truck freight ton-miles are projected to grow in the future, this level of improvement could save at least 2.6 EJ by 2010.

Both rail and water transport are much more efficient than truck transport on a tonmile basis. In 1984, the U.S. average energy intensity of freight movements was estimated at 1.610 British thermal units (Btu)/ton-mile for trucks, while waterborne shipping averaged 350 Btu/ton-mile and rail freight was 510 Btu/ton-mile (Holcomb et al., 1987). To the extent that shippers could be encouraged, either through price incentives or other policy mechanisms, to shift from truck transport to these modes in the future, net energy use for freight transport could be reduced. One interesting approach is being tested by General Motors Corporation (GM). GM has developed a new truck trailer that can also be easily converted to a rail car and connected to a freight engine. This would allow loading of truck trailers at source points, truck hauling to the nearest rail terminal, and conversion to rail without unloading/reloading. Likewise, near the destination, the transition back to



truck is simple. GM has estimated that for hauls of over 200 miles, this approach could reduce energy use to 20% of current energy use for an all-truck haul or 50% of a conventional rail shipment (Sobey, 1988).

Improvements in ship fuel efficiency are also possible. Using some of the same diesel engine technologies identified for truck engines, 30-40% improvements in efficiency may be possible over the next several decades. Wind-aided cargo ships may also improve efficiency somewhat in the future.

Aircraft. Dramatic improvements in fuel efficiency have been achieved in the airline industry over the past decades. From 1970 to 1980 fuel use per passenger mile in the U.S. declined by over 40% (Holcomb et al., 1987). Nevertheless, by 1980 energy still accounted for about 30% of total operating costs for commercial airlines in the U.S. (Goldemberg et al., 1988). Since 1980, energy intensity has continued to decline due to some additions of more efficient aircraft and continued improvements in load factors (revenue passenger miles divided by available seat miles -- U.S. DOT, 1988), but at a slower rate (from 1980 to 1984 the improvement was about 4% -- Holcomb et al., 1987). The decline in the rate of efficiency improvement is highly correlated with declining energy costs. For example, between 1980 and 1987, nominal fuel prices declined by nearly 40% (U.S. DOE, 1988b), reflecting a drop of more than 50% in real terms. Combined with some efficiency improvements, this has resulted in energy costs being reduced to a much smaller percentage, 10-15%, of total operating costs. Thus, the economic incentive to reduce energy intensity has been greatly reduced.

Because of the historical importance of fuel costs, however, a great deal of research has been conducted within the industry to for efficiency identify opportunities improvements. Currently, commercially available new planes are more than 25% more efficient than the 1980 fleet average (Smith, 1981, for 1980 average; Ropelowski, 1982, for test results of new 757 and 767 models). Already improvements have been identified that, if incorporated into aircraft design, could reduce fuel use per passenger mile to less than one-third of the current average

(Maglieri and Dollyhigh, 1982; Smith, 1988). It may be technically possible to reduce fuel use per passenger mile to 50% of the current average by the year 2010.

The rate at which airline passenger miles will increase in the future is, however, a matter of considerable uncertainty. Some industry sources are projecting very high rates of growth in the next few decades, which could more than offset the projected gain due to improvements in energy per passenger mile. Kavanaugh (1988), for example, projects increases in global jet fuel use of 60-120% by the year 2025 despite assuming significant substitution of more fuel-efficient aircraft during the same period.

Alternative Fuels

A number of alternative fuels for vehicles have been proposed in the past few years. In the U.S. these proposals have been driven primarily by concerns about the effects of emissions on urban air quality and the impact of petroleum-based fuels on energy security. Only recently have analysts focused attention on the greenhouse contributions of alternative fuels. Near-term options of interest include the use of alcohols -- both ethanol and methanol, as blends with traditional fuels or as complete substitutes -and direct use of compressed natural gas. The discussion below refers to dedicated alternative-fueled vehicles designed and optimized for the alternative fuel. In the near term, however, "flexible fuel" vehicles may be produced; these would be capable of burning one or more of the alternative fuels as well as gasoline. In this case, because vehicles are not optimized, energy efficiency may be less than optimal (and greenhouse gas emissions would be higher).

Methanol. Although methanol can be produced from biomass, in the U.S. and globally, natural gas would be the most likely feedstock for methanol in the near term. The estimated net contribution to greenhouse gases when natural gas is used as a feedstock will be roughly equivalent to that from burning gasoline from petroleum. On the other hand, greenhouse gas emissions from the use of coal-based methanol, measured over the entire fuel cycle, are about double those from crude-oil-derived gasoline (DeLuchi et al., 1987). A shift from natural gas to coal in the long run could lead to large increases in greenhouse gas emissions.

Compressed natural gas (CNG) as a transport fuel produces fewer CO₂ emissions per unit of energy released than any other fossil fuel and also seems to be among the cleanest fuels available when considering its emissions of other gases that affect urban air quality (e.g., NO_x, CO, and VOCs, although some questions remain about the level of NO. emissions from CNG vehicles). However, leaks of natural gas, primarily methane (CH_4) , from the production, distribution, and refueling processes, could add to the concentrations of this greenhouse gas. Some researchers estimate that this increase in CH_4 could offset the advantage of lower CO_2 emissions. The degree to which CH₄ releases would increase or could be controlled is highly uncertain.

CNG is currently used as a transport fuel in Canada and New Zealand, among other industrialized countries. In New Zealand, CNG, liquified petroleum gas (LPG), and synthetic gasoline (from natural gas) meet half of the total gasoline demand. Other industrialized countries have small alternative fuels programs, mainly based on CNG, LPG, and methanol (Sathaye, Atkinson, and Meyers, 1988).

Ethanol. Ethanol is likely to be produced from biomass but is also likely to have difficulty competing economically unless its production is subsidized by government. Additionally, ethanol production by means of current technologies relies on biomass feedstocks such as corn and sugarcane, which are also food crops. This competition with food production raises concerns about the long-term viability of this approach. As discussed later, new technology for producing ethanol from woody biomass may become commercial and alleviate this concern in the If fossil fuels are used in the long term. production process (e.g., in farming operations to produce biomass or during distillation), this could offset the greenhouse gas benefits of biomass as a feedstock.

In summary, it appears that in the near term there is limited technical potential for

industrialized countries to achieve reductions in greenhouse gas emissions from the use of alternative fuels. The CO_2 reductions from alternative fuels in industrialized countries would not be enough to offset projected growth in VMT. However, the use of alternative fuels in combination with fuel efficiency improvements may help alleviate other concerns related to urban air quality and energy security without increasing the global warming commitment. As discussed later, in the longer term, alternative fuels derived from renewable sources may play a key role in reducing greenhouse gas emissions in the transportation sector.

Strengthen Vehicle Emissions Controls

The United States and most other OECD countries currently regulate the emission of hydrocarbons (HCs), CO, NO_x , and particulate matter on a gram per kilometer (g/km) basis. Many developing countries have recently adopted some emission control standards as well. The standards vary for the weight class of the vehicle as well as by the type of engine.

International comparisons of emissions standards are difficult because test procedures vary, but it is generally recognized that U.S. standards are among the most stringent in the world. For light-duty gasoline vehicles (which constitute a majority of the U.S. fleet), the U.S. standards are 2.1, 0.25, and 0.62 g/km for CO, HCs, and NO_x, respectively. Emission standards in most European countries are significantly less stringent than in the U.S. (OECD, 1988). Many developing countries have much less stringent standards, or none at all.

Vehicles sold in the United States control emissions in two steps. The first step \cdot is to control the amount of pollutants formed during the combustion process. During combustion, the primary determinant of the amount of CO formed is the air/fuel mixture. As the air/fuel ratio increases, CO emissions fall. On the other hand, NO_x emissions increase as the air/fuel ratio rises, a result of the concurrent increase in combustion temperatures, the primary determinant of NO_x formation. Higher combustion temperatures are often associated with increased power. An engine designed for greater power will generally produce higher "engine-out" NO_x emissions than an engine designed for fuel economy. Electronic engine management systems, however, have been able to minimize these tradeoffs, since many of the critical engine parameters (like the air/fuel ratio) can be controlled much more precisely (NAPAP, 1987; OECD, 1988).

The second step is to treat the "engineout" exhaust after combustion to reduce emissions to the acceptable standard. To control the "engine out" emissions, both catalysts and exhaust gas recirculation (EGR) are used on virtually all new U.S. and Japanese passenger cars, usually in conjunction with electronic engine management systems. Since 1981, the primary catalyst system used on U.S.-bound cars has been the three-way converter -named for its ability to reduce emissions of HC, NO,, and CO, as opposed to just one or two of the gases. Some cars also use a second oxidation catalyst to catch additional HC and CO. Catalysts use a variety of precious metals, including platinum, rhodium, and palladium, to break down or reduce the unwanted emissions without causing the metals themselves to react (Automotive News, 1988; OECD, 1988; White, 1982). EGR reduces NO, emissions by reinjecting a portion of the inert exhaust into the engine's incoming air. The inert exhaust gas cannot react in the combustion process and reduces peak temperatures during combustion. As a result, less NO, is formed. Today, all U.S. light-duty vehicles have EGR systems (Husselbee, 1984).

Some tightening of existing U.S. standards has been considered and determined to be technically feasible, although probably expensive on a dollar-per-ton removed basis (NAPAP, 1987). More significant improvements in global emissions of NO_x and CO could result from the extension of U.S. standards to the rest of the OECD and ultimately, to the rest of the world.

Current technologies for compliance with U.S. emissions standards have added substantially to the cost of new vehicles, although improving technology may reduce the incremental cost in the future (U.S. EPA, 1985; NAPAP, 1987). Also, with existing technologies, a modest tradeoff has been documented between emissions control, and fuel efficiency and performance, at the current level of U.S. emissions standards (White, 1982; OECD, 1988). Tradeoffs and cost for tighter standards, however, would depend on the stringency of the standards and the level of technology, as well as the demand for other characteristics like performance.

Enhance Urban Planning and Promote Mass Transit

In addition to fuel economy technical improvements, some near-term opportunities undoubtedly exist for reducing VMT in personal vehicles. Programs to encourage car pooling and use of mass transit by urban communities may be justified on the basis of traffic congestion and/or local air quality benefits, but would also reduce energy consumption and greenhouse gas emissions. Similarly, programs to improve maintenance practices and to modify traffic problems (i.e., sequenced traffic lights, one-way streets) to encourage driving at more efficient speeds, also have multiple benefits.

Near-Term Technical Options: Developing Countries

Transportation energy use is a serious concern in developing countries for several Worldwide, energy used for reasons. transportation is almost exclusively from oil. From 1973 to 1986 oil use by developing countries increased by 60%. During this same period, oil use by OECD countries declined Recent projections by the U.S. by 13%. Department of Energy (U.S. DOE) indicate that the overwhelming majority (86%) of growth in oil consumption in the "free world" (defined by U.S. DOE to exclude the centrally-planned economies of Eastern Europe, the Soviet Union, China, Cuba, Kampuchea, North Korea, Laos, Mongolia, and Vietnam) through the year 2010 could come from developing countries (U.S. DOE, The largest component of the 1987c). dramatic increases in oil use in developing countries during the last decade is in the transportation sector. For 15 of the largest developing countries, about 50% of the growth in oil consumption in the 1970-1984 period has been in transportation applications

(Meyers, 1988). Thus, indications are that energy use for transportation has been growing at a very rapid rate in recent years in developing countries, and this high rate of growth is projected to continue in the future.

Although some developing countries have been successful in implementing programs to reduce fossil fuel use (or at least oil use) in other sectors, very little attention has been paid to the transportation sector, either by these countries themselves or by international development assistance agencies (with a few notable exceptions, e.g., Brazil and, more recently, the Philippines). It is difficult for developing countries to implement the technical options that have been relatively effective to date in the industrialized countries.

First, information about transportation energy use is limited in many developing countries. It is very difficult to estimate, for example, what portion of the fuel is used in new versus old vehicles, light-duty trucks versus heavy-duty trucks, two- and threewheeled vehicles, etc. The information that is available, however, suggests other problems.

The average age of road vehicles tends to be higher in developing countries for two reasons. Vehicles tend to be kept in service longer, and used vehicles from industrialized countries are often resold to developing countries. In addition, vehicles are often used for purposes other than what they were originally designed for. There is some evidence that aging vehicles are often poorly maintained in developing countries. Poor roads also contribute to increased energy use per vehicle kilometer of travel (VKT). Urban congestion can also have this effect, although in some cases it may also act as a deterrent to increases in VKT. Although heavily utilized, mass-transit systems in developing countries are generally poorly developed and are also affected by poor or congested road systems.

Thus, the approaches that have been successful in slowing the growth of transportation energy use in the industrialized countries over the past 15 years may not be as effective in many developing countries. Industrialized countries have been able to significantly reduce the average consumption of fuel per highway mile by replacing existing vehicles with more efficient newer models and developing or expanding mass transit in urban areas. The effectiveness of both strategies in most developing countries is much more limited because of the slower turnover of vehicles and lack of capital to invest in infrastructure improvements.

On the other hand, it is expected that as developing countries reach a certain per capita income, there will be a rapid explosion in the demand for personal vehicles, which will dramatically increase transportation energy use (Sathaye et al., 1988). The fuel efficiency of new vehicles available during that period can have a significant effect on future transportation energy use.

Those developing countries that do not have domestic oil resources are concerned that increasing their imports of oil will diminish the already-limited foreign exchange available to finance development and hence, will limit long-term growth. Thus, there is great interest emerging in limiting oil use for Efficiency improvements, transportation. though often more difficult to achieve than in industrialized countries, clearly are part of the solution. Biomass-based alternative fuels are very important for some developing countries (Brazil, for example) in the near term. Other developing countries (like some industrialized countries) may have natural gas that can be used for transportation or other types of biomass-based options. Generally, the transportation energy solutions that would be attractive to developing countries for the purpose of reducing oil imports -- efficiency improvements and alternative fuels -- are also in reducing greenhouse beneficial gas emissions. One exception is the use of coal as a rail fuel, which occurs in China and India and results in both lower energy efficiency in rail transport and in more CO₂ per unit of fuel consumed. This option may appear attractive to countries concerned primarily with minimizing oil imports.

Increase Fuel Efficiency

As individual developing countries reach a certain level of economic activity and per capita income, it is expected that the demand for personal vehicles will "take off," as occurred historically in several more industrialized countries. Currently, gasoline prices are higher in many developing countries, and oil imports frequently make up a large fraction of total imports. Therefore, improvements in the efficiency of new vehicles, both light- and heavy-duty, should be very attractive in developing countries to reduce fuel costs.

Because of capital scarcity, all types of vehicles are kept in service far longer than they are in industrialized countries. Certainly for some developing countries, programs to improve the quality of maintenance or accelerate retirement of older vehicles may be very useful in reducing oil consumption and greenhouse gas emissions.

For the same reason that aging vehicles kept in service, new classes of are intermediate vehicles, often used as low-cost transport vehicles, have emerged in developing countries. These are generally produced locally, often by small companies or even a single individual. Some alternative notably the Chinese vehicles, tractor converted for passenger transport, are adaptations of vehicles designed for other purposes. In India also, a significant amount of road transport in rural areas is accomplished with tractors. As a means of passenger or freight transport, many of these vehicles are very energy-inefficient. The Chinese tractors, for example, are estimated to use 75% more fuel than would a 4-ton truck while carrying only 1 ton; these tractors account for 27% of the total diesel fuel use in Programs to China (World Bank, 1985). improve the efficiency of these vehicles or to replace them with more efficient alternatives may be very effective in the near term in some developing countries.

Alleviate Congestion and Improve Roads

In rural areas of many developing countries, roads are so poor that traffic must move much more slowly than is customary for intercity travel in industrialized countries. Frequent stops and starts are also a problem in these areas. These conditions inevitably lead to reduced energy efficiency regardless of the quality of the vehicles themselves. A recent study has concluded, however, that poor road conditions do not appear to act as a deterrent to increased vehicle ownership in rural areas of developing countries (Meyers, 1988). Thus, carefully planned highway improvements could result in net reductions in fuel use in some countries. In addition to reducing fuel use in the existing mix of vehicles, better roads may allow "upsizing" of some of the existing traffic to larger trucks and buses that are much more efficient on a passenger- or ton-km basis. Encouraging the use of more efficient modes of transportation, such as rail transport, may also be possible in some cases.

In urban areas, congestion is clearly already a major problem in many developing countries (as it is in many industrialized countries) and is likely to become more severe as rapid urbanization continues in many developing countries. Although congestion, as already mentioned, reduces efficiency in fuel use, it may also act as a deterrent to increased vehicle use, promoting widespread use of more efficient the alternatives to personal automobiles, such as motorcycles and mass transit. The degree to which congestion functions as a deterrent to increased transportation energy use is uncertain and needs further investigation.

Thus, it is important to carefully evaluate local conditions in designing improvements to urban road systems, including more extensive roads, but also better road maintenance and road planning. It may also be important to combine road improvements with other measures such as mass transit to achieve overall improvements in energy efficiency.

Promote and Develop Alternative Modes of Transportation

In addition to encouraging expansion of urban mass transit, developing countries may wish to promote alternatives to highway transport in both rural and intercity travel. Because major investments may be required to develop or improve highways for these types of travel, it may be more economically attractive to direct this investment into improved rail systems, for example, which move passengers and freight more efficiently. If highway improvement programs are carried out, however, they may be combined with the introduction of efficient bus systems, which would offer an attractive alternative to owning and using a personal vehicle.

Use Alternative Fuels

Alternative fuels based on locally available resources may be economically viable and important options in developing countries much sooner than is the case for industrialized countries. In countries that have abundant agricultural land, like Brazil, commercial technologies to convert crops such as sugarcane or corn for ethanol production may make sense (see PART TWO for more detailed discussion of the Brazilian ethanol program). A fuels program based on sustainable biomass production can be extremely beneficial in reducing net CO₂ emissions. However, most developing countries would have difficulty in diverting significant amounts of biomass, which is currently used for food, to energy purposes. Converting agricultural residues or forest products to fuel may make more sense if the conversion processes can be made economically attractive.

In other countries locally available natural gas may be readily converted to CNG, which would reduce emissions of CO_2 as well as many other air pollutants and also reduce oil imports. A recent review of international programs noted that most Asian countries and many Latin American countries that have domestic gas resources are conducting feasibility studies of CNG use and many have pilot programs in place (Sathaye et al., 1988). Where natural gas is currently vented or flared as a by-product of oil production, (e.g., in the Middle East), the availability of cheap local oil discourages investments in natural gas distribution and utilization systems.

A final fuel-switching option that could be helpful in the near term is replacing coal with diesel fuel or electricity in rail transportation systems. Coal is seldom used anymore as a rail fuel in industrialized countries -- primarily because coal-fired rail systems are markedly less efficient than the alternatives. In energy consumed per mile travelled, diesel trains are more than 3.5 times as efficient, and electrified rail transport is 13

times more efficient (compared on the basis of secondary energy consumed). If electricity is generated from coal, primary energy consumed is three times greater than the enduse energy consumed. Electric rail transport in this worst case would be about four times more efficient than coal-fired rail transport in primary energy consumption and net CO₂ emissions. However, a few developing countries with abundant coal resources and extensive rail systems -- notably India and China -- still use coal in rail transport. India has a program of gradual replacement underway, which is expected to eliminate coal use in rail systems by the year 2000. A shift to diesel fuel should reduce the CO_2 emissions from this source by a factor of five. Research is also underway to develop advanced, more efficient technologies for using coal as fuel in rail transport (Watkins, 1989). This could also reduce CO_2 emissions per mile travelled.

Near-Term Technical Options: USSR and Eastern Europe

In the USSR and Eastern Europe, transportation makes up a much smaller proportion of total energy use than in industrialized countries -- primarily because there are many fewer automobiles and trucks. However, that number is growing rapidly: from 1970 to 1980 the number of automobiles in the Soviet Union increased from 1.6 to 6.9 million (a rate of 15%/year), and the number of trucks rose from 3.2 to 5.1 million (4.7%/year).

On the other hand, fairly significant improvements have been made in recent decades in the efficiency of freight transport, primarily transport by rail. From 1960 to 1975, ton-kilometers of freight hauled by all forms of transport in the Soviet Union increased by 276%, while fuel use increased by 2.4% and electricity use increased by 418% (from a very small base). Overall, this represents a significant increase in energy efficiency that is primarily due to the replacement of coal locomotives by much more efficient diesel and electric engines (Hewett, 1984).

Given the rapid growth in the numbers of automobiles and trucks in the recent past, and in the number projected in the scenarios developed for this report, it appears that an important option for these countries will be to increase the efficiency of new highway vehicles. In addition, because of the large natural gas resources available in the Soviet Union (discussed in PART TWO), the feasibility of using compressed natural gas as a vehicle fuel may deserve further investigation.

Long-Term Potential in the Transportation Sector

The number of technical possibilities for reducing greenhouse emissions in the transportation sector increases considerably over the long term. The range of options runs from making further improvements in highway vehicles and expanding the use of using alternative fuels, to alternative transportation modes, to developing measures that would reduce the need for transportation. All options for the long term are somewhat speculative and very sensitive to assumptions about the nature of society in the long term. The discussion here is intended to illustrate possible options rather than to suggest choices.

Urban Planning and Mass Transit

A major concern in many urban areas throughout the industrialized countries (and in many developing countries as well) is increasing traffic congestion. When vehicles spend an increasingly greater proportion of their time idling in stop-and-go traffic, they use more fuel and emit more air pollutants In the near term, per mile travelled. solutions to urban congestion problems are extremely difficult. For the long term, however, alternative approaches to alleviating this problem will tend to incidentally benefit the climate warming problem. Mass-transit systems not only reduce highway commuter traffic, but also use much less energy per passenger mile. Average intensities (over all time periods) for bus and rail transit are reported to range from about 2.0-2.5 megajoules (MJ)/passenger-km (Holcomb et al., 1987). At normal commuting times, transit systems tend to be much closer to fullyloaded, however, so that the energy intensities per passenger-mile would be even lower. Similarly, carpooling can relieve congestion and reduce fuel use at the same time.

Another possibility is shifting to smaller, commuter vehicles. General Motors Corporation is testing a three-wheeled, one-or two-passenger, narrow, commuter car, which is essentially more like a covered motorcycle than a traditional automobile. Because the vehicle is much narrower than a normal passenger car, a standard traffic lane could be split in half to double the carrying capacity of existing roads. Because the vehicle is small and aerodynamically designed, it would also be much more fuel efficient than today's cars, achieving over 100 mpg (Sobey, 1988). Clearly, some safety issues and other complexities in integrating such vehicles into current urban traffic patterns must be resolved.

The technical potential exists to design and construct urban areas that are much more energy efficient in terms of their transportation requirements (as well as in their energy requirements for other end uses). By comparing cities whose transportation energy use is very low, relative to global averages, with cities whose energy use in this sector is high, it is possible to identify differences in location patterns, mass-transit systems, and other factors that can partially explain the differences in energy demands. In theory, it should be possible to introduce incentives that would encourage the more energy-demanding cities to develop along the lines of the less energy-demanding cities over time. This may be especially important in developing countries where populations, especially urban populations, are growing rapidly.

Alternative Fuels

Use of **alcohol fuels** as an alternative to gasoline in highway vehicles is an option that is already receiving considerable interest for a number of reasons. Technologies currently exist for producing ethanol and methanol from various types of biomass. Further research, testing, and commercial demonstrations could be helpful in improving performance and lowering cost. In the long run it appears that production of ethanol using current grain- or sugar-based technology could play only a limited role. Methanol may be the preferred alternative because its biomass feedstock does not necessarily have a food value and therefore is not in direct competition with food production. Research is underway to develop and commercialize technologies for ethanol production from nonfood biomass such as wood, grass, and waste paper (Lynd, 1989). If these technologies become cost effective, ethanol may play a much larger role as a long-term transportation fuel. (See PART TWO for more discussion of alternative fuels.)

Technologies currently exist for operating highway vehicles with hydrogen fuel. Such vehicles are not currently viewed as commercial, primarily because of the high cost of hydrogen fuel and the difficulty of storing enough hydrogen on board for highway A hydrogen-powered automobile driving. built by Daimler-Benz of West Germany and a hydrogen-powered bus built by the Billings Energy Corporation of Provo, Utah, are examples of current test vehicles. These two vehicles use metal hydride storage tanks, one promising approach to the storage problem (Ogden and Williams, 1988). In addition, if the fuel-efficiency improvements described above are incorporated, future vehicles may be able to achieve driving ranges comparable to today's vehicles while carrying much less fuel on board. The possibilities for producing hydrogen at competitive costs are also improving with the development of solar photovoltaic technology (see PART TWO). Another attractive feature of hydrogen vehicles is that the engines and internal structure required are very similar to what CNG-powered vehicles would require. CNG is already being used in fleet applications in some countries and will be more widely used in the future. This could provide a market for the initial transition to hydrogen when and if cost and storage problems are resolved.

Electric-powered vehicles have been discussed for many years as an option for reducing oil use and/or urban pollution. As with hydrogen, the problem of storing enough energy on board to provide a reasonable driving range is an unresolved obstacle. In addition, vehicle cost and performance ability comparable to the cost and performance of today's vehicles have not yet been realized. Concerns about higher future electricity costs could also retard penetration of electric cars, even if other problems are resolved.

The source of primary energy for both electric and hydrogen-powered vehicles will determine whether a switch to these fuels increases or decreases greenhouse gas emissions. Use of non-fossil sources of electricity, such as solar or nuclear energy, would decrease emissions of CO_2 and other greenhouse gases. Conversely, use of coal-fired generating capacity as the primary source of electricity or hydrogen would increase greenhouse gas emissions.

Emerging Technologies

Telecommunications may substitute for many transportation services in the future. Teleconferencing is already replacing some types of business travel, although the magnitude of this substitution has not been quantified in energy terms as yet. In the future, as video conferencing equipment improves and is more widely available, this option could become more important, particularly if higher transportation costs and congestion act as incentives. Catalogue electronic shopping, mail, electronic advertising, and electronic banking are other applications of telecommunications that are used to accomplish tasks and conduct business that formerly required travel. A recent analysis projects that transportation energy use may decline in OECD countries because of these substitutions. As is the case with many energy efficiency improvements, the motivation for this substitution has very little to do with energy use. These substitutions are taking place because consumers and businesses perceive advantages in convenience, time saving, access to wider selections, and cost savings (Schipper et al., 1989).

Fuel cell technology has many potential applications (described briefly in PART TWO). Two appealing characteristics of fuel cells are that cost-effectiveness is not fundamentally a function of size, as with many energy technologies and that the cells are virtually pollution-free at the point of use (Jessup, 1988). Because of these characteristics, one possibility is to use small fuel cells to power highway vehicles. Input fuel can be derived from natural gas, coal, or, ultimately, renewables-based hydrogen. Several different fuel-cell approaches are being researched and tested currently. If they prove economic, the fuel cell could provide very efficient and clean power for mobile sources at some point in the future.

High-speed rail systems are currently in commercial use in Japan and France. They compete well with aircraft or automobiles on a performance basis for some intercity travel. Energy consumed per passenger-km is significantly lower than with automobile or air travel alternatives. As technologies develop in the future (e.g., superconductors), these systems could become more efficient and economically attractive. The primary constraints appear to be the cost of constructing the systems and concerns about safety and rights of way.

RESIDENTIAL/COMMERCIAL SECTOR

In the United States residential and commercial energy services consumed 17 EJ in 1985, or about 29% of total secondary energy (36% of equivalent primary energy). For the OECD as a whole, the picture is quite similar, with residential and commercial energy use amounting to about 30% of the total secondary energy. Figure 5-4 shows the distribution of energy use within the U.S. residential/commercial sector. The largest component (more than one-third) of residential/commercial energy use is for space heating; combined with air conditioning and ventilation, the overall use of energy for space conditioning accounts for more than half (54%) of all residential and commercial energy use. Lighting accounts for another 15%, hot water heating, 11%, refrigeration, 7%, and the remaining energy (13%) is divided among all other appliances and equipment used in residences and commercial establishments (U.S. DOE, 1987b).

Global energy use in the residential and commercial sectors is expected to grow significantly in the future. In addition, a shift toward electricity for a higher percentage of energy use in these sectors is likely, resulting in increases in end-use efficiency, but implying that primary energy required (accounting for losses in electricity generation) will grow more rapidly.

It is expected that residential and commercial energy use will grow most rapidly in developing countries as economic growth rapidly translates into increasing demands for energy-related amenities in homes and commercial buildings. In the USSR and Eastern Europe large increases are expected for similar reasons.

Due to major technical improvements in recent years, future demonstrated residential and commercial buildings could require substantially less energy for heating and cooling. Because the stock of buildings turns over so slowly, it is also important to focus on retrofitting, which could reduce air conditioning and heating needs in existing Dramatic improvements buildings. in efficiency are also possible in lighting, particularly in commercial buildings, where lighting may account for a large share of the electrical energy used. Improvements in lighting efficiency also frequently have the added benefit of reducing the amount of waste heat produced by the lighting system and thus reducing the air conditioning requirements as well.

Options for reducing energy use in the residential and commercial sectors are fairly well characterized, at least in the OECD. As discussed below, potentials are very great, but due to the long turnover time of building stock, improvements may have to be phased in over a long time period. In addition, alternative fuels may be introduced, particularly in developing countries, which would further reduce the greenhouse impact of energy use.

With aggressive programs to improve the energy efficiency of buildings, it appears technically feasible to reduce projected U.S. energy use in the residential/commercial sector at least 50% by the year 2010. The technical potential in the OECD as a whole is probably close to that of the U.S. Although more detailed analysis is required, preliminary indications are that the technical potential to reduce projected residential and commercial energy in the much more rapidly **FIGURE 5-4**



Source: U.S. DOE, 1987a.

growing developing countries and in the USSR and Eastern Europe is even greater than that estimated for industrialized countries.

It appears technically feasible with space today's technology to reduce conditioning energy requirements in new homes by 50% relative to the current average for new homes. Retrofits of existing homes could reduce space conditioning energy use by an average of 25% with the "house-doctor" approach. It may be technically feasible to reduce energy use in existing commercial buildings by at least 50%, and new commercial buildings could easily be 75% more efficient than the average U.S. In 1985 the U.S. commercial building. consumed about 15.3 EJ of energy (primary energy equivalent) for residential and commercial space conditioning (U.S. DOE, 1987a). Retrofits to existing stock could save at least 4 EJ.

Current estimates indicate that residential and commercial energy use in the U.S. and in the OECD as a whole may remain roughly constant through 2025 under "business as usual" assumptions. With rapid widespread penetration of the most efficient instead of gradual buildings, new growth in energy improvement. the consumption from new buildings could be greatly reduced.

Based on potential energy savings of more than 60% for almost all types of appliances, a 50% overall reduction in appliance energy use by the year 2010 is technically feasible. To achieve this reduction would require aggressive policy actions that would (1) ensure that all appliances produced in the next decade be as energy efficient as the best current technology can produce and (2) encourage rapid turnover of existing appliances. Current energy use from such appliances is in the range of 7.4-8.4 EJ (expressed as primary energy equivalent).

Near-term technical options in the residential/commercial sector for industrialized countries, developing countries, and the

USSR and Eastern Europe are discussed below.

Near-Term Technical Options: Industrialized Countries

Improve Space Conditioning

Improved efficiency in space conditioning (heating and cooling) can be obtained in several ways. First, the design of new buildings can be altered to improve their insulating qualities, thus reducing losses in heating or cooling. Second, improved technologies can be applied to make existing buildings more weathertight, requiring less energy for heating and cooling. Finally, advanced technologies for heating and cooling equipment can be dramatically more efficient than devices currently in wide use. A number of very thorough and high-quality reviews of potential for energy the efficiency improvements in buildings have been produced in recent years (see, for example, Hirst et al., 1986; Schipper et al., 1985). The discussion below draws on the extensive published literature to illustrate the technical potential for improvement.

The potential for New Residences. improving energy efficiency in new homes is very significant. Simply by modifying the building shell to improve its insulating capabilities, space heating energy requirements can be reduced dramatically. Current new homes in the U.S. require, on average, almost 40% less energy to achieve the same level of heating as the average existing house in the U.S. (See Box 5-3, which illustrates the range of energy requirements for space heating on a per unit of floor space basis.) What is even more interesting is that the most efficient new houses are 50% more efficient than the average new home. (However, relatively few of these very energyefficient homes are currently being built.) Very advanced prototypes and design calculations indicate that it is technically possible to build homes whose heating energy requirements would range from 15 to 20 kilojoules per square meter per degree day (kJ/m²/DD), or 10-12% of the average requirements for today's homes.²

BOX 5-3. Improving Energy Efficiency in Single-Family Homes						
Space Heat Requirements in Single-Family Dwellings (kJ/m ² /DD)						
United States	<u> </u>					
Average, housing stock	160					
New (1980) construction in U.S. Mean measured value for 97 houses in Minnesota's	100					
Energy Efficient Housing Demonstration Program	51					
Mean measured value for 9 houses built in Eugene, Oregon	48					
Calculated value for a Northern Energy Home, New York area	.15					
Sweden						
Average, housing stock	135					
Homes built to conform to the 1975 Swedish Building Code	65					
Mean measured value for 39 houses built in Skane, Sweden	36					
House of Mats Wolgast, in Sweden	18					
Calculated value for alternative versions of the prefabricated house sold by Faluhus						
Version #1	83					
Version #2	17					

Source: Goldemberg, 1988.

The striking energy savings (compared with the average home), up to 90%, that is possible with new "low-energy" homes, as illustrated by the figures above, are achieved through the use of state-of-the-art construction and design techniques and technologies; a few of the areas where significant changes have occurred include the following:

• Building Envelope -- Larger wall and ceiling cavities, allowing for significantly more insulation, have been obtained with new construction materials and designs, such as "I-beam" framing members, raising R-values to as high as R-38 in some low-energy homes. Polyethylene vapor/air barriers in external walls reduce infiltration of outside air, one of the major sources of heat loss in most homes. Windows are being triple and even quadruple glazed, and, in some cases, incorporate low-emissivity films and inert gases, such as argon, between the panes to improve their insulating quality.

BOX 5-3. Improving Energy Efficiency in Single-Family Homes (continued)

• Mechanical -- These include heating, cooling, and ventilating systems. In addition to high-efficiency furnaces, heat pumps, and air conditioners, many low-energy homes incorporate air-to-air heat exchangers. These are needed to bring fresh air into the house, since natural infiltration is significantly reduced, but they improve energy efficiency by extracting approximately half the heat from the exhaust air and transferring it to incoming air. The newest development in mechanical ventilation is the heat-pump exhaust system, which uses warm exhaust air to provide water heating.

Active/Passive Solar Design, Thermal Storage -- Many different designs have been developed to make better use of solar gain to provide heat. These include use of south-facing windows, greenhouses, atriums, etc., and are often combined with thermal storage systems that store heat collected during peak daylight hours for redistribution when it is needed at other times. Storage systems can also work in the reverse way, collecting cool air during the night and circulating it during warmer hours.

In addition to the potential for improving the thermal properties of building shells, equally important advances have been made in developing high-efficiency equipment for both space heating and cooling. Already being marketed in the U.S. and in Europe are high-efficiency gas and oil furnaces that are about 95% efficient, compared with the average of 75% for new furnaces in the U.S. (Geller, 1988).

Substantial energy savings are possible in electrically heated (and cooled) homes with recently designed efficient heat pumps. The most efficient pumps on today's market are about one-third more efficient than average. Advanced ground-coupled heat pumps have recently been commercialized and will provide even more efficient options over the next decade. These commercial systems have been shown to achieve a "seasonal performance factor" (SPF) of 2.5-3.0, which compares with an SPF of 1.5-1.9 for electric air-source heat pumps (Strnisa, 1988). In addition, gas heat pumps are currently being demonstrated and may be commercial soon. These systems may be even more efficient than advanced electric heat pumps.

With super-insulated shells it may not be necessary to install a central heating system at all. Some of the advanced designs require so little heat input that small electric resistance heaters may be cost-effective in moderate climate areas. The greatly-reduced capital cost for this option may offset the increased cost for the superinsulating features. In very cold regions, the added cost of very efficient gas or oil furnaces would be justified. In regions where cooling is also required, the advanced heat pumps would probably be the most economic choice.

If all options were used in combination, it appears technically quite feasible for advanced building shells and efficient heating and cooling equipment to reduce space conditioning energy requirements in new homes to less than 10% of current average use.

Existing Residences. It is expected that the net growth in housing stock will be slow in the future in industrialized countries because of the extensive existing stock and low population growth. In addition, existing housing stocks have very long lifetimes. Therefore, existing stocks will dominate the residential sector for many decades. Thus, it is extremely important to focus on opportunities for reducing energy requirements in existing buildings. Many of the advances that have made possible the enormous potential energy savings for new homes are to some extent applicable to existing homes.

In general, retrofit improvements are somewhat less effective and more costly than those incorporated in the initial design of a new home. Nonetheless, cost-effective technical options exist for substantially reducing energy requirements of existing homes. Storm windows, added insulation, clock thermostats, and retrofit of heating systems have been considered conventional conservation measures for several years. In addition, improved maintenance of equipment and building shells and more attention to operation of equipment (i.e., automatic setback thermostats, automatic light switching) could reduce energy consumption in existing buildings at relatively low cost. Programs to encourage consumers to implement these conservation options have been carried out in a number of areas and have shown considerable success. One study of 40,000 retrofits monitored by U.S. utility companies in the early 1980s showed that energy consumption fell by 25% on average, and homeowners received a 23% return on their investments (Goldman, 1984).

Despite the favorable economics of some retrofit conservation measures, only a small portion of the potential energy savings from conservation retrofits has been realized This is especially true in rental to date. housing where the landlords do not perceive a financial interest in investing in retrofits. Also, low-income families, even if they own their homes, often lack the information or upfront capital to carry out cost-effective conservation measures. If conventional retrofit programs could be extended to larger percentages of existing housing stock, energy savings could be substantial.

Beyond conventional conservation programs, there are now more sophisticated options for improving the retrofit savings. Detailed measurements since the late 1970s have shown that existing homes have obscure defects in their thermal envelopes, leading to very large heat losses. Conventional walkthrough energy audits are unlikely to identify defects, would these nor subsequent conservation retrofits correct them. New instrumented analysis procedures developed over the last few years can locate these defects quickly, but these instrumented audits are expensive compared with the standard energy audits now provided by many utilities.

On the other hand, many of the "hidden" defects, once detected, can be easily corrected at small cost. This has led to the development of the "house-doctor" concept as an alternative to traditional audits. For this type of audit a team of technicians conducts an instrumented audit and repairs many of the defects on the spot. One test of this concept showed average immediate energy savings of 19% from one-day "house-doctor" visits. Subsequent conservation retrofitting done at the recommendation of the house doctors increased the average energy reduction to 30%. The average cost of all retrofit measures was \$1300 and the average real internal rate of return in fuel savings was 20% (See Goldemberg et al., 1988).

Another approach to improving residential and commercial energy efficiency has been proposed recently by researchers at Lawrence Berkeley Laboratory. Their approach is a reworking of the age-old concept of using shade trees to assist in cooling residential buildings. In their analysis the authors point out that in addition to the direct benefit in terms of reducing air conditioning loads at each house, the indirect effect of planting trees throughout an urban or suburban area, as well as other measures to increase the reflectivity of surfaces, can reduce the "heat island" effect, lowering ambient temperatures and further reducing air conditioning loads. In addition, of course, the trees directly remove CO₂ from the atmosphere, although the CO₂ reductions due to reduced cooling loads from well-placed trees are probably much greater than the CO_2 absorption by the trees (see Rosenfeld, 1988; Akbari et al., 1988). The city of Los Angeles has announced their intent to start such a program (Washington Post, 1989).

The advanced furnaces and heat pumps available for new homes could also provide significant benefits in the retrofit market. Economics of efficient equipment are generally more favorable as retrofits. Even after a retrofit shell improvement program, including the house-doctor approach, energy use in existing homes will remain well above the best levels achievable for new superinsulated homes. Thus, the added expense of advanced heating and cooling equipment will be paid back much faster in energy savings.

In one example, existing homes that had already been visited by house doctors and had received associated shell improvements were evaluated for improved furnaces. Shell improvements were shown to have reduced gas use for space heating to about 70% of the previous requirement. Researchers estimated that retrofit of advanced condensing gas furnaces would further reduce space heating energy use to 44% of the original requirement. The estimated incremental investment (to replace a worn-out furnace with the 95% advanced furnace rather than a conventional 69% model) was estimated to average \$1000 and result in fuel savings that correspond to a real rate of return of 15% (Goldemberg et al., 1988).

Commercial Buildings. Like residences, commercial and institutional buildings currently use significant amounts of energy, particularly for space conditioning and lighting. Opportunities for efficiency appear significant. improvements also Commercial buildings in the U.S. use about 3.6 EJ of fossil fuels annually (mostly gas in the U.S. -- other OECD countries continue to heat a significant percentage of buildings with oil) and about 2.6 EJ of electricity (equivalent to about 8 EJ of primary energy) (Rosenfeld and Hafemeister, 1985).

Some progress is already being made in improving energy efficiency in commercial buildings. While surveyed commercial space in the U.S. increased by almost 10% between 1979 and 1983, total energy consumption actually declined by about 4%. Electricity consumption, however, increased in absolute terms as well as in share of total commercial energy use. Thus, the primary energy equivalent of commercial end-use energy consumption has increased (U.S. DOE, 1987a).

While progress has been made, it is evident that commercial energy use in the U.S. could still be reduced significantly with cost-effective efficiency measures. Estimated commercial energy use in the U.S. was about 3.0 gigajoules $(GJ)^3$ per square meter per year in 1980 (expressed as equivalent primary energy production). This figure is down from 5.7 GJ in 1973, but could still be greatly improved (Flavin and Durning, 1988). One recent analysis estimated that energy use in new commercial buildings could be reduced by more than 50% below the current averages (Rosenfeld and Hafemeister, 1985).

As in the residential sector, traditional building shell conservation measures, such as added insulation and window glazing, reductions in infiltration rates of outside air, passive solar energy concepts, and heat exchange between exhaust and incoming ventilation air are effective although less important. The traditional approach of tree shading combined with reflective surfaces to achieve direct cooling can, as discussed above, also be applied to commercial buildings.

In addition, some more sophisticated techniques are cost effective for larger commercial buildings. New commercial buildings are being designed with "smart" energy management systems. These computerized systems monitor outdoor and indoor temperatures, levels of sunlight and location of people in the building. The system can then allocate heating, cooling and ventilation efficiently (Brody, 1987).

Another advanced technique being applied for commercial energy efficiency is thermal storage. In this case, some storage medium, such as a body of water, is used to store heat or cooling when it is readilyavailable and then the warm or cool air is released later when it is needed. This concept has been used in new commercial buildings in Sweden, storing heat energy from people and equipment, and in Nevada to chill water with cool night air and use the chilled water to offset the need for air conditioning during the day (Rosenfeld and Hafemeister, 1985). Window technology is also improving rapidly. A special "heat mirror" film, which doubles the insulation value of windows, is now commercially available. The film is designed to let light in without allowing heat to escape. Another available technology is to create a vacuum in the space between two panes, creating a thermos effect. These and other advanced technologies may allow commercially-available windows in the 1990s to have the same insulating value as ordinary walls (Brody, 1987; Selkowitz, 1985).

As was the case with residences, many of the advances in energy efficiency for new commercial buildings are transferable to retrofit applications to a lesser degree. A study conducted some years ago attempted to estimate the potential energy savings available from retrofits of existing commercial buildings. The conclusion drawn from a survey of several experienced engineers and architects was that a target of a 50% reduction in energy use in U.S. commercial buildings by the year 2000 was reasonable (SERI, 1981).

More recently, Amory Lovins and others at the Rocky Mountain Institute conducted a detailed analysis of the retrofit potential of commercial buildings in the Austin, Texas, area. This study identified potential savings in electrical energy that totaled 73% of the buildings' current electrical energy use (for lighting and other equipment as well as space conditioning). The cost of these measures was estimated to be lower than the operating costs of existing powerplants (Rocky Mountain Institute, 1986). There is some question as to what proportion of these calculated savings could be achieved in practice.

Heating Cooling/ District and Cogeneration. Use of district heating and cooling (DHC) can be an extremely efficient approach to space conditioning, particularly in dense urban areas and when the heat source cogenerator of electricity. also a is Technologies for cogeneration -- simultaneous production of electricity and heat or steam for other useful purposes -- are described in PART TWO. Cogeneration with DHC could serve a very large potential market for these efficient technologies, with the possibility of

offsetting significant amounts of oil and natural gas that would otherwise be used in dispersed space heating applications. In addition, heat from a central cogenerator can be used to generate air conditioning in high efficiency, heat-activated chillers that do not use chlorofluorocarbon (CFC) refrigerants, possibly offsetting significant amounts of electricity use and contributing to needed reductions in CFC production. This approach is already widely used in the Soviet Union and in many European countries and may be expanded in the future. In Denmark, for example, 46% of current space heating requirements are met with district heat ---27% based on cogeneration and the other 19%, single district heating. A recent projection estimates that by 2000 district heating based on cogeneration will satisfy almost 37% of total space heating requirements (Mortensen, 1989). The efficiency improvements in this type of system are substantial and contribute to reduced CO_2 emissions even if fossil fuels are used, as is normally the case. The International Energy Agency (IEA) is coordinating a significant amount of research by member countries to develop more cost-effective technologies for DHC. A recent report documents 47 advanced technologies that can improve efficiency or lower costs (IEA, 1989).

Interest in DHC has grown in the U.S. as well in recent years. In New York, for example, three demonstration systems are currently in operation in Buffalo, Rochester, and Jamestown. Studies are underway to design systems in five other communities (Strnisa, 1988). At a recent conference on DHC technology, one participant estimated widespread application of that cogeneration/DHC systems could reduce U.S. carbon dioxide emissions by 10-15%. This would also be expected to produce significant local and regional economic benefits -reducing and stabilizing energy costs to local government and business communities, creating jobs for skilled and unskilled workers, and retaining a greater proportion of total energy expenditures in local areas (Clarke, 1989).

Indoor Air Quality. One of the concerns about increasing the energy efficiency of buildings is the increase in

indoor air pollution that can result, primarily from efforts to reduce air infiltration. Most homes in the U.S. have air exchange rates, on average, of more than one change per hour, meaning all the air in the house is replaced by outside air once each hour. As new homes are constructed more tightly and some older homes are retrofitted with vapor barriers and better seals around doors and windows, the air exchange rate drops. Without additional ventilation measures, concentrations of several harmful pollutants, including radon gas, formaldehyde, combustion products from tobacco smoke and wood stoves, and asbestos particles, can reach harmful levels.

Control strategies for these forms of indoor air pollution include air cleaning, local ventilation, mechanical ventilation with heat recovery, and exhaust ventilation with heat pump heat recovery. Heat recovery or air-toair exchange systems have become more popular as homes have become better insulated and more tightly sealed. These can ensure the generally-accepted minimum standard of about 0.5 air changes per hour, while reducing heat loss by using the heated exhaust air to warm the incoming fresh air. Unfortunately, the costs of these systems are high and studies in Canada suggest that their efficiencies may be lower than manufacturers have claimed (Hirst et al., 1986). This may be due in part to improper maintenance by homeowners. Heat recovery systems, which usually draw air continuously and can have problems with condensation forming in the heat exchanger, require more routine maintenance than the average homeowner is accustomed to devoting to a major appliance. The use of exhaust ventilation systems connected to an air or water heat pump is a new technological approach that may hold some promise for improving cost-effectiveness and improving some of the maintenance These systems are being developed issues. primarily in Sweden. It appears that currently-available commercial technology can be applied to maintain indoor air quality standards while significantly reducing energy requirements. Current technology development efforts directed at reducing costs and maintenance requirements should be a high priority research area.

Use Energy-Efficient Lighting

Lighting consumes about 20% of U.S. electricity, most of it in residential and commercial buildings. This end use offers some of the most cost-effective opportunities for saving energy. One study has estimated that 40 large U.S. powerplants could be replaced by simply implementing currentlyavailable, cost-effective lighting efficiency improvements (Rosenfeld and Hafemeister, 1985). Cutting electricity use for lighting in industrialized countries by three quarters has been proposed as a reasonable goal (Flavin and Durning, 1988). Box 5-4 describes several key advanced lighting technologies.

A number of currently commercial measures, implemented in combination, can achieve dramatic energy reductions -- over 75% in commercial/institutional settings. These measures include improved controls, reflectors, spacing of lighting, and more efficient bulbs and ballasts. The University of Rhode Island reported reductions of 78% in lighting energy after implementing such a program. The cost of saved energy was calculated to be less than 1 cent per kilowatthour (kwh) (New England Energy Policy Council, 1987). An added benefit of lighting improvements in warm climates is that more efficient lighting reduces waste heat and, therefore, air conditioning loads. The California Energy Commission has estimated that in Fresno, every 100-watt savings in lighting reduces air conditioning energy requirements by 38 watts (Rocky Mountain Institute, 1986).

Use Energy-Efficient Appliances

After space conditioning and lighting, remaining energy uses in residential and commercial buildings are largely associated with large appliances. Opportunities for significant energy efficiency improvements in this category have been well documented. Table 5-4 illustrates some of these opportunities. U.S.-made refrigerators, for example, currently average 1450 kwh per year. The best currently commercial model in the U.S. uses about half that much energy. A recent study calculated that efficient new
BOX 5-4. Increasing Lighting Efficiency

Research and development into energy efficient lighting and design features has produced a constant stream of new products and advances. Below are brief descriptions of several of the areas where major advances have taken place.

- Compact Fluorescent Lamps: Compact fluorescent lamps are designed to be screwed into a standard light socket and thus have begun to compete directly with incandescent bulbs. Because they are 60-70% more energy-efficient than incandescent (Hirst et al., 1986) and are beginning to gain wider acceptance, they represent potentially significant energy savings. If compact fluorescent replaced all incandescent lighting, it has been calculated that this could displace 7.5% of total electrical consumption in the U.S. (Lovins and Sardinsky, 1988).
- High Intensity Discharge (HID) Lamps: These are designed primarily for warehouses, factories, street lighting, etc. Three types of HID lamps are currently in use: high-pressure sodium, low-pressure sodium, and metal halide. High- pressure sodium and metal halide give approximately 45-60% savings over mercury vapor or fluorescent lighting. Low-pressure sodium is somewhat more efficient, but its intense yellow light can be undesirable for many applications (Hirst et al., 1986).
- Electronic Ballasts: In conventional fluorescent lights the voltage required for operation is provided by an electromechanical ballast which itself consumes a portion of the energy used. New electronic ballasts reduce this additional power consumption by 20-35% (Hirst et al., 1986) and, because of their smaller size, are a key factor in the emergence of compact fluorescent lamps.
- Daylighting: Daylighting is a design approach that enhances the use of natural light either from windows, sidelighting, clerestories, monitors and skylights, or from the use of light pipes or optical fibers to transmit light to the location needed. The use of light colored paints and light shelves helps to distribute the light into the building interior.
- Additional Advances: Several other advances in lighting technology and design deserve mention. One advance is specular ("mirrorlike") reflectors that increase total reflectivity, direct the light in a more optically favorable direction, and maintain their high reflectivity significantly longer. Lighting controls, which include time clocks, scheduling controls, personnel or occupancy sensors, and daylighting sensors, reduce power consumption by turning off lights when they are not needed. Task lighting improves efficiency by directing light onto the specific task area where it is needed most, rather than lighting entire areas.

TABLE 5-4

Summary of Energy Consumption and Conservation Potential with Major Residential Equipment

Product	1986 Stock UEC ^a	1986 New UEC ^b	1986 Best UEC ^c	Advanced technology for 1990s ^d
Refrigerator	1450	1100	750	300-500
Freezer	1050	750	430	200-300
Central AC	3500	2900	1800	1200-1500
Room AC	900	750	500	300-400
Elec. water heating	4000	3500	1600	1000-1500
Elec. range	800	750	700	400-500
Elec. clothes dryer	1000	900	800	250-500
Gas space heating	730	620	500	300-500
Gas water heating	270	250	200	100-150
Gas range	70	50	40	25-30

(kwh/yr or therms/yr)

^a Unit energy consumption per typical installation in the 1986 housing stock.

^b Unit energy consumption for the typical model produced in 1986.

^c Unit energy consumption for the best model mass-produced in 1986.

^d Unit energy consumption possible in new models by the mid-1990s if further cost-effective advances in energy efficiency are made.

Source: Geller, 1988.

refrigerator freezers that would use about 200 kwh per year, or less than 15% of the current average use, could be cost-effectively produced (Goldstein and Miller, 1986). Water heaters also account for a large percentage of appliance energy use. The potential for energy savings is significant through the use of the most efficient technologies and also by switching from electricity to gas. Other energy-intensive appliances also provide opportunities for energy savings. As shown in Table 5-4, the potential exists for advanced technologies that could be produced in the 1990s that are at least 50% more energy efficient than the 1986 average for all major energy-using residential appliances (Geller, 1988). As discussed in Chapter VII, recently enacted national appliance energy efficiency standards are expected to produce substantial improvements in the United States.

Near-Term Technical Options: Developing Countries

In developing countries markedly different strategies may be necessary to address residential and commercial energy services. In many developing countries there are distinct modern and traditional sectors. In the modern sector, energy-use patterns are very similar to those in industrial economies (adjusted climate for differences). Commercially-marketed fossil fuels and electricity provide the energy input for a similar mix of energy services: space conditioning, water heating, lighting, and appliances cooking, refrigeration, for entertainment, etc. This modern sector, however, is often smaller than the traditional sector, which exhibits completely different energy-use patterns.

The energy sources in the traditional sector are largely "noncommercial" biomass, used primarily for cooking and, in some colder or high-altitude regions of developing countries, for space heating. Also, fossil fuels (e.g., kerosene) are frequently used for lighting. (In China and the coal districts of India, unlike most other developing countries, coal is also used for residential cooking and space heating in the traditional sector.) The task of development projects in these poorer sectors is to vastly increase the level of energy services available for residential and

commercial applications. Altruism and development objectives aside, this approach significantly can contribute to solving the climate warming problem because many developing countries have used fuelwood to such an extent that they have become net consumers of forests, and global deforestation is one of the significant causes of increasing greenhouse gas concentrations. The important issue from a climate perspective is to increase energy services without increasing greenhouse gas emissions.

As the developing countries continue to increase their per capita energy use, the implications in terms of energy use and greenhouse gas emissions are enormous. It is technically possible, however, for developing countries to substantially increase per capita energy services without substantially increasing fossil-fuel use. Emissions-reducing strategies similar to those proposed for industrialized countries can be promoted in the modern sectors of the developing countries. However, strategies suitable for the traditional, poorer sectors must be integrated into ongoing economic development programs if they are to be accepted by the local population. Technical options for reducing greenhouse gas emissions must not only be efficient, but also be designed to increase energy services to these poorer sectors.

More Efficient Use of Fuelwood

The primary use of biomass energy in developing countries is in residential cooking, traditionally done in inefficient and smoky conditions. The inefficiency of combustion can exacerbate deforestation and lead to increased time and effort devoted to gathering fuelwood (and fodder), and the smoky combustion results in exposures to significant emissions of health-damaging air pollutants.

Recognition of these problems has focused a great deal of attention on improving the cookstove as a low-cost solution. Existing cookstoves have efficiencies only on the order of 10%. Relatively simple improvements in stove design can in theory reduce wood requirements by 35-70% (Goldemberg et al., 1987). However, getting people in developing countries to accept and use better-designed stoves has proved difficult

for a number of reasons (Miller et al., 1986). In spite of spirited efforts by a number of generous dedicated groups, grants bv international aid agencies, and substantial expenditures by many governments, it has proved surprisingly difficult to coax people away from traditional cooking stoves and practices. Traditional stoves come in a bewildering variety of designs and materials and have evolved to suit local fuels and diets. They perform a multitude of functions that were not considered by designers and promoters of early "improved" stoves. Failure of the newer designs to incorporate features that could perform some of these functions often hampered their acceptance. Current improved designs represent a third generation in this technology development process (Smith, 1989).

West Africa, Kenya and Karnataka, India, and a few others, are successfully promoting improved-design stoves (Baldwin et al., 1985; Reid et al., 1988). Successful designs are based on sound principles of heat transfer (Baldwin, 1987), are targeted to a particular region (generally where cooking fuel is traded), require no substantial behavioral modification from users, and are provided with follow-up support.

Predicted fuel savings with improved stoves, which are based on laboratory waterboiling efficiency tests, have invariably proved to be overestimates under field conditions. If fuel savings observed in the laboratory were directly transferable to the field, an improved stove with 40% efficiency would result in a 75% fuel saving when it replaced a traditional stove with 10% efficiency. Yet only a few programs have reported fuel savings (at best on the order of 20%), though greater savings could be possible as programs improve with experience (Ahuja, 1990).

Despite the limited efficiency improvement with new fuelwood applications, the payback period is on the order of a few months and therefore economically attractive (Manibog, 1984). As Williams (1985) points out, the adoption of improved stoves is a far more cost-effective method of dealing with the fuelwood crisis than any "supply-oriented" solution to the problem that emphasizes growing trees for fuel. Widespread introduction of the current designs of improved stoves, while reducing total emissions of oxides of carbon per cooking task, will change the ratio of CO_2 to CO emitted. This ratio on a mass basis for traditional stoves is close to 10:1, whereas for more efficient stoves it could be reduced to 5:1, reflecting the more complete combustion in traditional stoves (Joshi et al., 1989). Although CO is not a radiatively interactive gas, it does interact with hydroxyl ions; as a result, its presence increases the concentration of methane and ozone in the troposphere (see CHAPTER II).

Use Alternative Fuels

In the traditional sectors of many developing countries, substitution of fossilbased end-use technology for traditional biomass use may be desirable as part of a larger strategy even though it may directly increase greenhouse gas emissions to a small degree. Gaseous fuels (natural gas, LPG, etc.) are very attractive relative to fuelwood for several reasons, including their vastly superior convenience and controllability. In addition, a well-designed gas-fueled stove can be five to eight times more efficient than traditional firewood stoves (Goldemberg et al., 1988). Thus, the shift to gaseous cooking fuel can decrease the demand for fuelwood, which may slow the rate of deforestation in some areas, or free up vast amounts of fuelwood for use as a feedstock for advanced biomass energy systems, or both. In a few developing countries, such as China, coal is used for cooking and space heating; the advantages discussed above for gaseous fuels also apply as a replacement for coal (with associated reductions in greenhouse gas emissions).

In the traditional sectors of many developing countries, lighting frequently is achieved with very inefficient combustion technologies. In India, for example, it is estimated that 80% of the rural households illuminate with kerosene lamps. The efficiency of illumination of these lamps is very low. Providing the same level of illumination with incandescent electric bulbs would be 200 times more efficient at the end use (Goldemberg et al., 1988). (In fact, the availability of electricity will actually allow a

much greater level illumination in of Thus, even if the electricity homes). production is only 30% efficient, and is coalfired (worst-case assumptions), the equivalent electric lighting would still produce less net CO_2 . If the most efficient current compact fluorescent lighting were used, the benefit would be even greater. Of course, the major constraint to substituting electricity for fossil fuels is the limited availability of electricity in developing countries. Small-scale local generation based on renewable technologies could make major contributions in this situation. These and other options for increasing electricity in developing countries are discussed in PART TWO.

Retrofit Existing Buildings

For those residential and commercial segments of developing countries that have similar characteristics to industrialized countries, many of the same retrofit efficiency measures are appropriate. In fact, it is likely that many retrofit measures would be more effective in developing countries. As pointed out in a recent U.S. AID study (1988b), while "industrialized countries have made major strides in using electricity more efficiently over the last decade, few achievements have been made in developing countries in using electricity more efficiently. The opportunities for improvements are tremendous, and the cost is only a fraction of the generation In addition. expansion option." air are generally conditioning requirements heavier in tropical developing countries. Thus, improvements in building shells and air conditioning equipment could be very effective in reducing electricity use. Similarly, the air conditioning benefit of improved lighting (due to less waste heat) would also be greater in developing countries.

A recent study of Pakistan identified cost-effective efficiency improvements that could reduce electricity use in the commercial sector by over 30%. Based on commercially available improvements in lighting, air conditioning and fans, and thermal insulation, the study projected national savings of 1800 megawatts (MW) of generating capacity and 18,200 gigawatt-hours (GWh) of electricity generation (U.S. AID, 1988b). An analysis in Brazil indicated the potential to reduce electricity use for lighting by 60% in many commercial buildings (Geller, 1984).

Build New Energy-Efficient Homes and Commercial Buildings

Rapid expansion of the residential and commercial building stock is expected to occur in conjunction with economic development in the developing countries over the coming decades. Use of the efficiency options discussed for industrialized countries, adapted to local conditions and objectives, could minimize the increases in energy use associated with this growth. Obviously, since the rate of construction of new building space (and distribution of appliances, etc.) will be much higher in developing countries, the importance and potential impact of efficiency measures will be proportionately greater as well.

Several recent studies have identified significant potential for reductions in energy use in new commercial buildings in developing countries (see, e.g., Turiel et al., 1984; Deringer et al., 1987). In Singapore, careful use of daylighting alone has the potential to reduce energy use by roughly 20% relative to the current building stock (Turiel et al., 1984). Other important improvements include efficient lighting systems, external shading, and size and placement of windows.

Near-Term Technical Options: USSR and Eastern Europe

Energy use in buildings in the Soviet Union is dominated by space heating: 25% of the population lives in a climate that requires the use of heating between 210 and over 300 days per year. An additional 40% live in a climate characterized by a 180- to 280-day heating season (Tarnizhevsky, 1987). Since the early 1970s, the Soviets have made dramatic progress in improving energy efficiency in specific applications, "in large energy uses easily identified and controlled by the planning apparatus" (Hewitt, 1984). The dominant approach advocated by Soviet space conditioning is researchers for consistent with this experience. Centralized, or "district" heating systems, have been the preferred approach to space heating for some

time. By 1980, about 70% of residential and commercial heat demand in cities and towns was provided by central systems. Sources of heat for these systems are primarily cogeneration from both fossil-fueled and nuclear powerplants and some waste heat recovery from large industrial process heat uses (e.g., ferrous metal, chemicals, and petrochemicals) (Vavarsky et al., 1987). Most of the residences in the USSR are multifamily rather than single-family structures which should, in principle, require less space heat because of the lower surface-to-volume ratio. Living space per capita is also much lower than in OECD countries. A recent estimate for the USSR is about 15 square meters per capita as compared to roughly 50 square meters per capita in the U.S. (Schipper and Cooper, 1989).

Despite the predominance of district heating and multi-family structures, the energy intensity of space heating in the USSR appears high relative to OECD countries. Schipper and Cooper (1989) have estimated that space heating in the USSR requires about 230 kJ/m²/DD, which is about 50% higher than the U.S. average and about double the value for Sweden. There is obviously room for considerable efficiency improvement in space heating. This may be very important if heating space per capita increases with incomes in the future. Α Soviet research institute has projected that energy use in industrial and commercial buildings may rise by over 40% between 1985 and 2000 (Bashmakov, 1989).

There is already considerable interest in improving efficiencies in buildings in the USSR. Plans for improving energy efficiency include: 1) further replacement of local heat sources with district heat from cogeneration; 2) weatherization of buildings; and 3) reductions in heat losses in distribution networks (Tarnizhevsky, 1987). As many western visitors to the Soviet Union have noted, a common method for regulating temperature in over-heated buildings is simply open windows. Improvements in to temperature control systems could save considerable space heating energy.

Electricity consumption in buildings is also growing in the Soviet Union, principally

household appliances (including some electric ranges). The most significant sources of growth from 1975-1985 were attributed to increasing proliferation of applications associated household with improving living standards. One Soviet researcher estimated that significant electricity savings are achievable through manufacture of more energy-efficient appliances and lighting, optimized use of lighting, elimination of known losses or "wastes" of electricity, etc. (Tarnizhevsky, 1987).

Chapter V: Technical Options

Long-Term Potential in the Residential/ Commercial Sector

In the long term, the potential for reducing energy use in buildings considerable. The majority of current per capita energy consumption in buildings could be eliminated over the long run by simply incorporating the best currently available building and equipment technologies into housing and commercial building stock as it is expanded and replaced over the next 50-100 years. Further efficiency improvements could come from emerging technologies and broader application of existing technologies. In space conditioning, examples include "smart windows," which sense light and adjust opacity to utilize solar heat and light most effectively, and new building materials, which may provide better insulating qualities at a reduced cost. Existing technologies for large buildings, such as use of thermal storage and computer controls, could be applied to small buildings and residences as well.

As improved building and equipment technologies are incorporated over time, space conditioning will probably become a much smaller component of total building energy use. Appliances and information technologies (computers, telecommunications) may become more important determinants of residential commercial energy consumption. and Advanced technologies may provide comparable or improved services with less For example, some experimental energy. concepts have been developed for storing food that might greatly reduce the need for refrigeration. As information technology continues to evolve, it may well provide improved energy efficiency as a byproduct, as has been the case in the evolution from vacuum tubes to semiconductors to integrated circuits.

Alternative fuels could also play a more important role in buildings over the long term. Advances in solar photovoltaic and other small-scale renewable energy technologies may make it economical to generate most or all of the needed electricity locally. Hydrogen may become an energy option for building energy needs by utilizing or adapting the existing infrastructure for distribution of natural gas (see PART TWO).

INDUSTRIAL SECTOR

Industrial end uses account for the largest single component of energy use in the industrialized countries -- almost 43% of the energy consumed in the OECD in 1985 (in primary energy equivalent terms [U.S. DOE, Actual secondary 1987b]). energy consumption was about 36%. In developing countries, if agriculture is included as part of industry (as it is in this chapter), then the industrial sector generally consumes an even higher percentage of total commercially traded energy. In developing countries as a whole, industrial energy makes up almost 60% of total modern energy use. In the USSR and Eastern Europe, the percentage is slightly under 50% (see CHAPTER IV).

Industrial use is also an area in which impressive efficiency gains have been observed in recent years. In the United States, for example, "end-use energy consumption per constant dollar of industrial output declined by 28% between 1974 and 1984 -- reflecting substantial improvements in energy efficiency as well as the relative decline in output from energy-intensive industries in this country" (U.S. DOE, 1987b).

Several researchers have documented the components of changing industrial energy use in developed countries (see Ross, 1984, 1986; Goldemberg et al., 1987; and Williams et al., 1987). One significant component of declining industrial energy use is a structural shift to products that are inherently less energy-intensive to produce. It is now a welldocumented phenomenon that as industrialized countries proceed beyond a certain level of economic development and affluence, their per capita consumption of some of the most energy-intensive industrial products (e.g., cement, steel, and durable goods) declines. Thus, having approached many energy-intensive "saturation" in products, industrialized countries will likely continue to consume less energy per dollar of GDP in the future as incomes continue to Major programs to rebuild aging rise. infrastructure (roads, bridges, water and sewer systems, etc.) in the U.S. and other OECD countries are being discussed and could offset the saturation effect somewhat.

The other major component of declines in energy intensity over the past decade and a half has been actual improvements in the efficiency of production processes. Energy price shocks of the 1970s often affected industrial energy users more than other As stated by Goldemberg et al. sectors. (1988): "Because the cost of providing them energy involves much less unit transport and marketing cost, industrial users are more sensitive than other energy consumers to cost increases at or near the point of energy production." In addition, industrial users, particularly where energy costs are a significant component of product cost, tend to be more aware of and responsive to the return on investments in energy efficiency than are customers in other sectors. Ross (1986) has noted many cases in which industrial managers have pursued aggressive efficiency improvement policies in response to the price signals of the 1970s.

Efficiency improvements to date have largely been in a few industries that are the most energy-intensive: petroleum refining, chemicals, cement, metals, pulp and paper, glass, clay, etc. (see Table 5-5). There is reason to believe that efficiency improvements will continue rapidly in the future in the energy-intensive sectors of industry in the developed countries, particularly if real energy prices begin to rise again. It is also expected that the structural shifts to less energyintensive products will also continue in these countries (Williams et al., 1987). Technical options may exist for accelerating these trends and also taking advantage of additional efficiency improvements possible in other industries. Evidence exists that economically attractive energy conservation investment

TABLE 5-5

Reduction of Energy Intensity^a in the U.S. Basic Materials Industries (1972-1983)

	Percent
Chemicals ^b	31
Steel	18
Aluminum	17
Paper ^c	26
Petroleum refining ^d	10
Energy Weighted Reduction	21

^a Generally energy per pound of product, unadjusted for environmental and other changes. Purchased electricity accounted for at 10,000 Btu/kwh (2.5 Mcal/kwh).

- ^b Not including fuels used as feedstock.
- ^c Not including wood-based fuels.
- ^d Changes in inputs and outputs and environmental regulations have had a particularly strong impact on petroleum-refining energy. Adjusted for such changes, energy intensity was reduced 26%.

Source: Ross, 1985.

opportunities exist in industries outside of those few that are energy-intensive. For a number of reasons these investment opportunities are often being overlooked (Ross, 1984, 1986).

In contrast to industrialized countries, the developing countries generally are in the midst of, or beginning, a period of rapid expansion of energy- and materials-intensive industries to raise per capita income levels. In addition, industries in these countries currently use energy far less efficiently than do similar industries in industrialized countries. In many cases, this is related to the government's subsidization of energy prices, lack of access to the most modern technologies, and lack of management skills for identifying and implementing efficient options (Flavin and Durning, 1988). If developing countries industrialize without dramatically improving energy efficiency, the result would be enormous increases in industrial energy use. As these countries develop industrial infrastructure and as their standards of living rise in the future, the energy requirements for the production of basic industrial materials could be enormous.

There is a widening recognition, however, that this type of growth may not be sustainable and may indeed become selfdefeating. Continuing along current energyintensive industrial development paths may result in increases in energy imports, which absorb foreign exchange credits that are needed for further development. Local environmental concerns and capital scarcity may also constrain the conventional industrial development option. Developing countries and development assistance organizations are now beginning to focus much more attention on the energy consequences of industrial development decisions.

Technical options may exist for "leapfrogging" from current obsolete energyinefficient technologies directly to very advanced efficient technologies in some developing countries (although new policy actions will be required; see CHAPTER VIII). In addition, opportunities exist for designing industrial development based on locally available alternative fuels, which has been initiated in some developing countries.

In the USSR and Eastern Europe countries, significant heavy industrial capacity is already installed, with energy often used very inefficiently. For these countries reducing industrial energy demand may require structural shifts away from heavy industry as well as the use of more efficient industrial technology.

With the technical options identified below, industrial energy consumption could be reduced by 25% below levels projected for the 2000-2010 time frame. One recent analysis indicates that cost-effective conservation could result in an absolute decline of about 19% in industrial energy consumption (fuel and purchased electricity) in the U.S. by the year 2010 (Ross, 1988).

Some available projections based on trends in structural change and process technology improvement alone suggest that industrial energy use in the OECD countries may not rise significantly over the next 25-40 years (Williams et al., 1987). Very recent data for 1987 and 1988 in the U.S. show sharp increases in durable goods and basic materials production (U.S. DOC, 1988). If these very recent trends continue, industrial energy use in OECD countries could grow significantly in the future. Industrial energy consumption in the USSR, Eastern Europe, and developing countries is expected to increase substantially under "business-as-usual" assumptions.

Near-term technical options in the industrial sector in the three regions are described below.

Near-Term Technical Options: Industrialized Countries

Accelerate Efficiency Improvements in Energy-Intensive Industries

As discussed above, significant improvements in energy efficiency were made in the basic materials industries during the late 1970s and early 1980s (see Table 5-5 for improvements in key industries). Despite these improvements, in most industries the opportunities for further reductions are still quite large. This is true for two basic reasons. Industrial process technology has improved significantly in recent years, and the pace of energy-related technology investment has been relatively slow, particularly in industries that are not growing overall (Ross, 1988).

The steel industry provides one interesting example. For the integrated, or ore-based industry (excluding scrap-based steel making), the average energy intensity in the U.S. in 1983 was about 31.2 GJ per ton The reference plant (Ross. 1987). documented by the International Iron and Steel Institute (1982) would consume about 19.2 GJ per ton producing roughly the same mix of products. Thus, if existing U.S. capacity were replaced with plants equal in efficiency to this reference plant, it would produce a 39% savings. The costs and other implications of such replacement have not been assessed. Other estimates find a 20% savings possible, if necessary investments were made (Barker, 1990).

More energy-efficient technologies, once proven commercially, will likely be extremely attractive on the basis of cost-effectiveness, including improvement in overall process cost and environmental impact as well as energy efficiency. Thus, the marketplace can be expected to encourage all producers to adopt advanced technologies in the long run. From the perspective of climate warming, the important concern is whether there are opportunities for accelerating this turnover, either through research initiatives or through programs to promote more rapid capital replacement in selected industries.

Other major energy-consuming industries -- petroleum refining, chemicals, pulp and paper, etc. -- are also undergoing transformations that will result in continuing declines in energy intensity in the future. Quantifying the potential energy efficiency improvements in each major industry and in various OECD countries will require more detailed analysis than has been carried out to date. Technically-feasible improvements (e.g., assuming that each industry average improves to match the energy efficiency of the best currently-available or emerging technology) could be much greater. With the exception of primary aluminum, other energy-intensive industries have even greater technical opportunities for energy conservation than the steel industry (Ross, 1988).

One important component of the technical potential for reducing energy use in basic industries is materials recycling. Recycling of inorganic wastes, such as bottles and aluminum cans, saves energy and reduces waste streams. Substituting recovered materials for virgin materials to produce steel, aluminum, and glass conserves energy. Depending upon the types of materials recycled, estimates of energy savings can range from an average of 5 GJ per ton of material recycled (Gordon, 1979) to 25 GJ per ton (Stauffer, 1988). Recycling 24 million tons of paper, cardboard, glass, and aluminum (about 16% of our current waste stream) could result in savings of up to 0.6 EJ (Stauffer, 1988).

Unfortunately, economic policies discourage recycling and the use of recycled materials. Differentials in transportation rates favor virgin loads over secondary loads, and favorable tax treatment toward production from virgin materials continues to make recycled materials more expensive to use. If these policies were eliminated or reversed (e.g., creating incentives to boost demand for recycled products), the technical potential for energy savings is quite large. Increased recycling would also have the added benefit of reducing waste.

Aggressively Pursue Efficiency Improvements in Other Industries

While there is clearly measurable progress in the energy-intensive, and therefore energy-price-sensitive, industries, less progress has been made in energy efficiency in other industries. Industries for which energy is not a major component of product cost frequently pass up opportunities for investing in energy efficiency with high estimated rates of return (Ross, 1984).

The technical potential for energy savings could be important for widespread penetration of just a few energy-saving The Electric Power Research measures. Institute estimates that 95% of industrial electricity use is represented by three major applications: electromechanical drives or motors, 70%, electrolysis, 15%, and process heat, 10% (Kahane and Squitieri, 1987). Recent studies have estimated that costeffective replacement of motors and the addition of variable-speed drives could reduce total electricity use in motors by as much as 17% in some regions (Geller et al., 1987; Alliance to Save Energy, 1987).

Comparable efficiency improvement measures have also been identified for the other major components of industrial electricity use (Kahane and Squitieri, 1987). In addition, many of the efficiency measures identified earlier for lighting and space conditioning in large commercial buildings are also applicable to industrial users. A recent study examined current electricity-saving projects in automobile manufacturing plants in the U.S. and Europe. The results showed roughly 30% savings from the current cost of purchased electricity (Price and Ross, 1988).

Increase Cogeneration

Technologies for cogeneration -production of electricity and heat or steam for other useful purposes from a single combustion source -- are described in PART TWO. The primary market for cogeneration is in large industrial facilities (although large commercial/institutional and district heating applications are important in the USSR and Eastern Europe and are also beginning to be seen in the U.S.). From industry's perspective, cogeneration is one method for improving energy efficiency. The industrial facility benefits, either in the form of electricity used on-site or revenues from sales of electricity to the local utility, from the fuel it would otherwise have consumed solely for industrial production purposes.

Industrial cogeneration has grown rapidly in the U.S. since the 1978 passage of the Public Utilities Regulatory Policies Act (PURPA), which ensures that cogenerators (among others) can sell electricity to utilities at the utility's avoided cost (the cost that the utility would otherwise have to pay to produce or obtain the electricity). As of 1985, 13 GW of cogeneration capacity were in operation (Edison Electric Institute, 1985). Projects that would yield an additional 47 GW have been registered with the Federal Energy Regulatory Commission (FERC) through October 1987 (FERC, 1988). One company specializing in cogeneration has estimated that cogeneration capacity could reach 100 GW (equal to about 15% of current capacity) by the year 2000 (Naill, 1987).

All of these projects tend to reduce potential greenhouse gas emissions as they result in more efficient use of energy. To the extent that industrial cogeneration projects are based on natural gas or oil -- or industrial waste products such as black liquor or bark in pulp and paper -- and displace new coal-fired electric generating capacity, the net impact on greenhouse gas emissions (as well as local environmental loadings) could be much greater.

Near-Term Technical Options: Developing Countries

As noted above, developing countries generally are in the early stages of a rapid expansion in producing energy-intensive materials associated with infrastructure development and widespread access to basic consumer durables. If this process proceeds along the path experienced historically by the industrialized countries, the increases in energy consumption and CO_2 emissions will be enormous. In fact, the need to import fossil fuels to support rapid expansion of heavy industry could become self-defeating, operating as a brake on the rate at which some developing countries can industrialize.

Understandably, developing countries and development assistance organizations are concerned about alternative approaches to industrial development that would allow developing countries to increase economic activity without having to devote everincreasing shares of their foreign exchange earnings to financing fossil-fuel imports. Several possible strategies for achieving this goal are very compatible with concerns about long-term greenhouse warming.

Practice Technological Leapfrogging

This phrase has been used by Goldemberg et al. (1987) in discussing industrial development options for both industrialized and developing countries. Theoretically, at least, developing countries could adopt the most efficient process technologies currently available, or even push ahead with experimental technologies as they invest in major expansions of heavy industry necessary to foster economic development. If this strategy were implemented, the projected massive increases in industrial energy use in the developing countries would be significantly reduced.

There are a number of reasons why this may not occur in practice. Because capital (and entrepreneurial experience) is scarce in developing countries, there is a tendency to avoid risky investments. Conventional wisdom suggests that these countries should adopt technologies that are already "mature" in the industrialized countries. This "conventional wisdom" has affected decisions both by developing countries themselves and by relatively conservative lending institutions (banks or assistance organizations) called upon to provide capital. Often, though by no means always, advanced energy-efficient technologies require larger capital investments than older technologies. It is also extremely important to recognize the differences between developing countries and industrialized countries (and among individual developing countries) in terms of the availability and cost of certain components of production -- labor, capital, and natural resources.

Thus, developing countries will have difficulty achieving rapid industrial development with currently mature, but also energy-intensive, technologies relatively available from the industrialized countries. On the other hand, "leapfrogging" to the most advanced technologies now being developed in industrialized countries may be inappropriate in terms of the local availability of labor, capital, and natural resources. What appears to be needed is to identify and develop advanced industrial process technologies that are appropriate to each developing country's individual endowment of resources. To the extent that developing countries move in this direction, energy efficiency, or at least efficiency in fossil-fuel use, should be a major characteristic of the desirable options for most developing countries. Since many developing countries have difficulty raising the capital required for many investments, some special form of international financial arrangements may be necessary to assist developing countries in adopting energyefficient technologies as they industrialize (see CHAPTER VIII for further discussion).

Develop and Use Alternative Fuels

As discussed above, most developing countries are interested in limiting increases in fossil-fuel imports associated with industrialization. For this reason, they will undoubtedly provide a proving ground for development of heavy industry based on alternative fuels.

One option for some developing countries may be to develop potential hydroelectric generation resources and base on advanced development industrial electricity-intensive processes. (Opportunities and difficulties in developing hydroelectric generation are discussed in more detail in In general, developing PART TWO.) countries are relatively rich in biomass resources and, in some cases, undeveloped hydropower, while they are net importers of fossil fuels. Thus, the tailoring of industrial development strategies to local resources will likely reduce greenhouse gas emissions in addition to achieving other benefits.

For those developing countries with abundant coal resources, most notably China,

there may be a tradeoff between energy selfsufficiency goals and climate warming concerns. Even in these situations, promoting the most energy-efficient technologies should be a common goal. When developing countries have both natural gas and coal resources, local environmental and economic concerns, and consideration of the greenhouse phenomenon, should all encourage a nearterm emphasis on natural gas.

Increase Industrial Retrofit Programs

A recent report by the U.S. Agency for International Development (U.S. AID, 1988b) reviewed the electricity supply-and-demand situation in a number of developing countries. The report documented serious concerns in many developing countries about current or projected shortages in electricity. However, it also found that "few achievements have been made in developing countries in using electricity more efficiently. The opportunities are tremendous, and the cost is only a fraction of the generation expansion option." According to the report, over 40% of the electricity use in developing countries is by electric motors in the industrial (including agriculture) sector (U.S. AID, 1988b). One detailed energy analysis in Pakistan identified specific industrial efficiency improvements, including improved controls and lighting. which could reduce industrial energy consumption by more than 20% in 2005(Miller et al., undated).

Other recent studies in Kenva and South Korea indicate that efficiency programs have been successful in reducing energy use in heavy industry (Geller, 1986). A detailed analysis of the electricity conservation potential in Brazil indicates that improvements in electric motors and motor controls could reduce industrial electricity consumption by an amount equivalent to 8.7 GW of new generating capacity (Geller, Many of the potential industrial 1984). energy savings in developing countries are undoubtedly not yet identified because of the relatively little attention that has been given to these options in the past. However, the fragmentary evidence currently available suggests that these opportunities are much greater in percentage terms than those in industrialized countries and are much cheaper

than the incremental cost of increasing energy consumption.

Use Energy-Efficient Agricultural Practices

On a global scale, agriculture accounts for a small part of "commercial" (excluding traditional biomass) energy use -- about 3.5% in 1972-73. However, the percentage in some developing countries is higher. In addition, the projected transition in developing countries from traditional labor-intensive agricultural practices to modern mechanized practices is expected to increase the use of commercial energy in agriculture significantly in developing countries by the year 2000 (FAO, 1981).

A major goal of most developing countries is to increase productivity in agricultural production either for domestic consumption or for export purposes. If energy conservation is viewed as a constraint to such improvements, it generally will not be viewed as a more important objective. However, productivity increases may be possible through several alternative approaches, with markedly different implications for energy and employment.

Many developing countries are interested in holding down imports of fossil fuels. They may also suffer from widespread unemployment or underemployment and, therefore, may seek modernization without displacement of employment. It is important that agricultural modernization be incorporated into an overall development strategy appropriate to each individual country. In this context, energy savings may be achieved in conjunction with other objectives. Goldemberg et al. (1988) point out that some agricultural modernization can occur without such large increases in consumption commercial energy (and associated reductions in labor requirements). Using one type of rice production as an example, they illustrate that many benefits of the "green revolution" in increasing yields per hectare can be achieved with intermediate approaches that do not go as far in substituting mechanical energy for labor.

Expanded agricultural energy needs can also present an attractive opportunity for

biomass energy development. FAO (1981) projected that an increase of 17 petajoules (PJ) of oil-equivalent agricultural energy use would be required to double food production in developing countries by $2000.^{4}$ Goldemberg et al. (1988) calculate that this amount of energy in the form of methanol could be produced by thermochemical processes from 40% of the present organic wastes (crop residues, animal manure, and food-processing wastes) in developing countries. Alternatively, feedstocks could come from tree plantations representing land equivalent to 3% of current forest land in developing countries. Other possible areas for efficiency improvements include electromechanical pumping of water for irrigation, more efficient use of existing water resources, and the use of alternative energy supplies such as wind for pumping.

Near-Term Technical Options: USSR and Eastern Europe

In the Soviet Union and Eastern Europe, industrial energy use accounts for nearly 50% of secondary energy use. As a share of primary energy equivalent (with electricity conversion losses allocated to end uses of electricity) it is even larger (Mintzer, 1988). These countries have very high energy consumption per unit of GNP. One recent analysis indicates that the current energy intensity of the Soviet economy is "akin to the IEA energy economies of the early 1970s," as shown in Table 5-6 (IEA, 1988). In fact, while energy intensity in OECD countries was declining by over 20% from 1973 to 1986, energy use per unit of GDP in the USSR actually increased slightly.

Encourage Structural Change

One major reason for the very high energy/GDP ratio in the Soviet Union and many Eastern European countries is the large share of industrial activity devoted to heavy industry (production of basic materials such as metals, cement, etc.) which is inherently energy intensive. Over the past several years, a widespread belief has been expressed in these countries that their economies need to move rapidly toward producing a different (and less energy intensive) mix of goods and services (see, e.g., Gorbachev, 1987; Makarov

TABLE 5-6

Energy Intensities of Selected Economies

(energy/unit of GDP)

	1973	1986
Canada	0.88	0.76
United States	0.76	0.57
IEA Pacific	0.42	0.31
IEA Europe	<u>0.40</u>	<u>0.34</u>
IEA Total	0.56	0.44
Soviet Union	0.99	1.03

Source: IEA, 1988.

and Bashmakov, 1990; Sitnicki et al., 1990; Jaszay, 1990). The interest in "restructuring" or structural change is driven primarily by economic necessity. The economic concerns have both supply and demand components. On the supply side, Makarov and Bashmakov (1990), as well as Sitnicki et al. (1990), report rapidly rising marginal costs of increasing energy supplies in the Soviet Union and Poland. Thus, they argue that economic growth on the current energy intensive path will be constrained by the ever-increasing investment cost of producing more and more energy.

On the demand side, it is believed that a shift toward production of consumer goods and services is necessary to increase living standards and revitalize these economies. The mix of goods and services currently demanded in the more affluent market economies of the OECD countries requires less basic materials and considerably more fabrication and finishing as well as service-oriented economic activity per unit of GDP. Most of the countries of Eastern Europe, as well as the USSR, have indicated their intention to move toward market economic systems and away from central planning as the means of allocating economic resources and activity. This is viewed primarily as a means of improving the efficiency of economic activity, stimulating economic growth and ultimately raising living standards. To the extent that these economic reforms are successful, they will have significant ancillary benefits in reducing the rate of growth in greenhouse gas emissions.

Makarov and Bashmakov (1990) provide several alternative scenarios of economic activity and energy consumption in the Soviet Union. In the base case or "business-as-usual" scenarios aggregate energy efficiency improves very little through the year 2030. The authors conclude that continuation of this type of economic development would require investments of capital and other resources in energy production "so large as to preclude possibility of realizing any but the pessimistic economic

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growth case." The pessimistic economic scenario assumes growth of GDP at 2%/year. In contrast, a "structural change" scenario results in a 25% decrease in energy per unit of GDP by the year 2030. This allows more rapid economic growth (3%/year) while using about 15% less energy and reducing carbon emissions by 14% (below the base case).

Sitnicki et al. (1990) report even more significant reductions in energy consumption under a structural change scenario for Poland. Relative to a "business-as-usual" base case, the structural change case reduces energy consumption by 47% and carbon emissions by 43% in the year 2030. Jascay (1990) shows for Hungary that structural change in the economy could result in significantly lower energy requirements and carbon emissions in the future relative to the most recently published official economic projections. These analyses suggest that policies being considered in the USSR and Eastern Europe to encourage economic growth would also have significant benefits in reducing greenhouse gas emissions.

Other Emission Reduction Options

A closer look at some specific industries verifies the general impression of energy inefficiency. The USSR is by far the world's largest producer of steel (WRI and Unfortunately, it is also IIED, 1988). apparently close to last in the world in efficiency. Estimates for 1983 indicate that the USSR used 31 GJ to produce a ton of steel as compared to the Japanese standard of about 19 GJ (Chandler, 1986). As shown in Table 5-7, the Soviet Union and many Eastern European countries continue to produce a large percentage of their steel in very inefficient "open hearth" furnaces, which have been virtually eliminated in the OECD. They also do very little recycling, as indicated by the small percentage of steel produced in electric arc furnaces.

One analyst has suggested that Soviet industry has shown some success in improving efficiency in their heavy industry with existing technology (e.g., "housekeeping" measures, refinements of existing technologies), but has failed to assimilate distinctly different and inherently less energy-intensive technologies. An example is the cement industry, a heavy energy-using sector for which energy use can be greatly reduced by switching from the wet process to a newer dry calcining process. Although the dry process is available in the Soviet Union, it has not been widely utilized (Hewitt, 1984).

There are several reasons for the extraordinarily high energy intensity of Eastern European industry. The Soviet Union (and to a lesser extent Eastern Europe) has enormous energy resources and has historically invested heavily in energy development due to national economic policy rather than demand. Hence, scarcity of energy resources has not provided an incentive to conserve. In addition, the "markup" pricing systems used in these countries do not provide a strong incentive for efficiency improvements. In fact, it has been argued that the reward system has actually provided managers with an incentive to consume more energy (Chandler, 1986).

More recently, the value of energy efficiency has been recognized by Soviet leadership. As described by Soviet energy analysts, "the energy economy of the Soviet Union is entering a new period of development. The most economical and favorable located oil and gas resources . . . are gradually running out" (Makarov et al., 1987). The result is that development of new energy resources is much more expensive and difficult than in the past. One result of rising costs of energy development has been the explicit inclusion of energy efficiency measures in central economic and energy planning. Targets have been set that would result in more than a 20% reduction in the energy intensity of the Soviet economy (Makarov et al., 1987).

The Soviet Union has historically done very well in the utilization of industrial waste heat for electricity generation (cogeneration) and for other heat needs, such as district heating. This trend is continuing. In the Leningrad region, for example, the 1981-1990 energy plan calls for reducing projected industrial energy use by about 2 EJ through a combination of improved industrial technology and expanded use of waste heat

TABLE 5-7

Innovation in Steel Production Technology Selected Countries, 1985

Country	Economy Type	"Inefficient" Open Hearth (% of	"Recycling" <u>Electric Arc</u> production)
Spain	М	0	61
Italy	Μ	0	53
South Korea	Μ	0	31
United Kingdom	Μ	0	29
Japan	Μ	0	29
West Germany	М	0	19
Brazil	М	4	25
United States	Μ	7	33
Romania	С	29	22
China ^a	С	31	19
Yugoslavia	С	34	26
India ^a	С	42	19
Poland	С	42	15
East Germany	С	34	31
Hungary ^a	С	51	13
Soviet Union	C	57	11

M = Market-oriented; C = Centrally-planned.

^a Though this country's agricultural economy is market-oriented, its industry is not.

Source: Chandler, 1986.

for both electricity and other heat needs (Glebov and Kovlenko, 1987).

In addition to efficiency improvements, other options for reducing greenhouse gas emissions from industry in the USSR and Eastern Europe are possible through fuel switching. Although the major resources are generally located far from current industrial centers, the Soviet Union has the world's largest proven recoverable natural gas reserves in the world, amounting to about 39% of the World total (IEA, 1988). In addition, its undeveloped geothermal and hydroelectric resources are significant (as discussed in PART TWO). It would be technically possible, therefore, for the USSR to substitute various alternative fuels for current and projected coal use in the industrial sector, although the costs of such substitution have not been well analyzed.

Long-Term Potential in the Industrial Sector

Over the long term, technological options for improving efficiency in industrial energy use are very speculative. Several concepts advanced by various analysts may warrant further study to identify potential options for reducing long-term industrial demand for fossil fuels.

Structural Shifts

Over the long term, shifts in the structural composition of industrial activity will undoubtedly continue, with significant energy consequences. As discussed by Ross et al. (1987), production of basic (and inherently energy-intensive) materials has tended to decline over time as a share of GNP after an economy achieves a certain level of affluence. There are three components of this shift:

• substitution of new (and often less energy-intensive) materials;

• product and production design changes that result in more efficient materials use; and

• saturation of major markets for material-intensive products, including infrastructure and material-intensive consumer products.

These effects can be expected to continue in the future and to some degree are incorporated in all the scenarios of future energy use presented in this report (see CHAPTER VI). With combinations of policies, such as economic incentives and aggressive research and development, these effects can be accelerated considerably, especially in the developing countries where major increases in industrial energy use are expected. It is currently very difficult to identify, much less quantify, the effects of actions to achieve the technical potential. Further study of long-term trends in the structure of industrial activity and specific policy options for influencing these trends is needed.

Advanced Process Technologies

As pointed out by Ross (1985), major reductions in energy intensity in industrial processes can come about through "revolutionary" change in process technology. Typically, such change is not motivated primarily by energy conservation; however, large reductions in energy intensity often result from technological advances. As an example, advanced steel-production technology now under development could result in very large energy savings per unit of output. About 40% of the energy used in iron and steel production is related to shaping and processes utilize treating. Advanced controlled solidification, often very rapidly, of thin castings that approximate the final shape. When fully developed, this technology should eliminate almost all of the energy use currently associated with rolling and shaping (Ross, 1985).

In the petrochemical industry, research is currently underway to identify advanced separation techniques that could eliminate many of the losses inherent in the current distillation process. Gas separation membranes, gas adsorption, and liquid mass separating agents are all currently commercial for very specialized petrochemical applications and use considerably less energy than the distillation processes they have replaced (Mix, 1987). Over the long term, wider applications of these or similar technologies may further reduce process energy requirements.

In general, advanced technologies are attractive because of the lower total cost, better quality control, reduction in inventories, greater flexibility, etc., as well as the improved energy efficiency. It is difficult to identify possible process technology improvements that could become available through research and development over the long term, although it is likely that energy efficiency improvements will be part of these developments.

Another long-term area of process technology advancement is the use of biological phenomena in production processes. Although it is difficult to even identify specific applications of biological processes at this time, they appear to offer possible improvements in the speed, control, and precision of process technologies (Berg, 1988). As such technologies emerge, they will undoubtedly offer additional opportunities for reductions in fossil energy use. Industrial policies designed to stimulate technological advances and capital turnover will ultimately also lead to reduced energy requirements.

Non-fossi! Energy

Although it is likely that energy intensity of industrial activity will continue to decline over the long term, significant levels of energy consumption will no doubt still be required. Opportunities exist for meeting these demands with non-fossil energy sources. Many industrial technology experts (see, e.g., Berg, 1988; Schmidt, 1987) have suggested that increased use of electricity in industrial processes over the long run is likely because of its superior characteristics of controllability and minimal loss or error.

Even though production of electricity involves large losses, this is often offset because the more sophisticated and precise production processes it allows are generally less energy-intensive at the end use. Increasing electrification of industrial processes at the end-use point allows for a wide variety of alternative generation options (as discussed in **PART TWO**), which can reduce greenhouse gas emissions.

In addition, one analyst has suggested that economic competition will cause energyintensive industries over the long run to locate in areas where isolated resources of cheap and hard-to-transport energy are available. Examples cited include natural gas and hydro locations in Canada, Brazilian hydropower sites, and natural gas locations in the Middle East (Ross, 1985). The same logic could also apply to locations with geothermal and solar resources as those technologies become competitive. Policies could be implemented to discourage fossil-fuel use (see CHAPTERS VII and VIII), as well as to encourage movement of heavy industry to locations where renewable resources are economically attractive.

PART TWO: ENERGY SUPPLY

This section discusses technical options for reducing greenhouse gas emissions by (1) making more efficient use of fuels for power generation and (2) altering the types of energy supplies we use. These two goals have one common objective: to supply a similar amount of useful energy services compared to current energy consumption practices, but in such a way that greenhouse gas emissions are minimized. Options for reducing greenhouse gas emissions in end-use applications, particularly by improving energy efficiency and switching fuels, were discussed in PART ONE: ENERGY SERVICES. This section focuses on possible options for improving the delivery of energy services by reducing the losses during energy production and conversion processes. Additionally, the types of energy supplies can be altered by developing sources of energy that do not emit greenhouse gases.

The first part of this section discusses possible options for altering current patterns of fossil fuel use. This is clearly one of the highest near-term priorities, since as discussed in Chapter IV, current commercial energy use globally is dominated by fossil fuels. In many cases, however, options exist for reducing emissions from these applications. This is followed by a discussion of possible supply alternatives to fossil fuels, including increased use of biomass, solar resources, additional renewable energy resources, nuclear power, and options for enhancing energy storage and delivery to final consumers.

FOSSIL-FUEL OPTIONS

As discussed in Chapter IV, fossil-fuel consumption is responsible for the vast majority of CO_2 emissions. On an energyequivalent basis, coal produces the most CO_2 (about 25 kg C/gigajoule); oil, about 80% that amount (about 20 kg C/gigajoule); and natural gas, about 55-60% that amount (about 14 kg C/gigajoule). Given these rates of CO_2 emissions, fossil-fuel consumption would have to be drastically reduced or eliminated over the long run to control greenhouse gas emissions. With the current global reliance on fossil fuels, however, the shift away from fossil fuels cannot be accomplished easily, even with international agreement to pursue this objective. Steps can be taken now to begin or accelerate the transition to non-fossil energy by minimizing the greenhouse impact of the fossil fuels that are used. Possible actions include improving the efficiency with which fossil fuels are produced and converted to electricity, switching from more carbonintensive fuels to less carbon-intensive fuels (e.g., from coal to natural gas), and applying various engineering controls to reduce emissions of greenhouse gases during the production and consumption of fossil fuels (e.g., NO_x control, CH_4 recovery).

Since one of the primary uses of fossil fuels currently is the production of electricity, one potential option is to produce electrical power more efficiently, using less energy input to produce electricity. For example, in the U.S. during the 1950s and early 1960s, the efficiency of powerplants consuming fossil fuels increased from 25% to about 32% (see Figure 5-5). This improvement has stalled since the early 1960s because of fewer technical improvements in combustion techniques, higher energy consumption by auxiliary equipment used for pollution control (e.g., electrostatic precipitators for particulate removal and scrubbers for SO_2 removal), and increased use of less efficient fuels, such as subbituminous coal and lignite.

Although electricity production is currently one of the primary uses for fossil fuels, other applications have been proposed in order to meet future energy needs. Specifically, as conventional petroleum resources are depleted, it is possible that much of the demand for liquid (oil and natural gas liquids) and gaseous (natural gas) fuels will ultimately be met by synthetic fuel production from solid fossil fuels. Although there is currently little synthetic fuel FIGURE 5-5



production in the world, processes have been developed to convert relatively abundant solid energy resources such as coal, oil shale, and tar sands to liquid or gaseous products that could be consumed in the same end-use applications as more conventional resources.

The production of synthetic fuels, however, typically requires the consumption of significant amounts of energy to produce the liquid or gaseous fuels. These conversion processes produce greenhouse gas emissions, particularly CO_2 , so that the total emissions per unit of energy are higher for synthetic fuels than for conventional fossil fuels. For example, the CO_2 emissions from production and consumption of liquid fuels from coal is about 1.8 times the amount from conventional liquid fuels from crude oil (see CHAPTER IV for further discussion).

The following sections explore possible options for reducing the greenhouse impact of fossil fuels. Using fossil fuels more efficiently is discussed, including refurbishment of existing powerplants, repowering opportunities (including application of "clean coal technologies"), and cogeneration. Greater use of natural gas is then discussed since it produces less CO_2 than oil or coal. Methods for controlling greenhouse gas emissions are also presented.

Refurbish Existing Powerplants

Energy use at existing powerplants can be reduced by refurbishing the plant to keep it operating at optimal efficiency. Over time, these efficiencies decline due to wear and various aging processes. For many economic reasons it has become clear over the past decade that utilities in the U.S. are planning to keep existing powerplants in service longer than initially planned (Democker et al., 1986). It is likely that this trend will occur globally as well to minimize the need to invest in new powerplants. As these powerplants age, however, declining efficiency will become more widespread than in the past.

In response, the U.S. electric power industry has developed new techniques for extending the life of powerplants. The extent of efficiency improvement depends on how badly the specific plant had degraded and the extensiveness of the upgrades. Increases in efficiency in the range of 3-4% appear to be possible at many existing units, with even greater improvements possible in some cases (PEI, 1988).

In developing countries. the opportunities for improving the efficiency of electricity generation may be much greater. According to a recent study by U.S. AID (1988b), "The majority of thermal powerplants in developing countries operate at lower-thandesign capacity and efficiency." Many of these powerplants use more than 13 MJ⁵ of fuel to generate a kWh of electricity, compared to typical design heat rates of 9-11 MJ/kWh. It is estimated that a rigorous program of powerplant rehabilitation could improve overall fuel use efficiency for thermal power generation by 10% or more in most developing countries (U.S. AID, 1988b).

Pursue Clean Coal Technologies

As new powerplants are constructed to meet increasing electricity needs, many of these plants are likely to be fossil fueled. To the extent that new powerplants use fossil fuels, greenhouse gas emissions can still be reduced by using the most efficient conversion technologies. The U.S. Department of Energy, the Electric Power Research Institute, and many other organizations have been investing significant funding in research, development, and demonstration of "clean coal technologies" designed to allow burning of coal to generate electricity with maximum efficiency and minimum environmental impact (U.S. DOE, 1987d). These technologies offer the potential to significantly reduce the amount of traditional air pollutants such as sulfur dioxide and nitrogen oxides. However; they may also affect the amount of greenhouse gas emissions, particularly for those technologies that improve the overall efficiency of converting coal to electricity. For example, some of these technologies such as the Kalina Cycle could improve efficiency by at least 10% relative to conventional coal combustion technologies.

Three of these advanced technologies currently in the demonstration phase are atmospheric fluidized bed combustion (AFBC), pressurized fluidized bed combustion

CO₂-emitting limestone or dolomite and is likely to be very similar in efficiency to conventional technology, and therefore, not beneficial in reducing CO₂ emissions. Moreover, it is believed research has indicated that this technology may significantly increase N_2O emissions as compared with conventional coal-fired powerplants. The PFBC and IGCC systems, however, can be combined and are projected to increase conversion efficiencies as much as 10-20%, with corresponding reductions in CO₂ emissions per unit of electricity produced (U.S. DOE, 1987d).

(PFBC).

and

Clean coal technologies can be used for newly constructed powerplants, but also to "repower" existing powerplants. In repowering, the basic combustion components of existing powerplants are replaced with one of the new technologies. Additionally, new components, such as a gas turbine cycle, may also be installed in combination with some refurbished components of the existing powerplant. The result is a hybrid plant with performance very much like that of an efficient new unit.

Increase Use of Cogeneration

Cogeneration refers to the production of both steam and electricity from the same source; the steam is used to meet heating and process requirements at the facility, and the electricity is used on-site or sold to electricity customers. Because it is more energy-efficient than conventional generating options, it has been encouraged in the U.S. recently by many regulatory and legislative initiatives. For example, the Public Utilities Regulatory Policy Act (PURPA) encouraged cogeneration by establishing a process ensuring that cogenerators with low production costs could sell this cogenerated electrical power to electric utilities.

As discussed earlier in PART ONE, cogeneration has been very popular with large industrial energy users as one approach for reducing their overall energy costs. Most of the approximately 18 GW of currentlyoperating cogeneration projects in the U.S. and an additional 29 GW under active development fall into this category (Williams,

1988). Similarly, as electric utilities face more competition from industrial cogenerators and independent power producers (i.e., companies that produce and market power but are not regulated as utilities), they may choose to retrofit some existing generating facilities with cogeneration, using the waste heat from electricity production for district heating or industrial process heat applications. Engineering assessments have shown this potential retrofit option to be economically attractive for powerplants that burn coal and are located close to steam load centers (Hu et al., 1984), though other fuel sources can be used.

Substitute Natural Gas for Coal

Natural gas (which is primarily methane) has 55-60% of the carbon per unit of energy as coal. In applications such as electricity production where coal is frequently used, switching to natural gas would substantially decrease CO₂ emissions. As discussed previously in PART ONE, natural gas is currently used in several key end-use applications, particularly in a wide variety of industrial energy applications and in residential and commercial space heating. In addition to its end-use potential, natural gas can be used as a fuel for electricity generation. The discussion below focuses on the technical options and advantages of using natural gas as a fuel for electricity generation. The role of natural gas as an end-use fuel and a fuel for electricity generation, however, depends on the natural gas resources available and the cost at which these resources can be supplied.

Natural Gas Use At Existing Powerplants

There are several near-term alternatives for increasing the use of natural gas for electricity generation. One relatively inexpensive option would be to increase the utilization of existing natural gas- and oil-fired (most of which can also consume natural gas) powerplants. For example, in 1987 average capacity utilization rates for U.S. oil- and gasfired powerplants were 40%, compared with 58% for coal-fired powerplants. Thus, there is some technical potential to increase gas use by increasing the utilization of natural-gasfired powerplants. However, these plants are

utilized less because the variable (operating and maintenance) cost of power is higher at most oil and gas plants than at coal, nuclear, and hydro powerplants. In addition, oil- and gas-fired powerplants can be easily operated intermittently and with less wear on the systems (i.e., to meet peak load conditions). Since electric utilities (usually) produce with their least electricity expensive powerplants, policies would first have to be adopted to increase utilization of natural gas capacity.

Advanced Gas-Fired Combustion Technologies

An additional option for increasing natural gas use is to construct new gas-fired combined cycle or combustion turbine powerplants. Although the variable cost may be higher, these powerplants cost significantly less to build than coal-fired powerplants and are typically more energy efficient. They could also be part of a near-term solution since the lead times for gas-fired plant siting and construction average about 2-4 years versus 6-10 years for coal-fired powerplants. These advanced combustion technologies are not in greater use primarily because of investors' expectations that the costs of natural gas over the operating life of the facility would be substantially higher than other fuel alternatives such as coal. As a result, despite the lower capital costs of these technologies, electric utilities have often invested in other alternatives because total generating costs of combined cycle or combustion turbine technologies have been perceived to be greater than those of coalfired powerplants.

Combustion Turbines: Simple/Combined Cycles. Combustion turbines are similar to jet aircraft engines in that fuel is burned in compressed air, with the combustion gases then used to turn a turbine for electricity This process is known as a generation. simple-cycle turbine. After the hot gases are used to produce electricity, the exhaust gases can be used to convert water to steam in a steam turbine. Together these two processes generate power in a process known as combined cycling. Most combustion turbines in use are simple cycles, which are used primarily for peak power requirements due to intermittent their favorable operating

characteristics (primarily their ability to increase power production quickly) and low capital costs, although operating costs are high. Combined cycle capital costs are higher but the technology uses fuel more efficiently, and hence, is currently preferred for units expected to be utilized more frequently.

Aeroderivative Combustion Turbines. Recent advances in jet engine (aeroderivative) technology, including new materials and designs that enable combustion to occur at higher temperatures, have made turbines more efficient. Many of these advances are being, or could be, applied to turbines for generating electric power. Existing simple and combined cycle systems have efficiencies of about 32% and 42%, respectively, compared to new conventional coal-fired powerplants, which have efficiencies of about 33-35%. Recent advances in aeroderivative technology could significantly improve these cycle system efficiencies. One technology that has been recently commercialized in California is the steam-injected gas turbine (STIG). STIG units take any steam not needed for process heat requirements and inject it back into the combustor for added power and efficiency. In a simple-cycle application, the efficiency of the turbine might be 33% with an output of 33 MW, while with full steam injection the efficiency would increase to 40% with an output of 51 MW (Williams, 1988). An improvement in steam injection that has been proposed is the intercooled steam-injected gas turbine (ISTIG). ISTIG cools the compressor bleed air used for turbine blade cooling, allowing a much higher turbine inlet temperature. With this technology, the single-cycle efficiency cited above would increase from 33% to 47% and output from 33 MW to 110 MW; the estimated capital cost of ISTIG is about \$400/kW (Williams, 1988).

Factors Affecting Use of Natural Gas

Resource Base. There is a significant amount of research and debate over the quantity of natural gas that is available. As discussed in Chapter IV, global gas resources are estimated to be significantly smaller than global coal resources (resource estimates by the World Energy Conference indicate that coal resources are about 30 times greater than gas resources). Within the U.S., there is disagreement over the size of this difference. One source has indicated that in the U.S., the natural gas resource base is as large as the coal resource base when one compares the usable economically recoverable and resources; the supply should be adequate for hundreds of years (Hay et al., 1988). On the other hand, based on 1985 consumption levels of about 18.6 EJ, the U.S. Department of Energy (U.S. DOE) has estimated that technically recoverable U.S. gas resources would last only about 70 years at current usage rates, and only about 45 years if limited to supplies that could be marketed for about a maximum of \$5/GJ (see Table 5-8). In contrast, U.S. coal reserves are estimated to be about 350 times greater than 1985 U.S. consumption levels (U.S. DOE, 1988d).

Significant gas reserves are available outside of the U.S., though they are not well matched with potential demand centers. More than half of the world's proved reserves are located in just two countries, the USSR and Iran. Soviet gas reserves alone are eight times those available in the U.S., and Iran has over two and one-half times the quantity of U.S. gas reserves. While roughly 30% of the world's proved reserves of natural gas exist in the Middle East, only 5% are in Western Europe, and less than 1% are in China and Japan combined (British Petroleum Company, 1989).

Cost. In addition to the potential limit on gas supplies, there are also questions about the cost of additional gas supplies, the location of supplies vis-à-vis the areas of demand, the cost and availability of improved transmission and distribution systems, and in the case of international trade in liquified natural gas (LNG), the costs of liquefaction, transportation, and regasification facilities.

Concerns over the cost and availability of natural gas may appear unwarranted given the existence of excess capacity and falling prices in the U.S. gas industry in recent years. However, these market conditions may be temporary. Current excess capacity followed a period in the 1970s when natural gas was in short supply. The recent changes are primarily because of natural gas price deregulation, which allowed prices to increase from previously controlled levels. The price increases had two effects: (1) demand decreased and (2) supply increased. The duration of the current slack market conditions is a matter of much debate, but as the demand and supply for natural gas come into balance, natural gas may no longer be available at current prices.

The relevance of these concerns is not that natural gas cannot play a role in reducing CO_2 emissions; unquestionably, it can. However, the ability of natural gas to replace fuels with higher carbon content is a function of the quantity of natural gas available and the cost at which natural gas can be supplied to consumers. That is, even if natural gas is available, the extent to which it replaces other fuels will depend on its available supply and cost relative to alternative fuels and the available pipeline delivery system. Any policies promoting increased use of natural gas must recognize these factors.

Electric Utility Gas Consumption. In 1985, gas consumption by U.S. electric utilities was about one-fifth of total U.S. gas use, or about 3 EJ. Even though U.S. electric utilities consume only a minor fraction of natural gas, they can have a large impact on prices because they are frequently the marginal buyer. That is, utilities often have alternative generation options such as oil or coal and can easily switch, unlike many residential or commercial gas users who do not have such flexibility. Increases in electric utility demand for natural gas would affect residential, commercial, and industrial customers, who would be charged higher gas For example, assuming 13 EJ of prices. consumption, a \$1/gigajoule price increase would increase natural gas costs by \$13 billion per year among all consumers.

To replace a significant amount of electric utility coal consumption would require a very large increase in natural gas consumption. For example, utility gas consumption in 1985 was 3 EJ, whereas coal consumption by utilities was about 15 EJ. Thus, to replace 40% of coal consumption (6 EJ), a 200% increase in utility gas consumption would be necessary (assuming current efficiencies), raising U.S. electric utility gas use to unprecedented levels. As a

TABLE 5-8

Total U.S. Gas Reserves And Resources (Exajoules)

		Technically	Recoverable Gas by Price ^b	
		Recoverable Gas ^a	<\$3/Mcf	\$3-5/Mcf
Lower 48 States (Conventional)				
Proved Reserves, 12/31/86, Onshore and C	Offshore	171	171	
Inferred Reserves/Probable Resources, 12/2	31/86, Onshore	91	91	
Inferred Reserves, 12/31/86, Offshore		25	25	
Extended Reserve Growth in Nonassociate	d Fields, Onshore	128	60	19
Gas Resources Associated with Oil Reserv	e Growth ^c		66	12
Undiscovered Onshore Resources		236	95	63
Undiscovered Offshore Resources ^d		144	<u>_58</u>	<u>_30</u>
Sut	ototal	860	533	125
Lower 48 States (Unconventional)				
Gas in Low-Permeability Reservoirs		194	75	53
Coalbed Methane		52	9	4
Shale Gas		33	<u>_11</u>	5
Sut	ototal	279	95	63
Alaska				
Reserves		36	8	0
Inferred Reserves (Cook Inlet Area)		3	3	0
Undiscovered, Onshore and Offshore		<u>100</u>	2	2
Sut	btotal	139	13	2
Total		1,278	640	189

^a Volumes of gas judged recoverable with existing technology.
^b Volumes of gas judged recoverable with existing technology at wellhead prices shown (1987\$). Mcf represents one thousand cubic feet (about 1.1 GJ), which is a common measure of gas quantity.
^c Judged at oil prices of <\$24/bbl and \$24-40/bbl.
^d Outer Continental Shelf.

Source: U.S. DOE 1988c.

result, any policy to increase natural gas use needs to recognize possible impacts on gas supply and the market price of gas.

Methods of Increasing Gas Resources

Two ways to increase the available supply of gas to consumers are to (1) reduce or capture methane emissions during the production and distribution of natural gas and (2) extract methane from coal seams. In each of these cases, increasing the amount of methane available to consumers would often have other positive environmental benefits by reducing the amount of CH_4 and CO_2 emitted to the atmosphere.

Reduce or Capture Emissions from Natural Gas Flaring, Venting, and Leaking. As discussed in Chapter IV, during the production of oil and natural gas, natural gas may be vented to the atmosphere as CH_4 or flared (producing CO_2).⁶ Additional CH_4 emissions are also produced during the refining, transmission, and distribution of natural gas. These emissions can be reduced through more careful production and maintenance procedures or by capturing the gas for on-site use or sale to gas customers.

Gas vented or flared in the U.S. represents around 0.5% of annual domestic production, while gas losses during transmission and distribution have been estimated to represent less than 0.5% of gas consumption (A.G.A., 1989). These values are presumed to be much lower than the global average because of several factors, including regulations prohibiting the flaring and venting of gas in the U.S., and the existence of markets and infrastructure to transport and sell the gas. In areas in the U.S. where no market for the gas exists (e.g., Alaska), gas produced during oil production activities is reinjected into the reservoirs in order to maintain pressure. Opportunities exist in the U.S. for reducing gas (methane) losses during transmission and distribution, such as through maintenance and replacement of old, outdated distribution lines. Globally, a larger percentage of natural gas is vented or flared because of fewer regulations governing a less-developed these releases and infrastructure for utilizing the gas. The quantities of gas vented or flared could be

reduced through development of an infrastructure to market the gas or through regulations governing these releases.

Extract Coalbed Methane. As discussed in Chapter IV, during coal mining, particularly underground mining, methane trapped in the coal seam is released. Historically, trapped coalbed methane has been viewed as a safety problem since methane can accumulate in the coal mine to the point where it can explode. U.S. mining regulations require that underground coal mines be adequately ventilated to prevent this problem. Recently, however, there has been a growing interest in utilizing coalbed methane as a natural gas resource.

Methane extraction from coalbeds, which is being done commercially in a few areas in the U.S., differs from traditional natural gas production in several respects. Perhaps most importantly, the gas production profile differs from conventional gas wells in that maximum output generally occurs two to three years after the wells are in place, compared to immediately afterwards for conventional wells. For a given production site, more wells are drilled to maximize methane flow. Also, because these wells are drilled into available coal seams, they are generally quite shallow (i.e., not more than 3000-4000 feet deep). While the relatively shallow access helps to reduce drilling costs, more ground water is encountered, requiring additional efforts to extract clean gas.

Because coalbed methane recovery is a relatively new industry, it is difficult to quantify the potential size of this resource. In addition to offering another gas source, coalbed methane recovery could occur before the coal seam is mined. Such recovery would help to ease the problem of methane buildup in coal mines (possibly reducing coal mining costs) and reduce the emissions of CH_4 to the atmosphere that result from current coalmining operations.

Employ Emissions Control Technologies

One technological option for reducing the amount of greenhouse gas emissions is the use of emission control techniques on combustion technologies that generate these emissions. NO_x and CO_2 emission control options for stationary combustion sources, such as electric utility powerplants, are discussed below.

$NO_{\mathbf{x}}$ Controls

Nitrogen oxides (NO_x) are formed during combustion primarily by the combination at high temperatures of nitrogen (N_2) and oxygen (O_2) naturally found in the air, and secondarily by the nitrogen that is found in fuels such as coal and oil. Of these two factors, the combustion temperature is usually the most critical factor affecting the NO, emission rate. Fluidized bed combustion is one possible way to significantly reduce NO, emissions. There are several additional available methods for controlling NO, emissions (based on NAPAP, 1987):

• Low Excess Air (LEA)/Overfire Air. These two combustion techniques alter the flow of air during the combustion process. With low excess air the amount of excess combustion air is reduced, thereby lowering emissions by as much as 15%. With overfire air, some combustion air is redirected to a region above the burners, which can reduce emissions by as much as 30%. Potential drawbacks are incomplete combustion of the fuel, increased smoke, and the extensive plant modifications that may be required.

• Low NO_x burners. This control technique operates within the furnace to limit the mixing of coal and combustion air to create a low-temperature combustion zone. This technique can be applied to existing and new units, although experience on existing units is quite limited. Removal efficiencies in new units approach 50%.

• Air and Fuel Staging. When combined with low NO_x burners, these two controls can achieve up to 75% removal efficiencies. With air staging alone, up to 50% of the combustion air is directed above low- NO_x burners. With fuel staging (also known as reburning) additional fuel is burned in a region above the burners to create a fuelrich combustion zone. Within this zone NO_x is destroyed by reducing conditions that convert NO_x to molecular nitrogen. This technique has been used in full-scale applications abroad, but only in pilot-scale facilities in the U.S.

Selective Catalytic Reduction (SCR). SCR is a post-combustion control technology that uses a catalyst to reduce NO_v; reductions of 50-80% are possible. Its advantages include relatively simple equipment, no byproduct, and minimal efficiency loss. Its cost-effectiveness is unproven, however, and depends on catalyst lifetime, which depends primarily on fuel characteristics. SCR has been used abroad on low-sulfur coal, particularly in Japan and West Germany. Testing of this technology's performance on U.S. high-sulfur coal began in late 1989.

CO_2 Controls

Technologies have been developed to remove carbon dioxide from powerplant flue gases and dispose of it in a manner that prevents it from reaching the atmosphere. These technologies, however, are unproven and very costly at this time. In one process, carbon dioxide in the flue gas is mixed with water in a solvent solution at temperatures slightly above ambient conditions. The carbon dioxide binds to the reagent and passes to a regenerator chamber where temperatures are elevated. The reverse reaction then occurs and CO₂ is released, removed, pressurized, and liquified. The reagent is regenerated and reused. The liquid carbon dioxide could then be used for commercial applications, or pumped to deep ocean locations, deep wells, or salt domes for permanent disposal. The volume of CO_2 currently produced dwarfs existing markets for reuse, however, so any control program of significant scope would involve very large disposal costs.

In order to understand the relative costs of this CO_2 removal process, the costs of this system are compared to a conventional sulfur dioxide scrubber in Table 5-9. The carbon dioxide scrubber is 250-350% more costly than the sulfur dioxide scrubber and would increase electricity costs by 60-80%. The cost of transporting and disposing of the large volume of removed CO_2 has not been adequately assessed, but is likely to substantially increase this estimate. Although

TABLE 5-9

	00 0 11.0
CO ₂ Scrubber ^o	SO ₂ Scrubber
810	220
80-710	NA
NA	3.5
25	4.5
22	2.5
<u>NA</u>	<u> 10 </u>
36-47	10.7
	CO ₂ Scrubber ^b 810 80-710 NA 25 22 <u>NA</u> 36-47

CO₂ Scrubber Costs Compared To SO₂ Scrubber Costs^a

^a Ninety percent removal of both CO_2 and SO_2 .

^b Source: Steinberg, Cheng, Horn, 1984.

^c Source: U.S. EPA Interim Acid Rain Base Case Estimates, 1987.

^d Greenfield Site.

^c Sixty-five percent capacity factor; 9% capital charge rate; incremental power costs 65 mills per kilowatt-hour; new plant costs of 1,200/kW; fixed O&M for CO₂ scrubber is assumed to be \$10 per kilowatt-year for comparison purposes only, actual costs could well be higher; 1988 dollars assumed to be worth 42% less than 1980 dollars.

some CO_2 could be used for enhanced oil recovery or stored in exhausted oil and gas wells, large-scale disposal would most likely have to be in the ocean. This raises serious environmental concerns that have not been examined.

Consider Emerging Electricity Generation Technologies

There are several technological options that could be available in the longer term that would substantially alter the way fossil fuels are utilized. Two of the most-discussed options -- fuel cells and magnetohydrodynamics -- are discussed below.

Fuel Cells

Fuel cell technology is now in use in the U.S. space program and is expected to eventually be commercially available to the electric power industry. The technology converts fuel energy to electricity using an electrochemical process similar to that employed in chemical batteries.

Total fuel cell plants may achieve efficiencies of up to 85%. There are several drawbacks to the technology at this time, especially: (1) special fuel requirements, and (2) relatively low reliability.

The fuel cell closest to commercialization is the Phosphoric Acid Fuel Cell (PAFC). This fuel cell converts hydrogen into electricity and water. The hydrogen must be produced, however; considering the conversion losses, overall powerplant efficiencies for large fuel cell plants (e.g., several MW) approach 45%. Second-generation technologies, such as molten carbonate and solid polymer electrolyte fuel cells, could offer 60% efficiencies. In theory, the chemical reaction could continue as long as fuel is supplied, but in practice the materials fail after prolonged The current goal is 40,000 operation. generation hours which, even if achieved. is still well below that of conventional powerplants. Another drawback is that the production of hydrogen from fossil fuels creates CO₂.

The use of hydrogen in fuel cells suggests the possibility of coupling fuel cells

with renewable energy sources. For example, solar powerplants could use any power not delivered to customers to create hydrogen, which could then be used when solar powerplants are not operating or when demand exceeds solar capacity (Ogden and Williams, 1989). Molten carbonate fuel cells, under research and development at the U.S. DOE at this time, could expand the capabilities of fuel cells to include natural gas and gasified coals.

Magnetohydrodynamics

Magnetohydrodynamics (MHD) is an advanced, efficient generation technology that could use coal as a fuel. In a MHD system, coal is burned at very high temperatures and the hot combustion gases are chemically The gases then pass through a treated. magnetic field created with superconductors, thereby generating power. The gases can also be used in a steam cycle to produce The MHD system is additional power. expected to eventually achieve efficiencies of 60%. In comparison, existing conventional coal powerplants operate at about 31-32% efficiencies and advanced pressurized fluidized bed combustion (PFBC) and Integrated Gasification/Combined Cycle (IGCC) coal units, now being demonstrated, are expected to achieve 35-37% efficiency.

There are several drawbacks to the MHD technology. It is very capital-intensive, requires superconductors that have only reached the laboratory stage of development, and the high temperature combustion could result in high nitrogen oxide emission rates. Nonetheless, many observers believe MHD systems will eventually be available as these obstacles are overcome, creating an option for very efficient coal combustion.

BIOMASS OPTIONS

Biomass in one form or another continues to be the predominant source of energy for at least half of the world's population. In many countries, such as Nepal, Ethiopia, and Guatemala, over 90% of total energy used comes from biomass (Goldemberg et al., 1988). Although on a global basis it accounts for only one-seventh of all energy consumed, for over 2 billion people it is close to being the only source of energy.

A number of studies have reported on the alarming rate of global deforestation as the current demand for biomass resources far exceeds the natural rate of regeneration (e.g., IUCN, 1980; WRI and IIED, 1988). It is this difference between growth and use that contributes to net greenhouse gas emissions. Despite this current situation, biomass energy over the long term offers some of the most promising opportunities for displacing large amounts of fossil fuel use.

Although biomass fuels account for about 14% of global primary energy use, they deliver a much smaller fraction of useful energy because of the inefficient nature of their current use. However, technologies exist or are under development to provide many times the current level of energy services from the amount of biomass currently consumed In addition, it is also technically globally. possible to greatly increase the annual increment of biomass available for energy use. Methods for increasing supply through agroforestry, biotechnology, etc., and for reducing extractive use of forest products for non-energy purposes are discussed in PART FOUR: FORESTRY. In this section various approaches are discussed to reduce biofuel demand through fuel switching, by improving end-use efficiencies, and by increasing conversion efficiencies using upgraded fuels (see Figure 5-6).

Improve Efficiency of Direct Firing Methods

The primary uses of biomass in direct combustion applications include use in cookstoves, space heaters, bakeries, brick kilns, and boilers of various sizes. Typical conversion efficiencies range from 5-15%. There is tremendous potential for improving the end-use efficiency in each of these energy conversion processes. In fact, this may be the most cost-effective, immediate option for decreasing the demand for biomass resources (e.g., see discussion on technical options for improving efficiency of biomass use in PART ONE).

Wood or wood products (bark, sawdust, chips, bagasse) are already used directly as a

boiler fuel (especially in agroforestry-based industries with readily-available access to wood supplies). But there are a number of modern technologies that can be used to extract much more useful output. Due to the physical variability of biomass (and the lower density of crop residues), some improvements in combustion properties can very often be achieved just by properly sizing the solid biofuels. The energy requirements for sizing and densification must be weighed against improved combustion, convenience, and ease of transport. While this is not absolutely essential when the application is for heating, some amount of sizing and/or briquetting is critical in more efficient boiler or gasifier designs.

Another area in which combustion efficiency can be significantly increased is in the use of advanced burner systems, such as fluidized bed combustors. These use a stream of hot air to suspend the fuel and thus achieve more complete combustion. Some of these technologies can also use certain fuels with high ash or silica content, such as rice husks, that would be harmful to standard combustion systems.

In a few areas, central power stations have been constructed specifically to use wood The facilities that are burning as a fuel. wood for electrical power range in size from 5 to 50 megawatts. Depending on the cost of fuel, conventional wood burning is generally not competitive with conventional fuels due to lower combustion efficiency and greater fuel bulk, which necessitates larger fuelhandling facilities. The localities served by these plants gain various benefits that may offset these inefficiencies. For example, local timber industries may be assisted, and environmental benefits may be obtained from reduced CO₂ emissions.

Improve Efficiency of Charcoal Production

Charcoal is produced by heating wood in the absence of air (also known as pyrolysis). The traditional method of producing charcoal in kilns made of earth, as used for centuries in many regions such as Africa, is very inefficient. Only 15-30% of the energy content of the wood is retained in the charcoal as all of the gases produced during



FIGURE 5-6

pyrolysis are allowed to escape. Substantial efficiency improvements are possible, for example, Brazilian kilns built of brick, which produce charcoal for steel manufacture, have achieved overall efficiencies of up to 50%, twice that of traditional methods, by utilizing the gaseous by-products (Miller et al., 1986). Even further improvements are expected (Goldemberg et al., 1987).

Promote Anaerobic Digestion Technology

Anaerobic digestion is a biological process whereby a combustible gas is produced in the absence of oxygen; this gas is a mixture of methane and carbon dioxide similar to the marsh gas produced in swamps This technology has the and landfills. attractive feature of separating the energy content of biomass from its value as a soil conditioner and fertilizer. The energy content is released in a gaseous form (i.e., biogas) that can be utilized at a higher efficiency than the original solid biomass. Biogas is primarily used for cooking and lighting, but can also partially substitute for diesel in engines used for irrigation pumping.

China and India have had extensive biogas programs for more than 15 years (Moulik, 1985). Both programs have concentrated on household systems, with manure and other farm wastes being the most common feedstocks; over 7 million systems have been installed, most of these in China. Programs in both countries have had to deal with design, construction, and maintenance problems so that many of the digesters are no longer functioning (Miller et al., 1986), demonstrating the difficulty of introducing even relatively "simple" low-cost technologies in remote, rural areas of developing countries. Some larger institutional plants have had a higher probability of succeeding than household-size facilities.

Financially, the feasibility of biogas plants depends largely on whether the biogas and biomass residues substitute for fuels or fertilizers that have traditionally been purchased or obtained at zero financial cost. In cases where the biogas or residues do not generate incomes or reduce cash outflows, they are less likely to be economically viable. However, the nonfinancial benefits of these programs, such as improvements in public health due to lower emissions during cooking or increased mortality of pathogens in the digester, reduced deforestation, less reliance on imported fuels, etc., motivate countries such as China and India to continue subsidies for biogas projects (Gunnerson and Stuckey, 1986).

There are a number of other approaches being tried to make this technology more appealing. Ideally, what is required is a low capital-investment technology that permits the use of a wide variety of feedstocks and results in high gas yields over a range of ambient temperatures. In Taiwan, a durable and cheap above-ground bag digester made from bauxite refining wastes has been used with success (Miller et al., 1986). Other promising anaerobic digester designs being explored include the upflow sludge blanket and baffled reactor (Gunnerson and Stuckey, 1986).

Promote Use of Gasification

Many cellulosic materials can be gasified and then either used directly or liquified into methanol. There are two routes for gasifying biomass -- one resulting in producer (or wood) gas and the other in synthesis gas with higher calorific value. Producer gas is made by heating wood in an almost oxygen-free environment so that the unburned fuel breaks down into gases, ash, and tar. Producer gas was used to propel trucks in World War II when oil was scarce. Synthesis gas is made at higher temperatures with a purer oxygen source than producer gas, thus eliminating nitrogen, and lends itself to conversion into methanol (see Improve Technologies to Convert Biomass to Liquid Fuels below).

Producer gas can be made using a number of raw materials: wood, charcoal, crop residues, and urban refuse. There are more than 20 companies world-wide selling gasifiers, with Brazil and the Philippines leading in the use of this technology. Gasifiers have been used to power tractors, motor boats, and irrigation pumps and to provide electricity for food processing and other rural needs. They can also replace oil as a boiler fuel.

Kjellstrom (1985) has shown that for conventional power generation applications, biomass gasifiers compete favorably if the operating times are long, load factors high, and power outputs large. The economics are most favorable for wood-based systems rather than charcoal systems, and could become substantially more attractive if oil prices were to increase or biomass input costs were to decline. One drawback to gasifiers at this time is that current designs do not accept all types of crop residues. Kjellstrom also demonstrated that at 1985 diesel prices it would be uneconomic to run diesel tractors or trucks on producer gas or to use it in industrial applications except for industries with surplus biomass residues. Another technical problem is the need to understand the pollution impacts due to CO emissions and tar condensates from the biomass material.

While there are a number of problems to be resolved before biomass gasifiers can be easily used to replace natural gas in applications, research conventional at Princeton has shown that University integrated gasifier-combustion turbine systems could provide, at small scales (e.g., 5-50 MW), power that is less expensive than power from new hydroelectric, coal, or nuclear plants. (See Box 5-5; Larson et al., 1987).

Improve Technologies to Convert Biomass to Liquid Fuels

Biomass-produced ethanol and – methanol can be used as liquid fuels. In addition, other biomass-derived oils have been combined with diesel and used as fuel.

Methanol from Biomass

Methanol from biomass is attractive because current technologies use raw materials grown on lands not required for food production, unlike ethanol from corn or sugarcane. The state of Hawaii, which must import all of its oil, has enacted legislation supporting the construction of a methanolfrom-biomass facility towards the goal of replacing gasoline and diesel fuel with methanol (Phillips et al., 1990).

Methanol is produced by first making synthetic gas (a mixture of CO and H_2) by gasifying (partially oxidizing) biomass, and then catalytically reacting the product gases. Though the process for converting synthesis gas to methanol is fairly well established. promising research is underway to improve the conversion efficiency by using novel lowtemperature, low-pressure catalysts (Boutacoff, 1989). However, converting biomass to clean, usable synthesis gas provides a major technical and economic challenge. Various gasification processes are under development. for example, coal gasification technologies such as the German Winkler gasifier could be modified to accept wood as a feedstock (Williams, 1985). In the U.S., most evaluations have been based on bench-scale testing of gasifiers. The next milestone in commercializing this process calls for scaling up the gasification and gas-cleaning plants and operating the facility for extended periods to confirm gas yields, quality, and operational integrity (Phillips et al., 1988).

As with most renewable energy projects, economics of biomass-to-methanol the processes are less favorable now than they were in the early 1980s due to lower world oil prices. Moreover, it is significantly cheaper currently to derive methanol from natural gas. and even coal, than from biomass. With wood costing \$34 per dry ton (Phillips et al., 1988) methanol could be produced at a wholesale price of \$15/GJ. Taking into account that methanol has a 20% fuel economy advantage over gasoline, this is equivalent to a gasoline price of \$12/GJ (or about \$1.60/gallon). As a result, the production of methanol from biomass should be regarded as a long-term opportunity as conventional fuel prices rise and/or if improvements technical reduce costs (Williams, 1985).

Ethanol from Biomass

Biomass can also be used to produce ethanol. Ethanol is useful both as an automotive fuel and as a feedstock for the production of ethylene and other chemicals. Because of certain inherent requirements, as discussed below, its applicability is limited to

Box 5-5. Biomass-Fired Combustion Turbines

Adaptation of the integrated-gasifier-combustion-turbine technology discussed above (combined cycle or aeroderivative turbines -- see FOSSIL-FUEL OPTIONS) to use biomass presents an attractive option for generating electricity in developing countries (Larson et al., 1987), and could also become important in industrialized countries with advances in biomass plantation productivity (see PART FOUR). Indeed, the use of this technology with biomass should be simpler than with coal because biomass is easier to gasify and sulfur removal is unnecessary. The use of aeroderivative turbines (STIG and ISTIG, see Substitute Natural Gas for Coal) may be particularly attractive because this technology remains quite economic at small scales. While the individual components of such a system have been tested, a commercial demonstration of the integrated package could be very important in increasing investor confidence in this technology.

Biomass-based electricity generation is most economical where the fuel has already been collected for other reasons (e.g., the forest products industry, the cane sugar industry). A prime example is the use of bagasse (i.e., sugarcane residues) at sugar mills and ethanol distilleries. Although these waste products are currently used to provide on-site needs for process steam and often electricity, there has been little interest in increasing efficiency once on-site requirements are satisfied. Indeed, steam and electricity production is often intentionally inefficient because of the desire to consume the wastes. Substituting an ISTIG-based cogeneration system for current steam turbines could increase electrical output by a factor of 20, while still meeting process steam requirements; total system efficiency could exceed 50% (Larson et al., 1987). This could make the cane sugar industry a major electricity producer in developing countries: if this technology were adopted in the 70 sugar-producing countries, total capacity could exceed 50 GW, increasing electricity supplies by 25% in these countries.

Design calculations suggest that the costs would be very competitive with alternatives. Capital costs could be less than \$1,000/kW, and electricity could be generated for 3-4 cents/kWh where biomass is available for \$2/GJ or less (Larson et al., 1987). (Bagasse in the sugar cane industry is essentially free, implying that the additional costs for producing electricity could be less than 2 cents/kWh.) The barriers to adoption of this technology appear to be primarily institutional -- collaboration between the cane sugar or other biomass producers and the utility industry is required. Furthermore, an integrated biomass-based advanced turbine system needs to be commercially demonstrated, but it is difficult to attract investors in developing countries where this technology is most attractive for projects considered to entail technological risk (see CHAPTER VIII).

a few countries. However, to the extent it can replace petroleum products, net emissions of CO_2 will be zero since ethanol from biomass is produced on a renewable basis.

Today, Brazil has the most extensive ethanol development program in the world. The purpose is to provide alternative transportation fuels, based largely on sugarcanederived ethanol (Sathaye et al., 1988). Although Brazil has succeeded in reducing its oil imports, its program has received mixed reviews, largely because the program has depended on substantial subsidies to ensure its success. Similar efforts in other countries, such as Kenya, have been less successful, usually due to a lack of low-cost biomass or industrial expertise such as that available in Brazil (Miller et al., 1986). Despite these problems, alcohol production may offer future benefits, as a number of other feedstocks (e.g., grain, sorghum, corn) may provide cheaper ethanol and as technologies to produce ethanol from wood are developed (Brown, 1980).

Currently, the simultaneous saccharification and fermentation process (SSF) is believed to have the greatest promise to achieve low costs and high yields (Wyman and Hinman, 1989). The large volume market for demands that feedstock ethanol and conversion costs be low. Only the low costs of lignocellulosic feedstocks provide sufficient margin to cover conversion costs for efficient processes. Although the cost of ethanol from SSF has dropped from \$3.60/gallon to \$1.35/gallon over the last eight years, improvements are needed still in pretreatment, enzyme production, hydrolysis, xylose fermentation and recovery steps before ethanol can compete with conventional fuels at today's prices (\$0.75/gallon at the refinery gate) (Wyman and Hinman, 1989). This price reduction can reasonably be expected by the year 2000 even if research continues at today's levels (Lynd, 1989).

Biomass Oils as Fuel

One technically-feasible option with biomass-derived liquid fuels is to use coconut, palm, and other vegetable oils in combination with diesel fuel. These oils can be grown on plantations with high yields, but their worth is usually greater as food than as fuel. The Philippines briefly experimented with a mixture of coconut oil and diesel until changes in relative prices made the approach uneconomical (Miller et al., 1986).

SOLAR ENERGY OPTIONS

Solar energy technologies, as described in this section, are those that collect, concentrate, and convert solar radiation into useful energy. Technologies for converting solar energy into useable energy offer some of the greatest long-term opportunities for replacing fossil fuels. Within this category, however, there are several types of technologies. Some solar energy applications for the residential and commercial sectors were discussed in PART ONE. This section will focus on solar thermal and solar photovoltaic options.

Solar thermal systems that are more sophisticated than the residential and commercial systems described earlier and that can concentrate solar radiation to produce higher temperatures are being developed. These higher temperatures could be used to make steam, electricity, or power for other industrial process heat applications. The most sophisticated solar conversion approaches are photovoltaic technologies that convert solar radiation directly into electricity. These techniques have received considerable research attention over the last 10-15 years and have progressed considerably as a result. The potential of both photovoltaic and solar thermal technologies, which produce power directly only during daylight hours, will be even greater as more efficient storage technologies increase the cost-effectiveness of storing excess power generated during the daytime for use at other times, as discussed further in Enhance Storage Technologies.

Promote Solar Thermal Technology

Solar thermal technology is a promising area of solar research since it can provide thermal energy at temperatures from 150-1700°C for heat or electricity applications, at almost any scale, and with conversion efficiencies as high as 31.6% for electricity and 80% for heat (IEA, 1987). Solar thermal concentrating systems have been extensively demonstrated in recent years for both industrial heat and electricity generation. 670 MW of electricity generating capacity are already in place or under construction in seven countries (Shea, 1988). In the U.S., solar thermal capacity is projected to increase to 550 MW in the next 5 years based on announced industry plans (U.S. DOE, 1987a). The U.S. Department of Energy has estimated recently that a further cost reduction by a factor of 1.5 to 2 would make these technologies competitive with conventional electricity generating technologies. U.S. DOE has also identified several key technical improvements currently being researched that could achieve the needed cost improvements, leading to economic competitiveness by the mid-1990s (U.S. DOE, 1987a). In recent

years most research and development has focused on three thermal technologies -parabolic troughs, parabolic dishes, and central receivers.

Parabolic Troughs

Parabolic troughs are often referred to as line focus systems because they use one axis only to track the sun; each concentrator (collector) has its own receiver, with parabolic troughs often connected to form a series of collectors (see Figure 5-7). Troughs operate at lower temperatures than most other technologies, for example, up to 400°C, making them most suitable for industrial process heat applications. The thermal efficiencies of these units have improved significantly in recent years, reaching 65-70%, with availabilities exceeding 95% (IEA, 1987).

Parabolic Dishes

Parabolic dishes differ from troughs in that they are point focus systems, in other words, a two-axis tracking system is employed to follow the sun (see Figure 5-7). The higher concentration ratios allowed by this design (from one hundred to several thousand suns) produces temperatures approaching 1700°C, making electricity conversion possible. This technology currently holds many efficiency records, including the highest conversion efficiency (31.6%). Several of the most ambitious development projects are in the U.S., with installed capacity at some projects approaching 5 MW. DOE estimates total system cost at \$3,400/kW, although cost reductions of 40% are considered feasible (IEA, 1987).

Central Receivers

Central receivers represent the largestscale thermal technology. The receiver is typically mounted on a tower surrounded by a large field of nearly flat tracking mirrors called heliostats (see Figure 5-7). The heliostats focus the solar energy on the receiver, achieving working fluid temperatures of 1500°C or higher (IEA, 1987). Several countries are studying central receivers. The largest plant, located in southern California (10 MW), has exceeded peak design output by 20%, operated at night from storage, and achieved an overall plant efficiency of 13% (IEA, 1987). Heliostats account for 40-50% of total costs, and consequently are the focus of most cost reduction efforts; recent developments indicate that cost reductions of 50% could be achieved in one or two years (IEA, 1987).

Solar Ponds

Solar ponds collect and store heat in large bodies of water and operate at much lower temperatures than other solar thermal technologies (85-100°C). In a typical design, a salt gradient below the surface acts as an insulating barrier by trapping incoming solar radiation. Large heat exchangers are used to extract the thermal energy, which can be used for many purposes, including seasonal heat storage for space heating, low temperature process heat applications, or even electricity production. Research into this technology has achieved thermal efficiencies of 15%, with electrical conversion efficiencies of about 1-2% (IEA, 1987). Despite these low efficiencies, solar ponds can be attractive since capital costs are very low.

Improve Solar Photovoltaic Technology

Solar photovoltaic (PV) technologies convert solar radiation to electricity (DC, or direct current) without moving parts or thermal energy sources. Photovoltaic technology was initially developed in the 1950s; these first systems were about 100 times more expensive than conventional technologies, generation but maior improvements have reduced this differential to 3-4 times current energy costs. This differential is even lower when compared to current replacement costs. Figure 5-8 shows the dramatic progress that has been made since 1975 in reducing the costs of electricity from photovoltaic systems.

The principal drawback with photovoltaic technology is the high capital costs. The current goal is to reduce costs to about 6 cents/kwh (which is comparable to the best conventional powerplant costs), at least for conditions in the southwestern United States where insolation is high. The U.S. DOE is projecting that its cost goal (\$0.06/kwh) may be achieved in the 1990s and
•

FIGURE 5-7



Source: IEA, 1987.

FIGURE 5-8



that photovoltaic systems could provide up to 1.5 GW of generation capacity by 2005 (U.S. **Researchers at Princeton** DOE, 1987a). University are projecting also maior technological breakthroughs in amorphous silicon solar cell technology. They have projected that capital costs (almost the entire cost for PV) for these cells may decline by over 80% by the year 2000, while the conversion efficiency of photovoltaic arrays roughly doubles (Ogden and Williams, 1988). This could greatly expand the contribution of photovoltaic electricity generation over the next several decades.

The basic principle behind solar photovoltaic power is that as light enters the PV cell, electrons are freed from the semiconductor materials, thereby generating an To generate substantial electric current. amounts of power with PV, individual cells (which produce about 1 watt of direct current electric power) are combined into a weatherproof-unit called a module. Modules can then be connected together into an array, with the power output limited only by the amount of area available. The modular nature of PV arrays allows them to be built in increments to conform more closely to power requirements as demand for electricity grows.

The principal photovoltaic technologies for current commercial power applications use silicon for the semi-conductor materials. Several efforts are underway to improve silicon-based photovoltaic cells, including optical tracking that orients the cell toward the sun, concentrating devices that increase the amount of solar energy hitting the plate, layering materials to absorb more of the energy, and amorphous thin film techniques that can lower production costs.

Crystalline Cells

Crystalline silicon cells are the earliest and most-established PV technologies. The most popular material has been single-crystal silicon, which had 90% of the global market in 1980 but only 44% (10.8 MW) by 1985 (IEA, 1987). Single-crystal silicon PV cells are relatively efficient (production efficiencies are 12-14%; laboratory efficiencies up to 21%), but have lost market share primarily due to the high cost of manufacturing. This involves several energy-intensive stages to produce the large silicon crystal ingots from which wafers are cut (which destroys about half the crystal ingot), then final preparation and assembly.

In response to some of the problems encountered with single-crystal technology. other crystalline technologies have been developed. Polycrystalline silicon cells use a casting process that is less expensive but only slightly less efficient than single-crystal silicon, for example, commercially-produced cells have a conversion efficiency of 11-12%, with laboratory efficiencies of 18% (IEA, 1987). Polycrystalline silicon cells captured about 20% of the global market in 1985. Another alternative is polycrystalline silicon ribbon. which avoids the need to produce slices (or wafers) by producing sheets or ribbons of polycrystalline silicon. The advantages of this technology are the potential for high-speed production and less material waste, although its efficiency is somewhat lower, for example, efficiencies are 10-13% and production laboratory efficiencies are 17% (IEA, 1987). This technology has been commercialized only recently.

Thin-Film Technologies

As an alternative to crystalline technologies, researchers have focused on thin films. Thin-film solar cells can be produced less expensively using less material and automated production techniques. There are many semi-conductor thin-film materials under investigation, including amorphous silicon, copper indium diselenide, gallium arsenide, and cadmium telluride.

Amorphous Silicon. Amorphous silicon cells have received the most attention of the thin-film technologies, supplying 35% of the global market in 1985 (IEA, 1987). The vast majority of this was for use in the consumer market, especially calculators. Because this material does not possess the natural photovoltaic properties of crystalline silicon, efficiency levels have been a problem -laboratory efficiencies are about 13%. Additionally, amorphous silicon suffers from a light-induced power degradation problem that can cause a 22-30% loss of power output over time. Thus, large-scale projects can currently expect to achieve about 5% efficiency over the life of the project. Research into this problem continues, with amorphous silicon thin-film cells considered one of the best potential technologies for power applications as efficiencies improve and production costs are lowered.

Other Semiconductor Materials. Other materials are being investigated that do not utilize silicon, including copper indium diselenide, gallium arsenide, and cadmium Copper indium diselenide is telluride. attractive due to its high efficiency (up to 12% currently) and stability when exposed to sunlight over extended periods. Gallium arsenide technologies have achieved the highest efficiency of any PV material, 29% (Poole, 1988), but are also some of the most costly. Research continues on production processes, such as electroplating, that would significantly reduce current production costs.

Multi-Junction Technologies

Multi-junction, or tandem, technologies combine the characteristics of two or more different PV technologies to take advantage of different light absorption characteristics, thereby increasing total cell efficiency (e.g., two-junction devices can achieve efficiencies of 18-35%; U.S. DOE, 1987b). This technique has been used to produce the most efficient solar cell to date -- a 31% efficient cell that combined a single-crystal gallium arsenide cell and a single-crystal silicon cell (Poole, 1988). Multi-junction devices can also be used in solar concentrators, which are optical systems designed to improve PV output by increasing the amount of sunlight striking a cell by 10-1000 times. In combination these technologies may help to achieve in practice the 25-30% efficiency range considered critical for utility applications (U.S. DOE, 1987b). Multijunction thin film technologies are also expected to become more important as multilayering increases efficiency more quickly than system costs.

ADDITIONAL PRIMARY RENEWABLE ENERGY OPTIONS

There are opportunities for increased use of additional renewable energy sources, such as hydroelectric, wind, geothermal, and ocean energy. Many of these resources are utilized today (often to supply electricity) and, with continued research and development, have the potential to make important contributions to meeting future energy needs without increasing emissions of greenhouse gases.

Expand Hydroelectric Generating Capacity

Hydropower currently provides the largest share of renewable electricity generation in the U.S. and globally. In the U.S., hydroelectric capacity accounted for 10-14% of total electricity generation for the vears 1983-1987 (U.S. DOE, 1988a). Globally, hydroelectric generation accounts for about 20% of total electricity and 7% of primary energy production (United Nations, The technical potential exists to 1988). expand the contribution of hydro at least by a factor of two by the year 2025.

Industrialized Countries

Traditional large-scale hydropower projects are no longer a significant option for most industrialized countries. Many of the most attractive sites have already been exploited in these countries and remaining potential sites are often highly valued in their natural state for recreational, wilderness, or ecological purposes. The U.S. has more large hydroelectric capacity in operation than does any other country in the world. However, new sites are no longer being developed, and the U.S. Bureau of Reclamation, the federal agency historically responsible for large dambuilding projects in the West, announced in 1987 that its mandate to develop new water supplies has virtually expired and that it would be contracting in size and shifting its focus to other activities over the next decade (Shabecoff, 1987).

Among industrialized countries, Canada has the potential to greatly expand its hydroelectric generating capacity. The U.S. Department of Energy recently identified potential hydro sites in Canada which, if developed, could more than double peak hydro-generating capacity in Canada (from about 55 GW to over 127 GW). This level of expansion would not be required to meet projected Canadian demand for many years. However, excess capacity developed in Canada could be used to generate power for transmission to the U.S. where it could compete favorably with other generation options in many regions. The DOE analysis estimates that U.S. imports of power from Canada could more than doubled by 2010 if the potential hydro sites discussed above were developed (U.S. DOE, 1987c). In lieu of this hydro development, additional generating capacity in the U.S. during this period would predominantly be fossil-fueled. Thus, displacing U.S. capacity additions with Canadian hydro development would reduce CO_2 emissions. However, any hydro development raises potential bilateral and environmental issues with Canada that would need to be resolved.

Expansion of small-scale hydropower (e.g., less than 30 MW) could be an option in many industrialized countries. In the U.S. up to 10 GW of potential capacity additions in this category have been identified (U.S. DOE, 1987a). Other OECD countries, such as Canada and West Germany, are evaluating the potential for expanding small-scale hydroelectric generation (Shea, 1988).

USSR and Eastern Europe

In the USSR and Eastern Europe, there appears to be significant technical potential for expanding both large- and smallscale hydro use. In 1981, hydroelectric generation provided about 13% of total electricity in the USSR. Soviet researchers estimated that this was only about 19% of the country's potential large hydro capacity. Much of the untapped potential is in Siberia, requiring potentially costly long distance transmission to reach major load centers (Hewitt, 1984). In Eastern Europe there are indications that opportunities for large hydro projects still exist as well. Between 1980 and 1985 Romania increased its hydroelectric capacity by 2.5 GW, which was more than a 70% increase in total capacity (World Bank, 1984).

Opportunities also exist for expanding small-scale hydro in the USSR and Eastern Europe. Poland, for example, has recently initiated a program to rehabilitate 640 small dams that had fallen into disrepair and return them to electric generation (Shea, 1988).

Developing Countries

In developing countries the potential for large-scale and small-scale hydro development is very large. For example, by 1980 it is estimated that North America and Europe had developed 59% and 36% of their large hydropower potential, while in contrast, Asia, Africa, and Latin America were estimated to have developed only 5-9% of potential resources. In fact, most large-scale hydro development in the 1980s has taken place in the developing countries.

Between 1980 and 1985, hydro capacity additions in 12 developing countries totaled over 38 GW (over 8% of total generating capacity in developing countries). Several developing countries, notably Brazil, China, and India, have ambitious large hydro development programs planned for the future. Total capacity additions in developing countries could exceed 200 GW by 1995 if these plans are implemented (World Bank, 1984).

There is some question, however, if these plans will be fully implemented. A recent study by the U.S. Agency for International Development (U.S. AID, 1988b) points out that many developing countries are finding it increasingly difficult to finance capital-intensive power projects, especially hydro, which have construction periods of 10 years or more. In addition, the AID and others have pointed out that concerns about ecological and land-use impacts such as submergence of forested areas as well as resettlement impacts of large hydroelectric projects may slow such development in the future. As in industrialized countries, there is also significant potential for small-scale hydro potential in developing countries. At least 28 developing countries already have active programs for developing small-scale hydropower (World Bank, 1984). Equipment for small-scale hydro generation is now manufactured in a number of developing countries, resulting in designs that are both less costly and more suitable to local conditions (U.S. AID, 1988a).

Reduce Cost of Wind Energy

Wind-powered turbines were first connected to electric power systems in 1941. Currently, there are several technologies available, primarily horizontal axis wind turbines and vertical axis wind turbines. Under optimal conditions, these systems can produce power at 10 to 15 cents per kilowatthour, or about two to three times more expensively than conventional fossil-fueled powerplants. The goal is to reduce these costs such that in areas with wind resources, these systems can be used economically. In particular, wind energy systems may be very suitable for remote sites where the cost of conventional generation technologies may also be quite high.

Considerable improvement in the performance and economics of wind electric generation was achieved in the early 1980s. In California, electricity generated from "wind farms" increased from 10 terajoule-hours to (primary petajoule-hours energy 16 equivalent), while capital costs fell from \$3,100 to \$1,250/kW between 1981 and 1987 (Shea, 1988). The Department of Energy reports that the cost of electricity from wind turbines has fallen from about 30 cents/kWh to 10-15 cents/kWh in the 1980s. DOE projects that this improvement will continue and that wind energy could provide as much as 0.7 EJ of electricity in the U.S. by 2005 (U.S. DOE, 1987a).

Considerable international attention is now being paid to wind energy. Wind farms are being installed in Denmark, the Netherlands, Great Britain, Greece, and Spain (IEA, 1987). Other nations that have announced plans for expanded wind energy development include China, Australia, Belgium, Israel, Italy, the Soviet Union, and West Germany (Shea, 1988).

Exploit Geothermal Energy Potential

Geothermal energy is thermal energy stored in rocks and fluids within the earth. It has been estimated that approximately 10% of the world's land mass contains accessible geothermal resources that could theoretically provide hundreds of thousands of megawatts of energy for many decades (IEA, 1987). As indicated in Table 5-10, geothermal resources suitable for generating electricity are extensive and geographically widespread. From a global warming context, several countries with the most extensive geothermal potential, for example, the U.S., China, and the USSR, are also currently heavily dependent on coal consumption. Geothermal energy may, in these countries, provide one option for displacing coal as a source of baseload electricity generation and industrial heat. Significant geothermal resources also exist, and are being developed, in several Pacific Rim countries, where economic growth rates, and thus demand for additional energy, is expected to be high.

While certain types of geothermal resources, specifically hydrothermal and geopressured reservoirs, are not strictly renewable on a human time scale, resources are so extensive that with careful phasing and reservoir management, geothermal energy can make a significant long-term contribution to global energy needs. Unlike renewable energy sources such as solar radiation and wind, geothermal resources are available on a constant basis, making them suitable for baseload electricity generation and industrial applications without the storage problems associated with intermittent energy sources.

There are several types of geothermal resources that require somewhat different approaches for exploitation. *Hydrothermal* resources contain hot water and/or steam trapped in fractured or porous rock at accessible depths (e.g., 100-4500 meters). These are the most commonly used resources currently, and the only resources currently commercially exploited. Technology for exploiting these resources involves sinking wells, extracting the hot fluids, and using the

TABLE 5-10

Estimates of Worldwide Geothermal Electric Power Capacity Potential

(in Megawatts)

Country	MW	Country	MW
Argentina	19,950	Kenya	79,450
Bolivia	63,100	Korea (N. & S.)	79,450
Cameroon	15,150	Mexico	257,050
Canada	446,700	Morocco	19,950
Chile	30,200	New Guinea	30,900
China	537,050	New Zealand	30,900
Columbia	77,650	Nicaragua	33,900
Costa Rica	12,600	Peru	302,000
Ecuador	100,000	Philippines	67,600
El Salvador	5,000	Portugal	1,000
Ethiopia	154,900	Saudi Arabia	15,850
Greece	8,900	Soviet Union	239,900
Guadeloupe	387	Spain	5,900
Honduras	12,600	Taiwan	8,150
Iceland	22,900	Tanzania	6,200
India	15,200	Turkey	87,100
Indonesia	436,500	U.S.	501,200
Iran	75,850	Venezuela	39,800
Italy	33,900	Vietnam	37,150
Japan	79,450		

Source: U.S. DOE, 1985c.

Another type of geothermal resource of long-term interest is hot dry rock. These potential resources are widely distributed around the world, but more difficult to exploit than hydrothermal resources. To extract heat from hot dry rock, it is necessary to inject liquid into one well and withdraw it through another well after it has absorbed heat. Considerable research is underway to improve technologies for extraction of energy from hot dry rock. A geothermal resource still at the conceptual stage of development is magma, which is liquefied or partiallyliquefied rock. Potential resources may be greater than any other geothermal resource and the very high temperatures available suggest that power could be economically produced; however, development of the necessary technologies is seen as a major challenge.

Geothermal energy is currently used in several countries for direct heat and electricity generation. Table 5-11 shows the extent of direct heat use in 1984. Table 5-12 indicates the installed capacity for geothermal electricity generation by country in 1985. Although they represent only a small fraction of total energy use, these facilities have demonstrated the commercial viability of geothermal technologies. In the U.S. geothermal systems currently produce electricity at a cost that is competitive with coal and nuclear plants, and the average geothermal unit today is available on-line more than 95% of the time (U.S. DOE, 1987a). The Department of Energy projects that U.S. geothermal electric capacity will more than double by 1995 to about 4.7 GW.

Geothermal energy may also play an even more important role in some developing countries. Eight developing countries currently have installed geothermal electric capacity, and about 50 more have been identified as having potential for geothermal development (U.S. AID, 1988a). In the 1980s, the costs of geothermal technology have come down considerably, and small-scale, ready-to-install generators (1-1.5 MW) have also been developed and proven reliable. These and other developments should make geothermal electricity more attractive to many developing countries (U.S. AID, 1988a).

Research Potential for Ocean Energy

There are several types of potential ocean energy sources, including thermal gradients and waves. Research is underway in many countries, including the U.S., to develop technologies that can exploit these resources. In one technology, cold water located deep in the ocean is used to condense a working gas such as freon or ammonia. The liquid then is reconverted to gas by warm surface waters and used to drive a turbine and generate electricity. Current costs for such a system are roughly three times higher than commercial alternatives, and there remain significant technological uncertainties regarding system components and operation in an ocean environment.

NUCLEAR POWER OPTIONS

This section discusses the potential role for nuclear power to meet future energy From the perspective of global needs. warming, nuclear power technologies are attractive in that they emit only negligible amounts of carbon dioxide and methane (Wahlen et al., 1989). As will be discussed, however, there are serious problems that beset the nuclear power industry. Fission technologies are currently used to operate One of the key nuclear powerplants. attributes of this technology is its need for fissionable, radioactive material in order to operate. Fusion technology is a longer-term nuclear option currently in the research and development stage. Unlike fission technologies, fusion technologies would not require large inventories of radioactive materials such as uranium and plutonium.

Enhance Safety and Cost Effectiveness of Nuclear Fission Technology

Nuclear fission technology is an important source of electricity in many regions of the world. For example, nuclear

TABLE 5-11

Capacity of Direct Use Geothermal Plants In Operation - 1984

(For countries having capacity above 100 MW)

Country	Power	Energy	Load
	MW	GWh	%
China	393	1945	56
France	300	788	30
Hungary	1001	2615	30
Iceland	889	5517	71
Italy	288	1365	54
Japan	2686	6805	29
New Zealand	215	1484	79
Romania	251	987	45
Soviet Union	402	1056	30
Turkey	166	423	29
United States	339	390	13
Other	142	582	47
Total	7072	23957	39*

* Based on total thermal power and energy.

Source: IEA, 1987.

TABLE 5-12

Country	No. Units	Type(s) ^a	MW
United States	56	DS,1F,2F,B	2022.11
Philippines	21	1 F	894.0
Mexico	16	1F,2F	645.0 ^b
Italy	43	DS,1F	519.2 ^b
Japan	9	DS,1F,2F	215.1
New Zealand	10	2F	167.2
El Salvador	3	1F,2F	95.0
Kenya	3	1 F	45.0
Iceland	5	1F,2F	39.0
Nicaragua	1	1F	35.0
Indonesia	3	DS,1F	32.25
Turkey	2	1F	20.6
China	12	1 F ,1 F , B	14.32 ^b
Soviet Union	1	F	11.0
France (Guadeloupe)	1	2F	4.2
Portugal (Azores)	1	1F	3.0
Greece (Milos)	1	1F	2.0 ^b
Totals	188	<u></u>	4763.98

Geothermal Powerplants On-Line as of 1985

^a DS = dry steam; $1F_{2}F = 1$ - and 2-flash steam; B = binary.

^b Includes plants under construction and scheduled for completion in 1985.

Source: IEA, 1987.

plants provided almost 20% of total electricity generated in the U.S. in 1988. This total is projected to increase throughout the remainder of this century as about 16 GW of new nuclear powerplants, which are currently under construction, are completed. The prospects for further capacity additions, however, are clouded. According to the U.S. Department of Energy, "No additional orders for nuclear powerplants are likely in this country until the conditions of the past few years are changed" (U.S. DOE, 1987a). Moreover, between 2000 and 2015, about 40% of existing nuclear powerplant capacity will have to be retired unless current operating licenses are extended beyond their expiration dates.

The situation is somewhat similar in many other industrialized countries. The International Energy Agency (IEA) reports that nuclear energy was the fastest growing fuel for electricity generation in the OECD countries between 1985 and 1987, although, "It should be kept in mind, however, that present additions to nuclear capacity come from stations authorized in the second relatively intense "cycle" of nuclear plant construction activity in the 1970s. Compared with some 239 GW of nuclear capacity operating in the OECD countries at the end of 1987, around 52 GW are under construction" (IEA, 1988). In addition. planned nuclear electricity production in the 1980s in the USSR has been consistently behind schedule due to construction delays. By 1988, nuclear generation was providing only 13% of electricity in the USSR. In the wake of the Chernobyl disaster of April 1986, the Armenian earthquake of December 1988, and unprecedented public protest of nuclear power, the nuclear program in the USSR has experienced numerous reactor cancellations. Further delays in the nuclear power program are likely and future contributions are thus difficult to project (Sagers, 1989).

Nuclear power has been beset by a series of problems. Plant capital costs have increased so dramatically that new nuclear powerplants are no longer considered economical (see Figure 5-9). The real nonfuel operating costs of nuclear powerplants have also escalated rapidly (U.S. DOE, 1988b). Powerplant lead times (i.e., the time from project initiation to completion) are greater than ten years, increasing project risk. Additionally, in many countries such as the U.S., the regulatory environment is generally unfavorable toward large, long-term capital investments and nuclear powerplants in particular (U.S. DOE, 1987a).

Public opposition to new nuclear powerplants is strong, in part due to concerns about safety in the aftermath of the accidents at Three Mile Island and Chernobyl. In addition to plant safety, radioactive waste disposal is an issue of major concern. Although several countries utilizing nuclear power are working on the problem, none have identified an acceptable solution to the problems of long-term nuclear waste disposal.

Finally, the nuclear weapons proliferation issue must be resolved if nuclear power is to become publicly acceptable. A present-day 1000 MW nuclear plant produces some 141 kg of fissionable plutonium annually in its spent fuel. For comparison, it takes less than 10 kg of fissionable plutonium to make a nuclear weapon. Currently, this spent, intensely-radioactive fuel is stored at plant sites. If nuclear power were to be greatly expanded in the future, limited supplies of uranium worldwide would rapidly force a shift from today's "once through" nuclear cycles (i.e., the nuclear fuel is only used once) in the U.S. and Canada to fuel cycles involving the reprocessing of spent fuel and the recycling of recovered plutonium for use as fuel in present reactor types, as is commonly practiced in Europe and Japan, and a new generation of plutonium breeder reactors. The amount of fissionable material required would pose a formidable institutional challenge to the world community to safeguard relatively large quantities of plutonium that would circulate in worldwide commerce (Albright and Feiveson, 1987; Ogden and Williams, 1989).

In the U.S., the Department of Energy has recognized many of these potential obstacles. In its 1987 *Energy Security* report (U.S. DOE, 1987a), the U.S. DOE identified three basic obstacles that must be overcome before new orders will be forthcoming:





• Given current reactor designs and regulatory processes, nuclear power is not economically competitive with alternative generation options.

• Public concerns about reactor safety make licensing of new plants difficult.

• Currently unresolved questions about the viability of long-term radioactive waste disposal options have become a significant barrier to expansion of nuclear power.

The U.S. DOE has initiated efforts to deal with all of these problems. First, it has underway a research program aimed at the development of improved reactor designs. Program goals include new designs for "enhanced safety, increased simplicity, and improved reliability." To meet these goals, the new designs incorporate innovative concepts of passive safety that hopefully would ensure that any equipment or operator failure would cause the plant to shut down automatically. A second important attribute of the advanced designs is standardization of designs, which could reduce cost, shorten the permitting process, and improve reliability and safety. Third, the new designs are for smaller. modular units, which should make them more compatible with the utility industry's needs for smaller capacity addition. Another design concept is that the portion of the plant that is actually within the nuclear containment vessel can be minimized and modularized, thereby allowing the balance of the plant to be built according to standard construction specifications. An example of this approach is Sweden's ASEA-ATOM's PIUS reactor, which places the steam generator and primary pumps outside the containment vessel (U.S. DOE, 1988a). More stringent safety standards for nuclear powerplants could then focus on the smaller nuclear component. Ultimately, the nuclear portion may be designed to be fabricated at the manufacturing plant and transported in its entirety to the powerplant site for insertion into the remainder of the plant (Griffith, 1988).

These principles are being applied to several basic reactor types, such as:

• Advanced Light Water Reactor (ALWR). Light water reactor technology is currently the type most widely in use in the U.S. The hope is to develop a standardized design incorporating the lessons of recent experience.

• Modular High Temperature Gas Reactor (HTGR). This is an advanced concept that has not been demonstrated yet but is being designed to provide a nextgeneration nuclear capability that goes further toward meeting the design criteria mentioned above than the ALWR.

• Advanced Liquid Metal Reactor (LMR). For the longer term, designs are being developed that would incorporate the design goals stated above into a potential breeder reactor option.

Finally, on the radioactive waste disposal issue, DOE is evaluating the suitability of Yucca Mountain, Nevada, as a site for long-term deep geologic disposal of high-level wastes, while also favoring the construction of a Monitored Retrievable Storage (MRS) facility for spent reactor fuel (Blowers et al., 1990). Thus, DOE is attempting to address many of the constraints affecting the nuclear power industry. It is difficult to predict at this point how effective these programs will be. In addition, the DOE's Energy Security report does not mention the weapons proliferation problem that is also perceived as a long-term constraint by many observers.

Promote Research and Development of Nuclear Fusion Technology

Nuclear fusion, like nuclear fission, is an attractive power generation technology from a global warming perspective because it does not generate significant greenhouse gas emissions. Fusion power has two key advantages over fission power: (1) It uses secure and inexhaustible fuels, in that lithium and deuterium are obtainable from seawater, and (2) it does not create large inventories of radioactive wastes.

Fusion reactor technology, however, is only in the early stages of research and development; it is not expected to be a viable technology before 2025. The costs of development for this technology are expected to be high. To hasten fusion development and to defray the costs that need to be borne by any single country, additional international cooperative agreements concerning research and development of this technology are likely to be signed in the next few years.

ELECTRICAL SYSTEM OPERATION

One possible option for reducing the amount of greenhouse gas emissions from electricity is to improve the efficiency of transmission, distribution, and storage of electrical power.

Reduce Energy Losses During Transmission and Distribution

Electrical energy losses from transmission and distribution are normally in the 5-10% range in industrialized countries. When generation is primarily from fossil fuels, as in the U.S., programs to reduce efficiency losses associated with electricity transmission and distribution may provide one option for reductions in greenhouse modest gas emissions. In developing countries, however, it is very likely that significant improvements are technically possible. Many developing countries experience losses of over 20%, even inexpensive 30%. Relatively and straightforward technological solutions exist utility transmission and upgrading for distribution systems to recover a major portion of these losses. On the other hand, in many countries it is estimated that half of the "controllable" losses are due to theft (U.S. AID, 1988b); despite many reasons for reducing these thefts, it is not clear whether a straightforward solution to these electricity thefts exists nor would this mean a significant reduction in greenhouse gas emissions, except to the extent demand is reduced as consumers are charged for the power they use.

Electric utility companies normally operate their systems and interconnections with other systems in such a way as to minimize generation costs, subject to a number of other constraints. Thus, powerplants with the lowest variable operating (including fuel) costs would be operated more of the time, and power available from other utility systems would be purchased when its cost is lower than the incremental cost of generating additional power within the system.

Within this framework, there may be some flexibility to shift more of the overall load to non-fossil or natural-gas-fired capacity without greatly increasing overall generating Although difficult to achieve costs. institutionally, such alternative dispatching options may be technically feasible and costeffective in the near term. This could include "wheeling" power from region to region to take maximum advantage of non-fossil generating capacity. On its largest scale, of strategy could result in this type international electricity transfers from countries with less carbon-intensive generating capacity to countries with more carbonintensive available options. For example, expanded Canadian power imports to the U.S. based on hydroelectric generation would be one such possibility.

Superconductors offer no resistance to electrical flow. Recently, breakthroughs in superconductivity research have increased the prospects that this technology could be applied to power production. Until recently, superconductivity could only be achieved in extremely cold environments (e.g., more than 200°C below zero). The superconductivity effect can now be achieved at much higher temperatures, although they are still well below ambient conditions. In the long term, superconductivity could significantly improve Conventional the transmission of power. transmission systems lose about 8% of the power they conduct; superconductors could greatly reduce, if not eliminate, these losses. Superconductivity could also be beneficial for power production. For example, several technologies use electromagnets, including the MHD system discussed above. During the power production process, electromagnets are typically the source of some lost power.

Superconductors could reduce the energy lost in generating power by reducing the losses associated with electromagnets. Also, as discussed below, superconductivity could be useful for energy storage.

Enhance Storage Technologies

There are a variety of technologies currently available or under development for energy storage. Storage systems can perform several tasks, including the following:

• Load Leveling, which would allow inexpensive baseload electricity to be stored during periods of low demand and released during periods in which the marginal cost of electricity is high (e.g., powerplants could be run during the night and the power stored to meet peak requirements in the afternoon). One drawback is that storage may allow baseload coal to substitute for natural gas, increasing greenhouse gas emissions, unless renewable energy sources are used.

• Spinning Reserve, in which the energy would be used as backup in case of failed generating systems.

• System Regulation, in other words, to balance a utility's constantly-shifting generation and load requirements.

The development of adequate energy storage systems could be particularly crucial for the competitiveness of many renewable energy technologies that can only produce power when the resource is available, for example, during daylight hours for solar or when the wind is blowing for wind energy systems. To enhance their competitiveness, renewable technologies could be used in tandem with storage systems that would allow power to be generated whenever available and then stored until needed.

There are many different types of energy storage systems, including pumped storage, batteries, thermal, compressed air, and superconducting magnetic energy storage. Several major energy storage systems are discussed below.

Pumped Storage

Pumped storage is a hydroelectric power storage option that has been used recently by the electric utility industry to meet electricity requirements during periods of peak demand. With this system water is pumped from a lower storage reservoir to an upper storage reservoir during off-peak hours. using electricity from a baseload powerplant (which is frequently coal-fired or nuclear). During peak demand hours, the water is released to the lower reservoir much like it would be at a typical hydroelectric dam. This system essentially stores power from the baseload powerplant when it is not needed for use during peak demand periods when the baseload plant is already committed 100% to meeting the peak power requirements.

While there are numerous pumped storage plants in the U.S., their efficiency is low and additional siting is likely to be difficult if they involve large, above-ground reservoirs. When underground reservoirs are used, the systems are only economical in very large facilities (e.g., 1000 MW).

Batteries

Batteries are attractive primarily for their flexibility; because they are modular, plants can be constructed quickly on an asneeded basis. Recent research and development has focused on advanced leadacid batteries and zinc-chloride batteries. Lead-acid battery technology has been used for decades (e.g., in automobiles), although its use in utility applications may be limited by its capital costs. Due primarily to the lower cost of the construction materials, the zincchloride battery is expected to be less expensive than the lead-acid battery in the longer term; possibly less than \$500/kW compared to \$600/kW or higher for lead-acid batteries (OTA, 1985). Plans to test both types of batteries on a commercial scale are currently being planned. Other battery technologies that could be available in the longer term include zinc-bromide, sodiumsulfur, iron-chromium, and lithium-iron sulfide batteries.

Compressed Air Storage

Compressed air energy storage (CAES) uses off-peak electricity to store energy in the form of compressed air in an underground cavern such as salt reservoirs, hard rock reservoirs, or aquifers. The compressed air is used in tandem with natural gas or oil in a modified gas turbine where the compressed air is used in lieu of a conventional compressor in the turbine cycle, thereby allowing the turbine efficiency to increase up to three times its normal efficiency (OTA, 1985). CAES is dependent on geological characteristics that can be found in about 3/4 of the U.S. and uses technology that is welladvanced. However, no CAES facility has yet been built in the U.S.; there is a facility that has been operating since 1978 in West Germany. There are two sizes proposed for CAES plants; a mini-CAES (about 50 MW) costing about \$392/kW and a maxi-CAES (about 220 MW) costing about \$515/kW; construction lead times are estimated to be 4 to 8 years (OTA, 1985).

Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) would function like more conventional storage technologies, but would be able to store energy with an efficiency of approximately 95% compared to 75% for pumped storage or 65% for battery storage (Schlabach, 1988). At this time SMES is clearly a long-term technology pending further improvements in basic superconductivity design.

HYDROGEN OPTIONS

One concept for reducing CO₂ emissions is the long-term phaseout of a carbon-based economy and the adoption of one utilizing hydrogen and electricity as complementary energy currencies. Hydrogen would serve as an "energy carrier" since electricity or some other source of power is required to produce it. Hydrogen is attractive for this role because it is nonpolluting, portable, and relatively safe. Hydrogen could be produced in a number of ways, including chemical processes beginning with coal or natural gas, and electrolysis using electricity

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production options. Of course, production chemically from fossil fuels or the use of fossil-based electricity would not provide significant long-term reductions in greenhouse gas emissions. However, these technologies are currently available and could play a role in a transition to greater use of hydrogen as an energy source (Harvey, 1988).

One technology under development holds some promise for allowing hydrogen to be generated from fossil fuels without CO_2 emissions. The process, known as hydrocarb, produces hydrogen and carbon black through a process of gasification and distillation. When coal is used as the feedstock, approximately 20% of the energy value is converted into hydrogen. The carbon black produced could be disposed of in mines or other disposal facilities. Biomass can be used as the feedstock, although it is a less efficient source of hydrogen (Grohse and Steinberg, 1987).

While large-scale hydrogen use would have to be considered a long-term option, this fuel could begin to make contributions in the near term. Researchers at Princeton University have suggested that use of hydrogen as a transportation fuel in urban areas may be its first significant role toward replacing traditional fuels (Ogden and Williams, 1988). Existing transport fuels are high-priced (allowing hydrogen to compete more easily), and urban air quality problems are already forcing many cities to look for alternatives to gasoline and diesel fuel in the transportation sector. Ogden and Williams also suggest that recent and projected improvements in the economics of amorphous silicon photovoltaic cells may make hydrogen fuel production from solar PV electricity cost competitive in some areas of the U.S. before the end of this century.

Another attractive feature of hydrogen that would be helpful in a long-term transition away from fossil fuels is that it can substitute relatively easily for natural gas in many applications. For example, natural gas space heating could be replaced by hydrogen over the long term; natural gas pipelines could be used to transport hydrogen and hydrogen is the basic fuel for fuel cells. Storage of hydrogen could occur in salt mines, aquifers, and depleted oil and gas fields for large needs and as liquid hydrogen and metal hydrides for small applications.

In a long-term hydrogen economy, nonfossil energy could be provided by a variety of renewable sources, with conversion to hydrogen accomplished by the electrolysis of water.

Conversion efficiencies in producing hydrogen from renewable energy exceed 80% and efficiencies for conversion back to energy in fuel cells range from 58-70%.

PART THREE: INDUSTRY

Figure 5-10 illustrates the overall current contribution of industrial processes (excluding energy) to the greenhouse warming problem. By far the largest component is the production and ultimate release to the atmosphere of chlorofluorocarbons (CFCs), halons, and chlorocarbons. Other industrial processes are relatively minor, but growing, contributors: carbon dioxide (CO_2) is emitted from cement manufacture and methane (CH_A) is produced by solid waste landfills. In addition, industrial process emissions of carbon monoxide (CO) contribute to atmospheric chemistry, which indirectly affects the concentration of tropospheric ozone (O_3) and CH₄.

CFCs AND RELATED COMPOUNDS

As a result of the Montreal Protocol and the June 1990 London Amendments (discussed in CHAPTER VIII), emissions of the most important CFCs will be capped in 1989, reduced to half of 1986 levels by 1995, and phased out by 2000. Halons will be frozen at 1986 levels beginning in 1992 and phased out in 2000. In addition to the CFC and halon phaseouts, phaseout schedules for carbon tetrachloride and methyl chloroform were set, and a non-binding declaration was made regarding the phaseout of hydrochlorofluorocarbon (HCFC) production.

A series of recent detailed reports prepared under Article 6 of the Protocol by international experts examined the available and emerging options for reducing CFCs, as well as halons, methyl chloroform, and carbon tetrachloride, which are of potential concern for both stratospheric O_3 depletion and greenhouse warming (UNEP, 1989). These reports asserted that technical options are currently available for virtually eliminating all CFCs, methyl chloroform (reductions of 90-95%), carbon tetrachloride, and halons (minority view stated only 50% reduction possible). As a reflection of this technological progress, many industrial groups (e.g., rigid foam electronics, auto manufacturers) have announced goals of eliminating their use of CFCs in the mid-1990s or sometime before the end of the century.

Some of the substitute compounds affect greenhouse warming but to a much smaller degree than do the controlled substances. Most of the unregulated compounds have much shorter atmospheric lifetimes, which decreases their impact on the greenhouse problem.

Use and emissions of CFCs could be reduced by three possible mechanisms:

• Chemical substitution -- switching from production processes in which CFCs are used to those in which other chemicals are used; for example, using FC-134a or blends of other non-fully halogenated HCFCs instead of CFC-12 in mobile air conditioning.

• Engineering controls -- in the near term, switching to production technologies that use fewer CFCs (or substitutes) per unit of output, such as recycling equipment that collects and recycles CFC emissions during the production of electronics.

• Product substitution -- switching from CFC-using products to other products; for example, replacing CFC-based foam egg cartons with paper-based egg cartons.

This chapter surveys existing and future product substitutes, engineering controls, and chemical substitutes that can reduce use and emissions of CFCs and halons. The information presented is based on a detailed series of industry studies performed by the U.S. Environmental Protection Agency (U.S. EPA) for use in its *Regulatory Impact Analysis* for stratospheric ozone protection and from a technical assessment performed by the Parties FIGURE 5-10



to the Protocol (U.S. EPA, 1987). Unless otherwise noted, information in this section is drawn from U.S. EPA (1988b).

Expand the Use of Chemical Substitutes

Several chemical substitutes that have physical properties (e.g., boiling point) similar to those of CFCs either do not contain chlorine or have short atmospheric lifetimes that reduce their potential to deplete stratospheric O_3 .

FC-134a, HFC-152a and blends including non-fully halogenated HCFCs (HCFC-22, HCFC-124, HFC-152a) appear to be the most promising chemical substitutes refrigeration and air conditioning for applications, including commercial chillers and mobile air conditioning, and along with HCFC-141b and HCFC-142b appear to be likely alternatives to CFC-11 and CFC-12 in production of polystyrene sheet and polystyrene boardstock. Several major chemical producers have announced plans to build commercial-scale production facilities for FC-134a and HCFC-141b. An consortium international of chemical producers has been formed to undertake toxicity testing of FC-134a and other chemical substitutes.

HCFC-141b and HCFC-123 are expected to become commercially available in the early 1990s and could replace CFC-11 currently being used in manufacturing slabstock flexible polyurethane foam and rigid polyurethane foam. In blends with HCFC-22, HCFC-142b appears to be an option for replacing the remaining "essential" CFC use in aerosols.

HCFC-22 is currently used in residential air conditioners and might be used in commercial chillers. It could substitute for CFC-11 and CFC-12 as a leak-testing agent in several refrigeration applications. Mixtures of HCFC-22 and other compounds could be used in mobile air conditioners.

HCFC-22 has already been adopted as a substitute for CFC-blown polystyrene sheet products. It was recently approved by the Food and Drug Administration as an alternative blowing agent for use in food packaging. The Foodservice and Packaging Institute, in concert with several environmental groups, recently completed implementation of an industry-wide program to eliminate within one year the use of CFC-11 and CFC-12 in food service packaging by substituting HCFC-22.

A major manufacturer of extruded polystyrene boardstock recently announced that it will substitute HCFC-22 and other partially halogenated CFCs in its manufacturing processes beginning in 1989.

Blends of HCFC-22 with **dimethyl ether** and HCFC-142b can be used to replace the remaining "essential" CFC use in aerosols. **Hydrocarbons** have largely replaced CFCs as aerosol propellants in the United States. Other nations can reduce their use of CFCs in aerosol propellants by reformulating aerosol products.

Ethylene oxide (EO) is currently blended with CFC-12 for use in the sterilization of medical equipment and instruments. Reductions in CFC-12 use could be achieved by using pure EO, a blend of CO_2/EO , radiation, or the use of HCFC or HFC substitutes.

Aqueous cleanings and terpene-based solvents can be used instead of CFC-113 to clean electronic components. One major manufacturer expects to replace one-third of all its CFC use in electronics manufacturing with terpene-based solvents. Aqueous cleaning can also reduce CFC-113 use in many applications for cleaning electronic components.

Employ Engineering Controls

Recovery and recycling can reduce CFC emissions from several applications. Recovery and recycling during servicing of air conditioning and refrigeration equipment, such as commercial chillers and mobile air conditioning units, can achieve large reductions in CFC emissions. An industrywide voluntary purity standard for recycling CFC-12 from car air conditioners was recently adopted. U.S. EPA has recently been petitioned by an industry trade group to establish a national recycling program. Carbon adsorption units could be installed to capture CFC emissions during manufacture of slabstock flexible polyurethane foam. Simple housekeeping improvements and process modifications such as automatic hoists and covers, carbon adsorption, reclamation, and recycling can substantially reduce CFC-113 emissions during solvent cleaning. Furthermore, many electronics firms are finding that cleaning during the manufacturing process can be substantially reduced and in some cases eliminated without sacrificing product quality or reliability.

Alternative leak-testing agents can reduce halon emissions during discharge testing of total flooding fire-extinguishing systems.

Improved system design can reduce CFC emissions. Attractive techniques in mobile air conditioning include design improvements, such as the use of more refrigerant-tight hose materials, shorter hoses, and improved compressor seals and fittings.

Alternative processes can be used to produce final products without using CFCs. For example, the CFC-blown flexible foam process can be modified to eliminate use of CFC-11, but the foam will be slightly denser as a result. Nearly all uses of molded flexible foam could be converted to water-blown formulations.

Training could reduce unnecessary discharges of CFCs during air conditioning servicing. Adoption of new training procedures, such as use of simulators, could reduce halon emissions during military training exercises.

Use Substitutes for CFC-Produced Materials

Research efforts are exploring ways to replace the use of CFC-blown insulation in refrigerator walls by insulating vacuum panels. A prototype vacuum panel refrigerator, which could achieve sizeable gains in insulating properties, is currently being built.

CFC-blown slabstock flexible polyurethane foams can be replaced by other products. Fiberfill materials, cotton batting, latex foams, and built-up cushioning that contains springs may be suitable substitutes, but they are more expensive and lack the durability of flexible polyurethane.

Some product substitutes are available for rigid polyurethane foam products. Many alternative products are currently available for use as sheathing or roof insulating materials. Expanded polystyrene foam beadboard. fiberglass, fiberboard, and gypsum, for example, used could be instead of polyurethane foam, as they were 30 years ago when polyurethane foams were not yet manufactured. In some cases, wall and roofing insulation can be made thicker to achieve the same insulating capacity as at present, but the use of foam blown with chemical substances is likely to continue where it offers the advantages of reduced labor costs and smaller bulk and meets a building's energy efficiency requirements.

Some product substitutes are available for poured or sprayed foam, depending on the specific use. In applications such as packaging and flotation, product substitutes are numerous. Combinations of plastic and non-plastic materials can provide equivalent degrees of cushioning, shock resistance, and water resistance. At present, however, no other insulation materials have the equivalent ability to be poured or sprayed, nor can other materials of the same thickness insulate as well as rigid polyurethane foams.

Polystyrene sheet competes with many other disposable packaging and single service products, including paper, cardboard, solid plastic, metal foils, and laminar composites of foil, plastic film and paper. Any of these substitutes could eliminate CFC use in food packaging applications.

Current and possible future alternatives to foam boardstock as insulation include a host of product substitutes, including fiberglass board, perlite, expanded polystyrene, fiberboard, cellular glass, insulating concrete, rock wool, vermiculite, gypsum, plywood, foilfaced laminated board, and insulating brick. Greater thicknesses of these alternatives may be required to provide equal energy efficiency.

Pre-sterilized, disposable products are one possible alternative that will enable hospitals to reduce their dependence on CFC-12 for sterilization.

Pump sprays and roll-ons are product substitutes that can replace CFC-propelled personal care aerosols.

METHANE EMISSIONS FROM LANDFILLS

Over 1.6 million tons of municipal solid waste is generated on the planet each day (adapted from Bingemer and Crutzen, 1987). Approximately 80% of this volume is disposed of on land in landfills or open dumps. Anaerobic decomposition of municipal and industrial solid wastes in landfills results in the generation of 30-70 Tg of CH_4 each year (Bingemer and Crutzen, 1987).

The amount of gas produced by a given site is a function of the amount and composition of landfilled wastes. The rate of gas production is a function of the age of material in the landfill, oxygen and moisture concentrations, pH, and the presence of Methane production is highest nutrients. when the organic content of the refuse is high, the wastes are relatively new, and there is adequate moisture available. The decomposition process only occurs in an environment that is oxygen-free and has a moderate pH. There is a one- to two-year lag period between landfilling of wastes and the beginning of gas generation. Methane production occurs once all available oxygen has been consumed and the environment becomes anaerobic. Food and garden wastes generally decompose over a 1- to 5-year time frame, while paper wastes could require 5 to 20 years to decompose (Bingemer and Crutzen, 1987). These factors and the active life of a landfill affect the duration of CH₄ production. It can take anywhere from 10 years to over 100 years for a landfill to produce significant amounts of CH₄ (Wilkey et al., 1982).

Estimates place the rate of CH_4 production between 1000 and 7000 cubic feet per ton (31-218 m³/mt) of municipal solid waste deposited (Wilkey et al., 1982). The United States generated approximately 148 million tons of municipal solid waste in 1988 (U.S. EPA, 1988c), which, using the rates above, would produce between 2.9 and 20.7 teragrams (Tg) of CH₄. Using a CH₄ production rate suggested by Bingemer and Crutzen (1987), the same amount of solid waste would produce an estimated 7 Tg of CH_4 .⁷

Increase Methane Recovery

Landfill gas, which is typically comprised of approximately 50% methane, 50% carbon dioxide, and some trace constituents of volatile organic compounds, can be recovered and used as fuel. The gas is a medium-British thermal unit (Btu) fuel (approximately 500 Btu/standard cubic foot), which can be used directly in boilers or for space heating, in gas turbines to generate electricity, or can be processed to high-Btu pipeline quality gas (Zimmerman et al., 1983). The gas is purified prior to use: for medium Btu-gas, processing requires removal of particulates and water; for high-Btu gas, CO₂ and most trace components must also be removed.

Landfill gas can present an environmental hazard because of its high combustibility and ability to migrate through soil. Methane is flammable in concentrations between 5 and 15% by volume in air at ordinary temperatures. Methane can rise vertically or can migrate horizontally out of a landfill. Methane migrates easily through porous soils, drainage corridors and other open areas, often travelling significant distances. Migrating CH_4 gas has caused explosions and flash fires, resulting in property damage and death. Malodors and vegetative damage have also been attributed to migrating landfill gas.

Methane control systems, required under certain circumstances by the Resource Conservation and Recovery Act (RCRA), can help to mitigate malodors, gas hazards, and vegetative stress. RCRA requires that concentrations not exceed a lower explosive limit of 5% methane (10% landfill gas) at the landfill boundary. Controls include impermeable barriers, induced exhaust systems, evacuating and venting or flaring (burning) of the gas, and recovery for use as an energy source. Of these controls, only flaring and recovery of the gas reduce the amount of CH_4 emitted into the atmosphere.

Of the 6,584 municipal solid waste landfills in operation in the U.S., 1,539 (16.6%) employ some methane recovery or mitigation system such as venting or flaring. Only 123 of these sites (1.9% of total) recover methane for energy use (U.S. EPA, 1988c). New regulations proposed by U.S. EPA under the Clean Air Act would require collection and control of landfill gas at both new and existing landfills. These regulations have the potential to significantly reduce the emission of CH_4 from landfills in the U.S. (U.S. EPA, 1988a).

Estimates place the quantity of gas generated by sanitary landfills in the U.S. at 1% of the nation's annual energy needs, or approximately 5% of current natural gas utilization (Escor, 1982). The recovery efficiency of methane from landfills can range between 60 and 90% of the gas produced, depending upon the quality and design of the gas recovery system, spacing of recovery wells, and landfill covering.

The economic viability of CH₄ recovery at a landfill depends upon the landfill's size, location, proximity to potential users, current competing energy costs, and regulations governing the site. The capital costs of recovery projects are about \$1000/kW. Suggested minimum requirements for recovery include an in-place refuse tonnage of 2 million tons, a disposal rate of 150 tons per day, an average refuse depth of 40 feet (ft), a surface area of 40 acres, and two years of remaining active fill life (EMCON Associates and Gas Recovery Systems, Inc., 1981). Probably fewer than 1,000 landfills in the U.S. are of sufficient size to meet these criteria. Sanitary landfills in developed countries hold the best potential for economical recovery of methane. Currently, there is little potential for CH₄ recovery from open dumps in the developing world; if the practice of sanitary landfilling is adopted, the prospect of CH₄ recovery will improve.

Over 408 (about 5%) of the municipal solid waste landfills in the U.S. receive more than 500 tons of municipal solid waste per day (U.S. EPA, 1988c). Collectively, these landfills receive over 75 million tons of municipal solid waste each year (over 50% of the total generated in the U.S.). If CH_4

recovery were implemented only on the largest 5% of landfills in the U.S., an estimated 2.2-3.3 Tg of CH_4 could be recovered.

Constraints on the economic feasibility of recovery projects have hampered further adoption of this technology. Under current projects market conditions, are not economically viable unless there is a suitable gas user within two to three miles of the site, or the electricity generation can be tied into an electricity grid. Current regulations governing many sites also discourage the recovery of methane. Some state regulations resource recovery projects subject to unlimited liability for any potential contamination problems at a landfill -- a significant disincentive to recovery.

Various techniques can be used to enhance gas production and yield from a landfill, including controlled addition of moisture and nutrients (usually in the form of landfill leachate or landfill gas condensate), bacterial seeding, and pH control. The addition of leachate and condensate is only permitted at landfills where there is a liner. Further research in these areas could increase the economic viability of CH_4 recovery.

Employ Recycling and Resource Recovery

Recycling and resource recovery hold the potential to affect emissions of greenhouse gases through both waste reduction and reducing energy demand. Source separation and waste-stream reduction have many benefits for the municipality and the environment. A reduced waste stream means less refuse going to the landfill, an increasingly limited resource. In addition, the energy savings from recycling can be significant as discussed in PART ONE.

Separating organics from the waste stream, such as paper and food, lawn, and garden wastes, can achieve many benefits, including reduced production of CH_4 . Reducing organics in the landfill results in less CH_4 production from that source. Organics that are separated and composted do not produce CH_4 if the composting includes aeration to keep the process aerobic.

Within the industrialized countries of the OECD, garden and park wastes make up about 12-18% of the municipal solid waste stream and account for about 10-14% of its organic content, while food wastes make up between 20 and 50% of the stream and account for over 20% of the organic content. Within developing countries, garden and park wastes are insignificant, while food wastes account for between 40 and 80% of the waste stream and over 70% of the organic content (adapted from Bingemer and Crutzen, 1987). Given these high proportions of food, garden, and park wastes, the potential for reducing CH_{4} production through aerobic composting could be significant.

Reduce Demand for Cement

Carbon dioxide emissions from cement production originate from two sources: 1) as a chemical by-product of the manufacturing process, and 2) as a by-product of fossil-fuel combustion used for kiln firing and plant electricity. Energy consumption emissions are discussed in the end-use section of this chapter. The CO_2 emissions that result as a chemical by-product occur during the firing process, when the raw materials (cement rock, limestone, clay, and shale) are exposed to progressively higher temperatures in a kiln. It is during calcination, which occurs at approximately 900 to 1000°C, that the limestone (CaCO₃) is converted to lime (CaO) and CO₂, and the CO₂ is released. For every million tons of cement produced, approximately 0.137 Tg C as CO₂ is emitted as a result of this chemical process (Rotty, 1987). For comparison, approximately 0.165 Tg C per million tons of cement produced result from energy consumption.

Although cement manufacture currently accounts for only a small percentage (approximately 2%, not including the energy consumption emissions) of the global

anthropogenic source of CO_2 , emissions associated with this industry have increased rapidly over the last few decades and can be expected to continue to grow in the future as demand for cement grows. Between 1950 and 1985, cement production and associated CO₂ emissions grew at an average annual rate of 6%. Regional production growth rates have varied during this period due to economic fluctuation in the construction industry (cement's primary market) and shifts in international competition between the cement-producing countries. Today, the USSR, China, Japan, and the U.S. account for 43% of the world's cement production.

Since CO_2 is an inherent product of cement manufacture, the only way to slow the rate of growth in emissions is to limit the amount of cement required, that is, reduce demand through more efficient use of cement and/or through substitution with other materials (e.g., steel and glass). Increases in efficiency can be achieved through both material and fabrication improvements, for example, through the use of pre-stressed and steel-reinforced concrete products. Substitution of cement with other materials such as steel, glass, or wood also would slow the growth in cement demand, although substitution with such energy-intensive materials as steel may result in greater net CO_2 emissions. In fact, in some applications cement products have been used in lieu of other materials, such as steel. Improved efficiency has already occurred in much of the developed world due to improved engineering design in construction. Also, most basic infrastructure has been built in the developed world, so demand may slow somewhat in the future. This is not likely to be the case in the developing world, however, where demand will probably continue to grow more rapidly than GNP, particularly since cement is an inexpensive building material.

PART FOUR: FORESTRY

Forests, which store 20-100 times more carbon per unit area than croplands, play a critical role in the terrestrial carbon cycle (Houghton et al., 1988b). Active forest management to maintain high amounts of standing biomass, to reduce tropical deforestation, and to aggressively reforest surplus agricultural or degraded lands, offers significant potential for slowing atmospheric buildup of carbon dioxide (CO_2) , carbon monoxide (CO), nitrous oxide (N_2O) , and Forestry-related policy methane (CH_{4}) . responses to climate change are particularly important because they (1) are capable of partially offsetting current fluxes of CO_2 , (2) require modest costs relative to non-forestryrelated options, (3) do not require the development and dissemination of new technologies, and (4) offer a wide range of ancillary social benefits (e.g., increase fuelwood supply, reduce soil erosion, improve preserve wildlife habitat) significant enough to justify forestry options even without the specter of global warming (Andrasko and Tirpak, 1989; USDA/EPA, 1989). For a general overview of climate change and forest ecosystems and management (effects of climate change, adaptation options, and mitigation opportunities), see Andrasko (1990a, 1990b).

Most research on greenhouse gas emissions from natural and disturbed forest ecosystems, and on the implications of accelerating rates of tropical deforestation for global change, has focused on emissions of CO_2 and CO and large-magnitude fluxes in the carbon cycle from burning and gradual decay of biomass associated with clearing of tropical forests. Since less work has been done on other gases, this section will concentrate on the carbon cycle.

FOREST DISTURBANCE AND CARBON EMISSIONS

The ecological diversity and geographic range of vegetation communities determine the degree of carbon sequestering by forests

and the rate of carbon emissions due to disturbances of forests. Forests cover about one-third of the Earth's land, or 4 billion hectares (ha),⁸ of which about 42% is in developed countries (mostly temperate) and 58% is in developing countries (mostly tropical) (FAO/WRI/World Bank/UNEP, 1987). The carbon content of tropical moist forests (with closed canopies, like Amazonian rain forest) averages 155-160 tons of carbon per hectare (t C/ha) of standing biomass in Latin America and Asia and ranges up to 187 t C/ha in Africa.⁹ The carbon content of drv tropical forests (closed or open forests on relatively dry soils with grassy or herbal ground cover) averages 27 t C/ha in Latin America and Asia and 63 t C/ha in Africa (Houghton et al., 1988).

Recent estimates of boreal (northern, largely coniferous) forest in North America, however, suggest that all of our carbon content and biomass estimates commonly utilized in calculations of global carbon cycle fluxes may be seriously flawed. Botkin and Simpson (1990) recently used more statistically reliable methods to estimate North American boreal forest biomass carbon content at about 9.7 billion metric tons -only one-quarter of previous estimates of 13.8 to 40 billion tons of carbon used routinely to balance the global carbon budget.

Anthropogenic alterations of forest ecosystems now account for emissions of atmospheric CO_2 equal to about 10-50% of total emissions from combustion of fossil fuels, as carbon stored in vegetation and soils is released by clearing, fire, or decay Releases of gases (Houghton, 1988a). continue for a long time following forest clearing; emissions of CO_2 , N_2O , and CH_4 in Amazonia decline to one-third or one-half of their initial rate after 10 days, but then appear to continue for a year at a constant rate (Goreau and de Mello, 1988). One estimate of total CO₂ emissions from burning the entire Amazonia forest ecosystem suggests that only 15% of the total carbon emitted

would be contained in the initial biomass burning; fully 85% would be released over years or decades from soils (Fearnside, 1985).

Recent estimates of annual net carbon flux from deforestation range from 0.4 to 2.6 petagrams (Pg) C/yr for 1980,¹⁰ primarily due to land-use change in the tropics (Detwiler and Hall, 1988b; Houghton et al., 1987). Brazil, Indonesia, and Colombia were the largest of the top ten producers of net carbon release from tropical deforestation in 1980 (see Table 5-13), although new estimates of forest loss rates for the 1980s move Burma into the top three (WRI et al., 1990; Houghton, 1989, in Myers, 1989). These ten combined account for about 70% of the CO_2 emitted due to changes in land use (Houghton et al., 1987; WRI et al., 1990).

Very recent estimates of forest loss rates, some not yet fully reviewed by the forestry community and controversial, suggest far higher rates of deforestation and, hence, carbon emissions. Myers (1989) has estimated that the rate of conversion of tropical closed forests has risen 82% since the 1981 FAO estimate of 7.2 million ha/yr of closed forests, to 13.9 million ha/yr for 1989. This produces an estimate (by Houghton, in Myers, 1989) for current emissions of carbon from deforestation of 2.0-2.8 Pg, with a mean of 2.4 Pg, although this has not been widely reviewed by experts. Similarly, a tally of new country-level estimates for forest loss by WRI et al. (1990; see below) suggests that the standard FAO 1980 deforestation figure of 11.4 million ha may be revised upward by other new studies to about 20.4 million ha for 1989/90.

Uncertainties still exist in determining carbon storage in and emissions from changes in forest cover associated with various land uses. For example, emissions of greenhouse gases from cropping practices in swidden (i.e., shifting, or slash-and-burn cycle) agriculture versus sedentary (permanent) agriculture, including agroforestry systems, have not been quantified. Neither do we have reliable estimates of biomass, carbon content, and trace gas emissions in a truly representative sample of natural and disturbed tropical forests and carbon fluxes in disturbed tropical soils (which may account for one-third of carbon flux from deforestation) (Houghton et al., 1988). Permanent conversion of natural forest to pasture or cropland results in net loss of carbon stored both in standing biomass and soils; the amount lost is dependent on the biomass productivity and soil carbon storage rates of the former versus the new land use. Cyclical harvest of forest for timber or fuelwood similarly releases carbon from slash (nonmarketable tree parts: branches, leaves) that is burned or left to decay on-site, and from timber milled into non-durable wood and paper products (and wastes like sawdust and scrap) that are soon burned or discarded.

Forests in temperate regions are essentially now in balance in terms of carbon cycling, with annual incremental growth rates roughly equal to rates of timber harvest and deforestation for urban growth and other land uses. Consequently, temperate forests do not currently contribute significantly to the increase in atmospheric CO_2 (Houghton et al., 1987). However, they now cover much smaller areas than in the past, and have historically contributed heavily to global carbon emissions, as forests were cleared in Europe, North America, and Russia for agricultural production.

Widespread reforestation programs that could expand temperate forests into former forest ranges and reduce net carbon emissions are discussed below. Trees newly planted in urban areas would alleviate the greenhouse problem in two ways: (1) by reducing the need for air conditioning and hence electricity, and (2) by increasing the uptake of carbon in biomass growth (Akbari et al., 1988).

DEFORESTATION

Each year, at least 11.4 million hectares, and perhaps as much as 20.4 million hectares (see below), of forest are cleared in the tropics, an area larger than Austria or Tennessee (Lanly, 1982; IIED and WRI, 1987). The rate of deforestation -- combined with the escalating growth in demand for forest products -- is such that while 33 tropical countries are currently net exporters of wood products, this number may decline to fewer than 10 by the end of the century

TABLE 5-13

Estimates of Release of Carbon to Atmosphere from Top 10 Deforestation Countries, 1980 and 1989

(million tons of carbon)

1980		19	89
Brazil	336.1	Brazil	454
Indonesia	191.9	Indonesia	124
Colombia	123.3	Burma	83
Ivory Coast	100.5	Mexico	64
Thailand	94.5	Thailand	62
Laos	84.7	Colombia	59
Nigeria	59.5	Nigeria	57
Philippines	56.7	Zaire	57
Burma	51.2	Malaysia	50
Peru	45.0	India	41

Note: Estimates based on area deforested and biomass estimates, and reflect limits in data available.

Sources: For 1980: Houghton et al., 1987; for 1989: Houghton, 1989, in Myers, 1989.

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(Repetto, 1988). If this trend could be halted and reversed, tropical forests could serve as a vast carbon sink, reducing global CO_2 levels.

Figure 5-11 illustrates the movement of tropical forest lands among different stages of the deforestation cycle (an approach used by several researchers, e.g., Houghton et al., 1985; Lugo, 1988). The figure also summarizes the reductions or increases in forestland conversions that could shift tropical forests from net sources of greenhouse gases to net sinks using the range of technologies (i.e., forest management and land-use practices) and policies identified below as potentially available response options. Deforestation pressures and their socioeconomic and ecological consequences are complex, however, and greatly complicate the task of devising technical control solutions.

The underlying causes of deforestation vary widely by ecosystem and region, and are often complex, involving the interplay of historical, biological, economic, and political factors at both macro (national and transnational) and micro (household and village) levels. A recent international conference on the state of the world's tropical forests concluded that

> the causes of deforestation are well known. They include population pressure for agricultural land, the demand for industrial timber production and export, and inappropriate government policies regarding land tenure, economic incentives, forest settlement, and other population issues (Bellagio, 1987).

The 👘 predominant causes of deforestation vary by region. In tropical Africa and in South and Southeast Asia, rapid population growth appears to be the critical factor affecting deforestation. The majority of the population practices agriculture, and most of the increases in agricultural production necessary to sustain high birth rates have come from increases in the area under cultivation through deforestation. Seventy percent of Africa's deforestation stems from swidden (shifting) agriculture. Logging activities, both commercial and individual, in Malaysia, Indonesia, and the Philippines provide access to partially cleared forest lands that facilitates further clearing of forest for agriculture (Houghton, 1988a).

Rural populations rely on wood as the major source of energy, another important cause of deforestation. More than a billion people are currently affected globally by fuelwood shortages. The fuelwood deficit in arid and semi-arid regions of the world in 1980 affected 29.3 million people, and totaled 13.1 million cubic meters (m^3) of wood. This fuelwood gap between consumption and supply is anticipated to grow to 130% for the Sahelian countries overall by 2000, with single-country forecasts as high as 620% for Niger (Anderson and Fishwick, 1984).

One of the critical first steps in devising ways to slow tropical deforestation is for national and international development assistance agencies to support local people in introducing sustainable forest management and reforestation techniques that provide for basic needs -- fuelwood, food, fiber, and fodder -- for growing populations without mining primary forest.

The Amazon region in Brazil is experiencing one of the highest rates of tropical deforestation in the world (Setzer and Pereira, 1988; IIED and WRI, 1987; As a consequence, Fearnside, 1987). Amazonia is emitting greenhouse gases at rates and quantities high enough to affect global CO_2 and climate cycles. Salati et al. (1989) estimate that the Amazon region has already emitted from 3.5 to 12 Pg C to the atmosphere -- totalling 2-7% of the total release of CO_2 to the atmosphere from deforestation and biomass burning up to 1980 (see Table 5-14). Current annual emissions from Amazonia alone are estimated at 0.24 to 1.6 Pg C, or 4-25% of global CO₂ emissions from all sources, assuming 7 Pg C per year from all sources.

Centralized government policies that undervalue standing forest and provide tax and other fiscal incentives for conversion to crop and pasture lands contribute to increasing deforestation rates in Brazil (Binswanger, 1987; Repetto and Gillis, 1988). FIGURE 5-11

MOVEMENT OF TROPICAL FOREST LANDS AMONG STAGES OF DEFORESTATION AND POTENTIAL TECHNICAL RESPONSE OPTIONS



(Millions of Hectares)

Figure 5-11. Pathways of conversion of tropical closed and open forest lands, and where technical response options discussed here would intervene to slow conversion. Data were derived from FAO (1981) and from Lanly (1982) and are expressed in millions of hectares. Numbers inside boxes represent total area in category in 1980. Numbers on lines tipped with arrowheads represent annual rates of conversion. Data include both closed forests (complete canopy) and open forests (incomplete canopy and grass herbaceous layer). Source: Pathway data modified from Lugo, 1988. Houghton et al. (1985) offer similar conversion data.

TABLE 5-14

Recent Estimate of CO₂ Emissions from Biomass Burning in Amazonia

Estimate of Carbon	Range of CO_2 Emissions (x 10^{15} g carbon)		
Biomass Available ^a (tons/ha = 10^8 g/km^2)	Cumulative Total ^b	Total in 1988 ^c	
Lower (140)	3.5 to 8.4	0.24 to 1.1	
Upper (200)	5.0 to 12.0	0.34 to 1.6	

NOTE: Estimate based on the assumption that 100% of the burned biomass is transformed into CO_2 .

^a Based on data from Martinelli et al. (1988).

^b The total range of emissions is calculated as the product of the lower and upper estimates of the carbon biomass available and the lower (250,000 km² in INPE, 1989) and upper (600,000 km² in Mahar, 1988) estimates of the total area deforested.

^c The range of emissions for 1988 is calculated as the product of the lower and upper estimates of the carbon biomass available and the lower (17,000 km² in INPE, 1989) and upper (80,000 km² in Setzer and Pereira, 1991) estimates of the area deforested in 1988.

Source: Salati et al., 1989.

With the vast scale of its forest resources and international pressures, Brazil has the potential to slow deforestation if proactive adjustments in government, commercial, and colonizing forest use and development practices are adopted (e.g., see discussion of options to reduce biomass burning, below).

Brazil has 357 million hectares of closed tropical forest -- 30% of the global total, and three times as much as Indonesia, which is second to Brazil in its extent of forest area. The area deforested per year in the Amazonian state of Rondonia tripled from 7,600 square kilometers (km²) in 1980 to 26,000 km² in 1985, while the population increased roughly 15% per year during 1976-81 (Malingreau and Tucker, 1988; Woodwell et al., 1986). The major factors driving the loss of forests include land speculation, inflation, negative-interest and special-crop loans, government tax and fiscal incentives undervaluing standing forest (land is worth more cleared than forested), production of beef for export, and population redistribution in response to high growth rates and the mechanization of agriculture in southern Brazil (Repetto and Gillis, 1988).

The situation in Brazil is changing rapidly. Analysis conducted at the Brazilian Space Research Center found that forest fires during 1987 covered 20 million ha (77,000 square miles, or 1.5 times the area of New York state), of which 8 million ha were virgin forest (Setzer and Pereira, 1988). This observation has forced reevaluation of standard mid-1980s estimates (e.g., Lanly, 1982) of 11.4 million ha deforested for the entire globe's closed and open tropical forests and could raise estimates, to perhaps as high as 20.4 million ha/yr for the 1980s. The wide disparity between FAO's interim estimates for selected countries and newer studies, often relying on remote sensing, is shown in Figure 5-12 (WRI et al., 1990). The emissions from these fires contribute roughly 10% of total global emissions of CO_2 (Fearnside, 1985). If the Brazilian Amazon were completely cleared, 11 Pg C would be released immediately, augmented by a continuing gradual release that would elevate the total to 62 Pg (Fearnside, 1985). Thus, deforestation in Brazil poses serious global consequences

for climate change as well as the much discussed loss of species diversity.

TECHNICAL CONTROL OPTIONS

Technical control options involving forestry can sequester carbon through the growth of woody plants, reduce anthropogenic production of CO_2 , and complement other strategies for reducing the buildup of greenhouse gases. Forestry-sector strategies for responding to the threat of global warming fall into two major categories from an economic standpoint: those technical and policy options that reduce the demand for forest land and forest products, and those that increase the supply of forested land and forest products. From a greenhouse gas accounting perspective, these can be divided more profitably into three classes:

- 1. Reduce Sources of Greenhouse Gases;
- 2. Maintain Sinks of Greenhouse Gases; and
- 3. Expand Sinks of Greenhouse Gases.

Table 5-15 lists the components of these three classes of forestry-related strategies.

The set of potential response options in the forest sector fall into three categories. First, adaptive measures in forest management practices (e.g., planting drought-tolerant tree species in areas likely to undergo reduced precipitation during climate change, or shortening tree-crop rotations to allow planting of different species as growth conditions change), which are not reviewed here, offer one set of options (see Larson and Binkley, 1989; Binkley, 1990; and AFA, 1990). Secondly, technologies and land-use practices are currently available that, if widely utilized by forest managers, could reduce emissions from forestry. These are reviewed here. Lastly, government and corporate policies and fiscal incentives could be generated that would encourage market forces to reward forest managers for greenhouse-positive forest management (see CHAPTER VIII).

FIGURE 5-12



Sources: Used with permission of World Resources Institute, from WRI et al., 1990; original data for 1981-85 from FAO, 1988; most recent studies vary by country, and are referenced in WRI et al., 1990.

TABLE 5-15

Summary of Major Forestry Sector Strategies for Stabilizing Global Climate

Reduce Sources of Greenhouse Gases

- Substitute sustainable, sedentary agricultural technologies for swidden (slash-andburn) agriculture resulting in deforestation
- Reduce the frequency, interval, scale, and amount of forest and savannah consumed by biomass burning to create pasture and maintain grassland
- Decrease consumption of forest for cash crops and development projects through environmental planning and management
- Improve the efficiency of biomass (fuelwood) combustion in cookstoves and industrial uses
- Decrease the production of disposable forest products (e.g., paper, disposable chopsticks) by substituting durable wood or other goods and by recycling wood products

Maintain Existing Sinks of Greenhouse Gases

- Conserve standing primary and old-growth forests as stocks of biomass offering a stream of economic benefits
- Introduce natural forest management systems utilizing sustainable harvesting methods to replace inefficient and destructive logging
- Substitute extractive reserves producing timber and non-timber products with sustainable practices through integrated resource management and development schemes
- Increase harvest efficiency in forests by harvesting more species with methods that damage fewer standing trees and use more of total biomass
- Prevent loss of soil carbon stocks by slowing erosion in forest systems during harvest and from overgrazing by livestock

TABLE 5-15 (Continued)

Summary of Major Forestry Sector Strategies for Stabilizing Global Climate

Expand Sinks of Greenhouse Gases

- Improve forest productivity on existing forests through management and biotechnology on managed and plantation forests
- Establish plantations on surplus cropland and urban lands in industrialized temperate zones to produce high biomass and/or fast-growth species to fix carbon
- Restore degraded forest and savannah ecosystems through natural regeneration and reforestation
- Establish plantations and agroforestry projects in the tropics using both fast-growth and high-biomass species on short rotations for biofuels and timber
- Increase soil carbon storage by leaving slash after harvest and expanding agroforestry

In addition to the obvious benefit, from the climate change perspective, of increasing the supply of forested land (i.e., trees absorb CO_2), afforestation has a number of valuable ecological and economic benefits worthwhile on their own merits. For example, more forests may mean more jobs in the forest products industry, enhanced maintenance of biodiversity, better watershed protection, greater non-point pollution reduction, and more areas for recreation.

Compared with the annual crop cycles of agriculture, rotation time in forestry (the time necessary for one cycle of a forest crop to be planted, grown, and harvested) is slow, typically on the order of 25-80 years in temperate zones and 8-50 years in the tropics where growth is faster. Essentially, therefore, forestry climate strategies can create a net CO_2 sink for a fixed period, albeit long, since trees eventually die or are cut and release carbon through decay or burning. Harvesting on short rotations, at the point where the rate of mean annual increment (MAI) of biomass added per year begins to level off, in conjunction with aggressive replanting, must be combined with greatly expanded storage of carbon in durable products like construction beams, crates, or fences until they decay, and regeneration of new biomass at high rates of growth and carbon fixation.

The set of strategies in Table 5-15 could be evaluated by resource managers for the optimal mix of land use and forest management practices and policies best suited for any given forest management unit (e.g., a farm, watershed, national forest, integrated development project, or nation). Some options, however, are better suited to industrialized countries and some are more developing appropriate for countries. Strategies for maintaining the volume of standing stock, maximizing biomass growth rates, and expanding the area in sustainably managed, rapidly growing forest are all needed. Species and ecosystems that produce high volumes of biomass (e.g., Douglas fir old growth in the Northwest, mixed hardwoods in the East, and mahogany and teak in the tropics) usually grow slowly (e.g., 70-200 years to mature) and may be most useful as response options in industrialized countries

and well-managed protected areas in the tropics, where socioeconomic conditions favor long-term forest protection and intensive management. Developing countries especially need to maximize biomass growth rates, to restore degraded and desertifying lands, and to produce fuelwood and timber. Developing countries face rapid forest depletion and high population growth rates, and have limited institutional capability to guarantee long forest rotation times in the face of these realities. However, developing countries should also plant high-value, long-rotation hardwood stands and protect existing oldgrowth forests from cutting and burning.

Because of the long rotation times for forest growth, technical options will need to integrate short-term educational, harvesting, and research work with longer-term adaptations in forest planting, management, and product use.

All strategies should be, to the extent feasible:

• sustainable over time, without deteriorating the natural resource base or introducing ecological changes (i.e., pests), especially relying on improved management of both undisturbed (virgin) and secondary (disturbed or fallow) forests;

• capable of addressing the direct and indirect causes of forest loss by providing viable alternatives to current land-use patterns;

• economically attractive (low-cost and offering income commensurate to present land uses);

• capable of providing an equivalent spectrum of forest products (e.g., fuelwood, fodder) and jobs, at rates of return to labor (or time) and capital comparable to current forest-use patterns;

• socially integrative or adaptive, building on local needs and tradition;

• technologically simple and durable, to overcome low reforestation success rates on lands degraded by human resource use patterns (e.g., upland forests cut for timber and fuelwood and then overgrazed by goat and sheep); and

• readily adaptable to changing economic, political, social, ecological, and climate change realities (e.g., civil war, drought, resource-driven population shifts, and climate change impacts on forest growth).

Table 5-16 presents a summary of potential technical options for implementing forestry strategies to reduce demand and to increase supply.

Forestry Strategy I: Reduce Sources of Greenhouse Gases

Both tropical and temperate forest lands are in high demand to provide a range of alternative land uses and forest products. Forests are consumed in areas of rapid population growth worldwide as villages and cities expand, transportation corridors are built to connect them, and additional arable land is sought for food production. Other major forces contributing to deforestation in the tropics, include swidden (shifting) agriculture, large-scale economic development projects (often financed by multilateral banks), cattle ranches and palm oil, timber and rubber plantations, and fuelwood demand.

Based on population growth, projected demand for fuelwood by the year 2000 will require the creation of 20-25 million ha (or perhaps as high as 50 million ha) of new closed forest plantations for fuelwood, at a cost of \$50 billion, a rate 10-20 times current planting tallies (Nambiar, 1984; FAO, 1981; Lundgren and van Gelder, 1984). An additional 200 million ha of croplands will be needed (Postel and Heise, 1988) just to maintain the already inadequate 1980 levels of per capita food supply.

Currently, more than 10 hectares are lost to each one that is planted, based on the ratio of global deforestation to tree planting (Lanly, 1982). Models of forest product demand from 1980-2020 project tropical forest removals (harvest for timber) to double between 1980 and 2000, and then plummet to 72% of their 1980 level by 2020 (WRI and IIED, 1988; Grainger, 1987). Option 1: Substitute Sustainable Agriculture for Swidden Forest Practices

Sustainable agricultural systems are those that rely on biological recycling of chemical nutrients in soils and energy, and on naturally occurring mechanisms for protecting crops from pests, to produce annual harvests that can be sustained in perpetuity (Dover and Talbot, 1987). Generally, such systems use low levels of agricultural technology (i.e., minimal agricultural pesticides or fertilizers or improved seeds, and few conservation measures).

Sustainable agriculture, especially agroforestry, offers all three major types of greenhouse gas cycle benefits:

• Reductions of emissions of greenhouse gases:

-- reduced demand for natural forest wood products, since fuelwood, poles, and fodder are grown in many sustainable agricultural systems

-- reduced demand for new land cut from primary or secondary forest for swidden agriculture (by substituting highernutrient sedentary systems on permanent plots).

-- lower soil erosion, thereby less volatilization of soil carbon and methane,

-- diminished reliance on fertilizers, reducing N_2O emissions.

• Conservation and enhancement of gas sinks:

-- increased supply of woody biomass fixing carbon in trees and soils in forest-crop systems,

-- maintenance of soil carbon stocks, due to reduced erosion.

Swidden agricultural methods involve cutting and, usually, burning forest patches to plant crops that are harvested for 1-7 years, and then abandoning and leaving the patches fallow for about 7-14 years as new patches are
Potential Forestry Strategies and Technical Options to Slow Climate Change

Strategy	Technical Options	Regions Potentially Most Effective In
Reduce Sources of Greenhouse Gases		
Substitute sustainable agriculture	 Small-scale agroforestry Financial incentives for swidden colonists to shift to sustainable practices Technical aid in soil and crop selection Plan into development projects by banks, state agencies 	 Tropical moist and dry forests with strong central governments (Brazil, Colombia, Malaysia, Indonesia)
Decrease forest consumption for development and sustainable agricultural systems	 Assistance from multilateral banks and state agencies contingent on planning. Loans contingent on minimal forest loss Mitigation of loss by 2:1 protection of forest Government tax and fiscal policies to prevent loss 	 Strong central governments and banks with ability to plan and manage (Brazil, Costa Rica, India, China, Mexico)
Improve efficiency of biomass combustion	 Widely distribute efficient cookstoves Incentives for industrial cogeneration 	 Areas with inefficient current stoves, good extension, and difficult-access or expensive fuelwood (Nepal, India, Sahel, Haiti)
Decrease production of disposable forest products	 Substitute durable wood products for disposables Establish recycling programs for wood 	 Areas with cheap substitutes for wood and developed markets (industrialized areas of developing countries, Japan, U.S.)
Reduce biomass burning in forests and savannah	 Manage savannah more actively to prevent overgrazing of forage Establish fire prevention plans and brigades in forestry development projects Provide government surveillance and enforcement program 	 Savannah and dry forest areas already under active management and readily accessible Countries with remote sensing real-time detection of fires and will to enforce
Maintain Existing Sinks of Greenhouse Gases		
Conserve standing primary and old growth forests	 Establish protected areas and prevent forest loss Biosphere reserves 	 Old-growth forests in Pacific Northwest (U.S.), and developed countries Inaccessible and/or actively managed tropical moist forest

TABLE 5-16 (Continued)

Potential Forestry Strategies and Technical Options to Slow Climate Change

Strategy	Technical Options	Regions Potentially Most Effective In
<u>Maintain Existing Sinks of Greenbouse Gases</u> (Continued)		
Introduce natural forest management (NFM) systems	Introduce widely several NFM techniques	 Development or forest management projects in tropics
Substitute extractive reserves for unsustainable logging and agriculture	 Extractive reserves for rubber, fruits, and nuts Expand markets for non-timber forest products 	 Brazil, Indonesia, Malaysia Tropical forests with indigenes and colonists near markets and transport
Increase forest harvest efficiency	 Increase number of species harvested Decrease damage to standing trees Use harvest slash and mill scraps 	 Any area, if marketed, and countries with large or multinational logging concessions (Brazil, Malaysia)
Prevent loss of soil carbon	 Soil erosion via soil management, cover crops, windbreak plants Prevent overgrazing of pasture, forest via livestock management and fodder tree planting 	 Dry forest and savannah in tropics Hilly agricultural areas with active extension programs
Expand Sinks of Greenhouse Gases	 Manage temperate forests Apply natural forest management in tropics Increase plantation productivity Intensify timber stand improvement all forests Apply fertilizers and biotechnology to plantations Extend natural forest management practices 	 Developed countries and industrialized developing countries, with extension capability
Plant trees on crop and urban lands in temperate zone	 Expand tree planting programs Reforest croplands Reforest urban areas Reforest highway corridors Reforest surplus cropland Plant fast-growth plantations Plant trees near buildings, highways, rivers 	 Developed countries U.S.: Southeast, North Central states, West Coast

Policy Options for Stabilizing Global Climate

TABLE 5-16 (Continued)

Potential Forestry Strategies and Technical Options to Slow Climate Change

Strategy	Technical Options	Regions Potentially Most Effective In
Expand Sinks of Greenhouse Gases (Continued)		
Reforest degraded forest lands	 Incentives for agroforestry Establish extension farms and workers for agroforestry Require commercial and village loggers to replant Plant strip-mined, overgrazed, and abandoned lands in U.S. 	 Tropics, where rainfall and soils are adequate Degraded lands in U.S., with adequate soil nutrient and rainfall
Plant fuctwood and timber plantations in tropics	 Organize village tree planting Mobilize youth and religious groups to plant trees Include plantations in all development projects 	 Throughout tropics, especially in moist soils and in desertifying areas
Increase soil carbon storage	 Leave slash after harvest Prevent soil erosion with management practices 	• All managed temperate and tropical forests

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cut and farmed. About 41 million ha of tropical primary and secondary forest are burned annually (see CHAPTER VIII). Tropical forests store up to 90% of a plot's nutrients (some of which are released by burning) in woody plants, compared with temperate forests, where only 3% are stored in plants and 97% in soils (Keay, 1978). Swidden systems persist throughout the world, especially in remote and hill districts, and during times of individual or regional economic stress. For example, on Negros Island in the Philippines, the number of swidden farmers rose by 80% in only two years in the mid-1980s because of declines in the sugarcane industry that forced underemployed workers into swidden agriculture to grow food. Ecologists predict that a major rain forest there could be destroyed by the year 2000 (Dover and Talbot, 1987).

Sustainable agriculture and soil management systems can be introduced as a substitute for swidden systems that destroy virgin or secondary forest. For every hectare farmers put into such methods, 5-10 hectares of tropical rainforest may be saved from destruction to store carbon, conserve hydrologic cycles, and retain biological diversity, according to Sanchez (1988). Table 5-17 shows the equivalent area of forests needed for traditional swidden practices for every one hectare of forest land needed for more resource-intensive sustainable uses.

Agroforestry is the combination of agricultural and forestry techniques to produce woody plants on the same parcels as food or commodity crops or animals, with a mutually beneficial synergism. It offers one of the most promising approaches for providing both fuelwood and food needs, while reducing greenhouse gas releases and environmental (e.g., pesticide externalities use, pest irrigation population surges, high requirements) associated with monocultural row cropping. Interest in agroforestry has surged since the late 1970s, and development assistance for agroforestry during the mid-1970s to mid-1980s reached \$750 million in approximately 100 developing nations (Spears, 1987).

Agroforestry systems derive from traditional forest farming practices of many

indigenous peoples and are sustainable over long rotations, large acreages, and low population densities. The Lacandon Maya Indians, who live in the rainforest in Chiapas, Mexico, practice a multiple-layer cropping system utilizing up to 75 species in onehectare plots that produce crops for 5-7 years. As soil fertility wanes, the Lacandon plant tree crops (cacao, citrus, rubber, avocado) that provide valuable products as the plots regenerate with secondary forest. This forest is cut again when the trees overgrow the managed species. It is estimated that only 10 hectares of rain forest are consumed per farmer throughout his career with this method of sustained agroforestry. In contrast, immigrant colonists consume two or three times as much forest area (Nations and Komer, 1983).

Newer systems build on these local methods by incorporating trees and bushes in erosion-control strips, hedges, nitrogen-fixing trees in fields, and cash and fodder crops (e.g., see, Winterbottom and Hazelwood, 1987; Dover and Talbot, 1987; Kidd and Pimentel, forthcoming 1991; and OTA, 1984). For example, a typical agroforestry system in steep uplands with poor soils in Himachal Pradesh, India, is stocked with 20.5 trees/ha, which produce a yield of 2.0 m³/ha/yr of wood, or 0.8 t C/ha/yr, plus the potential savings of roughly a 5:1 ratio of hectare of virgin forest retained intact per hectare converted to permanent cultivation. A more intensive stocking rate of 322 trees/ha in home gardens in Surakarta, Indonesia, yields 7.3 m³/ha/yr wood, or 1.9 t C/ha/yr. Data from Indonesia and Tanzania indicate that 200-300 trees are sufficient to provide wood production needs of a typical household (Lundgren and van Gelder, 1984). An overview of potential carbon cycle benefits from a range of agroforestry systems is presented in Table 5-18, and a summary of greenhouse gas reduction potential implications of agroforestry is given in Table 5-19.

Obstacles to substituting agroforestry for traditional agriculture include the need for suitable environmental conditions (soils and rainfall), and human population densities and institutions adequate to encourage multi-year resource management. Either overcrowding

Comparison of Land Required for Sustainable Versus Swidden Agricultural Practices

Sustainable Agricultural Practices	Number of Swidden Hectares Required for Every One Hectare of Sustainable		
Flooded rice	11.0		
Low-input cropping (transitional)	4.6		
High-input cropping	8.8		
Legume-based pastures	10.5		
Agroforestry systems	not determined		

Sources: Derived from 17-year ongoing research by North Carolina State team at Yurimaguas, Peru, in tropical moist lowland forest (Sanchez, 1988; Sanchez and Benites, 1987).

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Potential Carbon Fixation and Biomass Production Benefits from Representative Agroforestry Systems

Type of System	Location	Trees Per Hectare	Productivity (t C/ha/yr)	Species Used	Products Produced
Natural forest management and crops	Guesselbodi forest, Niger		0.8	native shrubs (Combretum micranthum, Guiera senegalensis)	wood, mulch, crops, gums, fodder, medicines
Steep uplands, poor soils system	Himachal Pradesh, India	20.5	0.8		fuelwood, fodder, crops
Alley cropping	IITA, Nigeria		0.9-3	nitrogen-fixing shrubs (Glicidia, Leucaena, Calli- andra, Sesbania)	maize in alleys between hedgerows cut for mulch and stakes
Home gardens	Surakarta, Indonesia	322	1.9		fruit, fodder, mulch fuelwood
CARE Agrofor- estry and Re- source Conser- vation Project	Guatemala	400	4.7	conifers (high- lands), hard- woods (lowlands). 20 species in total	fuelwood, fodder, crops

Note: Soil carbon storage benefits are not available, and may be significant.

Sources: Winterbottom and Hazelwood, 1987, and WRI and IIED, 1988 (Niger, Nigeria); Lungren and van Gelder, 1984 (India, Indonesia); Trexler et al., 1989, and WRI, 1988 (Guatemala).

Assessment of Potential Reductions in Greenhouse Gases from Large-Scale Substitution of Agroforestry for Traditional Swidden and Monocultural Agriculture

Source of Gas	Gas	Potential Effect of Agroforestry
Clearing of forest	CO ₂ , CH ₄	Sustainable agroforestry would provide fuelwood and fodder, reducing forest clearing for unsustainable cropping and biofuels
Biomass burning	CO ₂ , CH ₄ , N ₂ O, CO, NO _x	Displacement of shifting cultivation would free forest fallow for reforestation and carbon fixation in biomass and soils
Cultivation and degradation of soils	CO ₂	Reduced disturbance of soils during plowing, reduced introduction of mulch to soils, and reduced erosion should increase carbon storage in soils
Denitrification by soils	N ₂ O	Agroforestry could reduce denitrification by improving soil chemical and physical properties
Denitrification of nitrogen fertilizer	N ₂ O	Agroforestry could substitute symbiotic fixation for fertilizer use, reducing N_2O emissions
Denitrification by Rhizobium	N ₂ O	Use of nitrogen-fixing tree species with associated soil and by root Rhizobial symbionts could facilitate denitrification

Source: Adapted from Franz, 1989.

or pervasive poverty will shift the focus to short-term survival. Social and economic factors likely to promote success include clear and relatively equitable land tenure for farmers, local decision-making, political systems that at least tolerate medium-term investment by villagers of various classes, developed and accessible markets for crop and forest products, and adequate protection of agroforestry systems from grazing livestock, villagers, civil strife, and rapid economic changes (Winterbottom and Hazelwood, 1987; IIED and WRI, 1987).

Constraints to wide diffusion of agroforestry include the difficulty of technology transfer to remote populations with traditional values that do not encourage innovation, the need for systems tailored to site-specific conditions, capital requirements to purchase and maintain seedling nurseries and to fund extension efforts and research, and the vast scale of implementation necessary to slow degradation forest (Lundgren and van Gelder, 1984). The longterm sustainability of new agroforestry systems has not been fully demonstrated in many firstgeneration projects, which often still rely upon high levels of fertilizer and labor.

Option 2: Reduce the Frequency, Interval, and Scale of Forest and Savannah Consumed by Biomass Burning as a Management Practice

Techniques to reduce the frequency, interval, and scale of forest and savanna burned during management for livestock grazing and for forest land conversion to agriculture and grazing may offer significant benefits in decreasing emissions from biomass burning. Little analysis of this potential has been performed. Another option may be to expand fire risk management on selected pasture and forest lands already under intensive management in the dry tropics through technology transfer. This option may be feasible as a new best management practice that alters burning frequency or extent enough to reduce greenhouse gas emissions. No detailed discussion of how such an expansion for climate change purposes could be achieved, and its benefits, is currently available.

Relevant examples of potential fire management practices include fire (and grazing) protection of abandoned pasture land around Guanacaste National Park, Costa Rica, to allow natural regeneration of dry forest (Jansen, 1988a, 1988b; see below), and fire protection as a component of the CARE/AES Guatemala forestry project designed to offset CO₂ emissions of an electric plant in Connecticut (Trexler et al., 1989; see below). In Brazil, the federal environmental agency IBAMA launched a vigorous burning management program in the dry season of 1989 in which the space agency INPE identified areas being burned through sensing; a helicopter remote with environmental police was then dispatched to the site within 6 hours to ascertain if a burn permit had been obtained and to levy fines. IBAMA has indicated that this enforcement program, along with the unusually long wet season, contributed to a major reduction in number of fires and area burned in 1989, although the program is being challenged in court at present and no fire fines have been collected as yet (Setzer and Pereira, 1991; U.S. EPA, 1989; Prado, 1990). Results of the 1990 dry season burning rates are eagerly awaited by analysts and IBAMA.

The constraints in limiting burning are many, including the low level of management often associated with grazing lands, highly decentralized land use and ownership, and ecological reliance on burning to stimulate nutrient flow and primary productivity of grasslands. Exploratory analysis of biomass burning response options is needed.

Option 3: Reduce Demand For Other Land Uses That Have Deforestation as a Byproduct

Large development projects, especially those planned in the tropics by transnational corporations and multilateral development banks, consume huge tracts of forest for roads, hydroelectric project reservoirs, and new communities. For example, the Mahaweli project in Sri Lanka will destroy 260,000 ha of tropical moist forest in order to generate 466 MW of electric power and provide flood control and irrigation benefits. The Narmada Valley Project in Madhya Pradesh, India, may inundate 350,000 ha of teak and bamboo forest (Kalpavriksh, 1985).

Pressure on banks and governments to reduce adverse impacts on tropical forests has mounted since 1980 and spawned new development planning methods that include protection of forest tracts in order to offset consumptive use of other forested lands (Rich, 1989; Gradwohl and Greenberg, 1988). In 1986, the World Bank issued a new sixelement policy on wildlands to guide planning of Bank development projects. This policy states preference for choosing already degraded (e.g., logged over) and least valuable lands for development purposes. It requires compensation for wildlands converted by Bank projects in the form of an added wildlands management and preservation component (Goodland, 1988; World Bank, 1986). India experimenting with compensatory is reforestation at a 2:1 replacement ratio for forest cut for hydro projects. Compensatory mitigation planning for forest areas during development project design can be expanded as a response option, although problems still remain with such approaches, including management responsibility over long time frames and potential productivity rates of new compensatory forests.

The probability of forest loss along transportation corridors and in settlement projects in Indonesia has been quantified by Soemarwoto (1990) based on data on population pressures, carrying capacity of given land tracts, and targeted standard of Several policies and practices with living. potential to reduce forest loss in new planned settlements, like the huge transmigration projects in Indonesia, were noted by Soemarwoto, including: increasing the agricultural production per unit area by improving technological inputs, introducing crops with high market values, increasing offfarm income, reducing the number of farmers alternative employment providing by opportunities through economic diversification, and reducing the population growth rate.

Forest loss for creation of new pasture in Amazonia has been estimated for 1970 to 1990 at 17.5 million ha, emitting about 2.6

billion tons CO_2 , resulting in a net loss (after accounting for growth of new biomass in pastures of about 10 tons/ha/yr) of about 2.4 billion tons CO₂ (Serrao, 1990). Response options identified by Serrao (1990) to slow this conversion include intensifying cattle production on pasture already degraded, using appropriate technology like second-cycle silvo-pastoral pastures and systems: regenerating degraded pasture with economic tree species offering additional income; and increasing use of existing natural grassland ecosystems, now undergrazed, to reduce demand for new pasture land.

Option 4: Increase Conversion Efficiencies of Technologies That Use Fuelwood

Fuelwood demand from tropical dry and moist forests accounts for significant deforestation, although often biomass is obtained from "invisible forests" around villages, such as trees in densities so low that they are not reported as forest area in government statistics. Household biofuel cooking systems contribute an estimated 2-7% of the anthropogenic emissions of greenhouse gases (Ahuja, 1990). Wood supplies over 90% of total energy use in Burkina Faso, Malawi, Tanzania, and Nepal, 50% in Indonesia, 25% in China, and 20% in Brazil (Starke, 1988). Annual average fuelwood consumption for agricultural and industrial uses in Tanzania from 1979-80, for example, was 1.9 million m^3 of fuelwood, which released 0.5 million t C to cure tobacco, smoke fish, dry tea, fire pottery, and burn bricks (Mwandosya and Luhanga, 1985).

The introduction of more efficient cookstoves and industrial technologies could reduce wood requirements by 25-70% at very low cost (Goldemberg et al., 1987; Postel and Heise, 1988). Current cookstove greenhouse gas emissions of 2-7% may be halved at a cost of about \$12/ton C (Ahuja, 1990). The successful strategy for reducing most fuelwood-related deforestation in the long run may be the substitution for inefficient biomass burning cookstoves (5-12% efficiency) of more efficient stoves powered by kerosene (40%), electricity, and widespread gas, and distribution of cogeneration technologies to produce higher benefits from fuelwood use.

Technical and policy options available to improve stove efficiency and widely disseminate better stoves include identifying areas where biomass has a cash value and biomass loss rates are high, and then substitute kerosene or gas at subsidized prices. The Annapurna Conservation Project of the King Mahendra Trust in Nepal has established kerosene depots that sell fuel at fixed prices subsidized by permit fees collected from tourist hill trekkers, and required all trekking lodges in critical areas to replace biomass with kerosene (ACAP, 1988). Cash markets can be created for biomass through fiscal incentives and regulatory mechanisms to encourage use of improved stoves, fuelwood conservation, and fuel substitution. New portable, efficient stoves need to be mass produced in order to reduce the unit cost, and to create markets for the production and sale of low cost stoves. Stove dissemination should be linked to guaranteed, sustainablyproduced supplies of biomass from fuelwood plantations integrated into energy and resource management systems, which would reduce pressure on natural forests (EPA Cookstove Workshop, 1989).

Option 5: Decrease Production of Disposable Forest Products

developing Forests harvested in countries or managed in industrialized nations to generate wood products that are consumed and then burned or buried in landfills in the short term (e.g., newsprint, paper goods, and fast-food packaging) contribute greenhouse gas emissions. Work has begun on introducing technologies and programs to replace consumable forest products with durable goods that are used repeatedly and/or recycled, avoiding these emissions and providing carbon storage. Two major control options are discussed below.

Substitute Durable Wood or Non-Wood Products for High-Volume Disposable Uses of Wood. Current storage of durable wood products has been estimated at 6-10 billion m^3 of solid wood (2.6 Pg of carbon), or roughly 25% of world industrial harvest over the past 35 years (Rotty, 1986; Sedjo and Solomon, 1989).

The global forest industry has been stagnating for the past 15 years, as real prices have decreased, growth in consumption has shrunk, and competition on world markets has accelerated from developing countries. FAO (1986a) and Kuusela (1987), however, project annual growth rates of wood-based panels will be about 2.5-4.0% between 1985-1995, down from 6.9% between 1963 and 1975, but along with printing and writing paper the most quickly rising rate among wood products. Total world production of principal forest products for 1978-82 averaged 805.5 million t/yr, or about 0.4 Pg C/yr, and is projected to rise to a mean estimate of 1333 million t/yr (0.66 Pg C) by 2000.

Accelerated harvest and storage of wood products could provide one option for reducing demand for products from virgin forest and increasing supply from managed forests. For example, if production of all wood products was increased by 30% on average above the projected growth from 1982-2000, and this increase occurred through increased use of durable wood products, then production would rise to 1733 million t/yr, storing an additional 0.4 Pg C over the 18year period. Potential storage over the next 50 years to 2030 has not been calculated, but might reach a total of more than 1 Pg C.

Examples of potential product shifts from consumables to durables include eliminating the use of disposable chopsticks in Japan and elsewhere in favor of permanent wood or plastic ones; replacing single-use wooden crates and pallets with metal or plastic ones; and widely installing wood paneling in homes and commercial structures. To achieve net greenhouse gas emission benefits, production processes for durables must minimize generation of gaseous byproducts through use of energy conservation measures noted earlier in this chapter.

Expand Recycling Programs for Forest Products. Global production of newsprint, paperboard, and other paper averaged 334 million t/yr from 1978-82, with growth rates to 2000 anticipated at around 3% per annum (FAO, 1986a,b). In the U.S., consumption of all paper products in 1988 totalled 79.8 million tons. Post-consumer recycling of paper in the U.S. now provides 28% of domestic production of paper and paperboard, and totaled about 22.3 million tons in 1986 -- virtually twice the amount recycled in 1970 (U.S. EPA, 1988). Current obstacles to enhanced recycling rates include market development, regulatory, and financial issues (Ruston, 1988).

Recycling paper products in the U.S. could be pursued as a climate change response option. If, for example, recycling rose to 80% (with 10% diverted to [stored in] durable books or construction and 10% disposed of), then the difference between the number of tons burned or buried in landfills in 1986 at 28% recycling (about 57 million tons) and at an 80% rate (about 16 million tons) would equal 41 million tons/yr. Methane production from landfills (see PART TWO) and carbon emissions from incineration would decline. Paper products formerly treated as consumables would convert to essentially durable recycled products, thereby increasing the net total stock of carbon (assuming that forests previously used to grow wood for paper remain undisturbed).

Forestry Strategy II: Maintain Existing Sinks of Greenhouse Gases

Maintaining standing primary forests, with their generally high levels of biomass per unit area, offers significant advantages over planting new stocks, and may be highly costeffective.

Option 1: Conserve Standing Primary and Old-Growth Forests as Stocks of Biomass Offering a Stream of Economic Benefits

Maintaining some high-biomass forests as "carbon sinks" is likely to be far more efficient from a greenhouse gas cycle standpoint, more cost-effective, and less likely to generate negative side effects than the competing strategy of afforestation to fix carbon (e.g., Postel and Heise, 1987).

Old-gr 100-400 year-old) forests of Douglas f 5 species in the Pacific Northwest 6 have been suggested as carbon sinks thee they have high recreational and wildlife values (e.g., as habitat for the endangered spotted owl), and are declining rapidly in area. Old-growth forests offer higher carbon storage than managed forests per unit area, on average (Row, 1989).

In response to the debate about whether to continue harvest of old-growth forests or leave them as a sink, analysts have used computer simulation models to estimate the implications on global warming and carbon storage, by comparing biomass (carbon) in old-growth left standing with managed Douglas fir harvested and replanted with shorter rotation silvicultural systems (Row, 1989; Harmon et al., 1990). Results of the two studies differ. Row envisions net carbon sequestration from harvesting oldgrowth and replanting Douglas fir managed on 70-year rotations of 15.0 tons of carbon/ha over the first 70-year rotation, figuring that 15.5 tons of carbon would be emitted or lost during old-growth harvest; but 34.1 tons of carbon would be sequestered by the second growth, and 3.5 tons of carbon would be lost from the degradation (discarded, burned, or decayed) of forest products made from the harvested old-growth (the rest is assumed, questionably, to be sequestered in products).

However, Harmon et al. reach the opposite conclusion: old-growth harvest and replacement with managed stands would generate net carbon emissions, not sinks, due to soil carbon loss, reduced growth rates of new stands, and exaggerated claims of carbon storage in forest products. Thus, conservation of old growth stands in the Northwest (and presumably in other locations) may offer carbon storage benefits over replacement with managed plantations. Further analyses are required.

Option 2: Slow Deforestation by Introducing Natural Forest Management of Little-Disturbed and Secondary Tropical Forests

Natural tropical moist forests produce annual wood increments higher than managed forests on average (IIED and WRI, 1987; Wadsworth, 1983) due to the latter's higher harvest offtake volumes, minimal replanting success, and reduced biomass in regenerating forests. From a carbon-cycle perspective, this argues in favor of a two-prong forest management strategy managing virgin and secondary forests as sustainable high-biomass sinks, and managing fast-growth plantations for provision of forest products. Natural forest management (NFM) techniques (discussed below) can generate products and services that sustain indigenous and village populations otherwise engaged in forest felling, and serve as high-biomass carbon sinks. Natural forests comprise 83% (35 million ha) of the tropical forest under intensive management; only 7.1 million ha of intensively managed tropical forests have been planted or artificially regenerated (IIED and WRI, 1987). Hence, NFM, while requiring considerable investments of labor, may present the most viable long-run option for forestry on a wide range of tropical forest lands.

Net deforestation in an area results when demand for timber, fuelwood, or forested land exceeds the local supply and the productivity rates of forest lands allowed to regenerate do not keep pace with the harvesting of products. One key method of reducing demand for virgin or secondary forest is to introduce sustainable natural resource management techniques at the village and regional levels that provide a stream of forest benefits but minimize cutting of natural forest. McNeely (1988) and McNeely and Miller (1984) offer theory and case studies illustrating the economics of non-consumptive, integrated natural resource management.

NFM applies silvicultural techniques to allow smaller sustainable harvests of natural forests instead of traditional clear-cuts of large tracts that only maximize short-term profits. NFM may increase forest productivity and provides a wide range of non-wood products with high economic returns (e.g., nuts, herbal medicines, nature tourism operations; see Gradwohl and Greenberg, 1988). Extractive reserves are a newly evolved example of NFM in which economic products like nuts and rubber are extracted from forest reserves in Brazil. They maintain standing forest while providing jobs and wages to rubber tappers and nut collectors otherwise dependent upon income from logging.

The Malaysian Uniform System is a 60year NFM rotation technique developed to

rapidly regenerate harvested dipterocarp forest (lowland closed forest dominated by trees of the Dipterocarpaceae family) in peninsular Malaysia. Another method is the Celos Silvicultural System, practiced on long-term research plots in Suriname, which uses carefully planned logging trails and winches to reduce damage to standing trees during harvest from 25% to about 12%. Numerous small areas are cut on 20-year rotations rather huge than single tracts. and three improvement thinnings of non-target tree species and vines are made each rotation.

The Palcazu Development Project in Peru, funded by the U.S. Agency for International Development, has devised a system of active forest management that harvests thin swaths of forest 20-50 meters wide on 30-40 year rotations. Old-growth forest left surrounding the strips naturally provides seed dispersal after harvest, as in natural tree-gap regeneration processes, and maintains biological diversity lost in logging operations. Potential net profits after the wood is processed could be as high as \$3500/ha worked, according to estimates by researchers (Hartshorn et al, 1987).

NFM systems could be widely introduced via forest extension programs, bilateral and multilateral rural development projects, and integrated management of protected reserves and adjacent lands (e.g., the Biosphere Reserve concept of multiplepurpose protected areas combining preservation, research, and economic use zones [McNeely and Miller, 1984]). NFM offers a promising vehicle for maintaining high-biomass standing forest, slowing deforestation, and allowing the 54 million ha of forests already logged (WRI and IIED, 1988) to regenerate.

Option 3: Conserve Tropical Forests by **Developing Markets and Extractive Reserves for Non-Timber Products**

Multiple-use management of tropical forests has been introduced in NFM, Biosphere Reserve, extractive reserve, and other land management systems to employ sustainable timber harvesting, replanting, stand improvement (release cutting), and forest protection to confer benefits from timber sales, recreation, and flood control. Fully 16% of tropical moist forest species have non-timber economic benefits according to one recent survey by IUCN (IIED and WRI, 1987). For example, minor forest products like rattan, latex, resins, medicinal plants, and bamboo contributed \$150 million to Indonesia's economy in 1982 (Repetto, 1988).

Recent research has shown that tropical deforestation, based solely on the value of the wood products, does not make financial sense. Perpetual, sustainable fruit and latex (rubber) harvest offers far larger economic returns than timber felling, plantation planting, or cattle grazing on the same land parcel. The net present value of future yields of a hectare of species-rich Amazonian forest in Peru was calculated by Peters et al. (1989) as \$6330 per hectare if fruits and latex are sustainably harvested, as \$1000 if all merchantable trees are harvested at once (but \$0 if as few as 18 fruit or latex were damaged during harvest), as \$490 if periodic selective timber cutting occurred, as \$3184 if the hectare of forest was converted to a plantation of Gmelina arborea managed for timber and pulpwood, and as \$2960 if converted to cattle pasture. The combined financial worth of this hectare is given as \$6820, of which 90% is the market value of fruits and latex (see Table 5-20).

Option 4: Improve Forest Harvesting Efficiency

Commercial forest management, especially in tropical forests with extremely high species diversity per hectare, has targeted harvesting on only about 5% of species. Reasons for this high-grading -- selective of high-value trees -- include cutting tradition, lack of demonstrated uses and markets for other species, and the availability of virgin stands open to resource "mining" management and without costly with government support. As a result, fully 85% of total wood produced from tropical natural forests in 1970 went unused, left as slash or wasted at the mill (Goldemberg et al., 1987).

A survey of Malaysian and Indonesian logged forests recently found that 45-75% of standing trees had been injured (Gillis, 1988). In southeast Amazonia, remote sensing study has revealed that while 90,000 km² had been

clearcut by 1985, three times that area (266,000 km²) had been seriously damaged by logging and colonization (WRI and IIED, 1988; Malingreau and Tucker, 1988). Improvements in forest management would reduce waste of non-target species damaged during logging (e.g., the Celos Silvicultural System, discussed under NFM options).

Efficient harvesting would require less virgin and mature secondary forest to be cut (Mergen and Vincent, 1987). Malaysian government policy has raised the number of commercial tree species for harvest from 100 in the mid-1960s to over 600 today (IIED and WRI, 1987). The harvest and marketing of under-used species and size classes throughout the tropics, encouraged by government regulations and forestry company practices, could reduce tree losses from harvest and improve stand yields more than silvicultural innovations could, especially in secondary forests (OTA, 1984).

Option 5: Prevent Loss of Soil Carbon Stocks by Slowing Erosion in Forest Systems During Harvest and from Overgrazing by Livestock

See Option 9: Increase Soil Carbon Storage by Leaving Slash Harvest and Expanding Agroforestry below.

Forestry Strategy III: Expand Sinks of Greenhouse Gases

Option 1: Increase Forest Productivity: Manage Temperate Natural Forests for Higher Yields

Modern forestry management techniques, including biotechnological (genetic) improvement of selected species, applied to commercial, state, and large private forest lands offer the greatest potential for largescale increases in productivity.

In the U.S., new forest area growing at average rates would not be sufficient to offset our current annual production of 1.3 Pg C. Per capita annual carbon production for 237 million Americans is about 5 t C/capita. U.S. commercial forests (those producing greater than 1.4 $m^3/ha/yr$ and not set aside in parks) totaled 195.3 million ha in 1977, with a net

Value of One Hectare of Standing Forest in Amazonian Peru Under Alternative Land Uses

Land Use System	Net Present Value of Perpetual Stream of Forest Products
Sustainable harvest of fruits and latex	\$6330
Clearcutting merchantable timber (not damaging fruit trees)	\$1000
Clearcutting merchantable timber (damaging >18 fruit trees)	\$0
Converting forest to Gmelina arborea timber/pulp plantation	\$3184
Converting forest to cattle pasture	\$2960
Total estimated value of hectare's forest products	\$6820

Source: Peters et al., 1989.

average growth rate of $3.15 \text{ m}^3/\text{ha/yr}$, or 0.82 t C/ha/yr. Thus, 6 ha (15 acres) of forest would be required to sequester each person's fossil-fuel emissions. For 237 million people this would require 1.5 billion ha of average forest -- a tract 50% larger than the 0.9 billion ha land area of the country (Marland, 1988).

However, intensive forest management to increase biological productivity or economic returns on forest land may offer a partial solution. Presently, it remains unclear whether increased stocking of existing stands is likely to significantly increase total biomass, or simply provide economic incentives that increase the volume of merchantable timber and hence store additional carbon by encouraging more intensive management and shorter rotations of larger stocks.

The U.S. Forest Service (USFS) estimates that if current commercial forests simply were fully stocked (i.e., they were universally managed to grow the tree densities and volumes of mature stands), their net annual growth could be increased by about 65%, which would sequester 0.1 Pg C/yr (USFS, 1982). This full stocking option is appealing, since many areas not presently growing forests are sites so poor that even intensive management or aggressive planting are likely to provide only negligible net annual growth (USFS, 1982). Forest Service estimates also indicate that forest owners could go further by managing forests to take economically advantage of feasible opportunities that would offer a 4% annual These management return on investment. options could produce an additional 18 billion cubic feet of annual forest growth, equal to 0.16 Pg C (327 million t wood) (Hagenstein, 1988; Moll, 1988).

Intensive management techniques that improve productivity include site-specific species selection (through provenance trials with seeds), thinning and release cuttings, control of spacing among trees, weed and pest fertilization, fire suppression, control, planting of genetically and irrigation, improved seedlings. All options requiring significant labor tend to be prohibitively expensive if implemented on large scales; however, access to volunteer labor from youth or citizen groups might make these options more feasible on some lands, especially those publicly owned.

Timber stand management measures to assist forests in adaptation to climate change conditions may accelerate the natural processes of change in ecosystems expected under increased temperatures and water stress, thereby allowing silvicultural intensification as a mitigation option.

By harvesting potential mortality prior to its occurrence, managers can increase production of merchantable volume, and allow accelerated conversion of a stand to the suite of species in the forest best adapted to a new climate, according to stand simulation results for a northern hardwood forest in New York State (Larson and Binkley, 1989; see also Kellomaki et al., 1988). Model results for 6 scenarios over 120 years in managed and unmanaged stands are summarized in Table 5-21. An increase in soil moisture in this northern stand drops productivity sharply. However, adaptive management techniques produce far greater merchantable volume than productivity achieved in unmanaged conditions, suggesting the benefits to commercial management -- and thus to increased carbon storage, indirectly -- of intensive management.

A country-level case study of Finland (reported in AFOS, 1989) reviews growth and carbon storage of pine, spruce, and birch in southern Finnish forests under existing climate and management (i.e., planting density, thinning, and harvest regimes), more intensive management, and altered climate (assuming a warming of 2°C for mean in growing season) temperature and Results reveal that Finnish management. forests could store 273 million tons more carbon in aboveground biomass in forests by altering management techniques -- a carbon figure equal to total Finnish emissions of carbon from fossil fuels during the next 39 years (if carbon emissions remain constant at 7 million tons per year). However, the warming considered might stimulate tree growth such that 470 million tons additional carbon could be sequestered in forests -equivalent to Finnish fossil-fuel use for the next 67 years. Altered management practices

Effects of Adaptive Forest Management Activities on Production of Merchantable Volume for a Northern Hardwood Forest Under Two Climate Change Assumptions

Warm/Wet Scenario	Managed	Unmanaged	Difference
Base (present)	4.97	4.03	0.94
Warm Scenario	7.57	5.93	1.64
Warm/Wet Scenario	3.16	0.74	2.42

Note: Volume = mean annual increment, $m^3/ha/yr$, for trees >18 cm.

Source: Binkley, 1990, based on Larson and Binkley, 1989.

would be capable of increasing carbon sequestration more than natural increases from CO_2 enrichment.

Other stand management options potentially available to assist forests in adaptation to climate change stresses and to increase stand productivity include:

(a) Introducing drought- and pestresistant species, including exotics (e.g., Nilsson, 1989),

(b) Changes in harvest practices and rotation lengths. Rotation lengths could be shortened to allow for a faster response to changes in stand productivity (e.g., Nilsson, 1989) and to harvest impending mortality via more frequent and intensive thinnings (Kellomaki et al., 1988). Planting species or genetic strains better adapted to impending changes in site conditions is widely recommended. Coniferous plantations will probably need more intensive tending to thwart increasing competition from broadleaved species, and pest management will need to be intensified (Kellomaki et al., 1988).

The economics of fertilization on large tracts varies. For many species and sites, the costs of chemical fertilizers exceed the amount of growth stimulated. Yet according to Ford (1984), "fertilization is the most important single treatment that the forest manager can apply during the growth of the crop to accelerate growth." More than half of the loblolly pine plantations in the Southeast would show value-added growth from fertilization, according to one observer (Binkley, 1986).

Obstacles to use of fertilizers include low nutrient recovery rates for trees due to leaching and microbial activity, the nutrient status of the site, and whether slash is removed from the site during harvest (tropical forests store 90% of available nutrients in biomass and only 10% in soils, compared with about 3% for temperate forest biomass) (Marland, 1988; Ballard, 1984). Increased fertilizer use would probably increase emissions of N₂O (see **PART FIVE**), and may interfere with CH_4 uptake by soils, leading to increased CH_4 fluxes from forestland soils. Further, a net analysis of the benefits of fertilizer use from a greenhouse standpoint has yet to be undertaken, but should include the releases of CO_2 during manufacturing and transport of fertilizer.

Nitrogen-fixing legume species, like black locust and honey locust in the U.S. and *Leucaena* and *Calliandra* in the tropics, offer the advantages of supplying their own nutrient requirements, thus growing well in the depleted soils of degraded lands and cutting fertilizer costs.

Other constraints to intensive management include the need for very short rotations to maintain high growth rates and associated labor costs, the need to sequester large volumes of harvested wood, pest and genetic diversity problems associated with monocultural stands, costs of energy and labor for plantations, the tradeoff between maintaining large volumes of standing biomass and fast growth rates, and fire management costs.

Option 2: Increase Forest Productivity: Plantation Forests

Plantation biomass productivity can be improved by three types of actions:

1. Silvicultural practices that yield biomass gains, especially in industrialized country forests,

2. Lengthened and stabilized land tenure for commercial and community forestry projects in developing countries, to encourage forest management for multiple (rather than single) rotations and the ensuing environmental benefits, and

3. Biotechnological advancements utilizing genetics and seed selection.

This discussion focuses primarily on biotechnology and genetic potential, since silvicultural management is addressed below and land tenure considerations are discussed in Chapter VIII.

Plantations managed to grow a mix of short-, medium-, and long-rotation species, if site conditions allow, are most likely to provide the continuous stream of forest products and income necessary to meet timber and fuelwood demand in developing country villages. Similarly, mixed-stand (multiple species) plantations in temperate zones may reduce ecological problems (e.g., pest infestations) and timber market disruptions, although mixed-stand plantations may require more intensive management and harvest techniques.

Applied genetics or tree improvement may produce greater increases in yields of biomass than improved silvicultural methods, Short-rotation intensive culture (SRIC) efforts apply intensive agronomic practices to growing selected and/or genetically improved hardwood species in plantations to achieve maximal productivity rates at competitive costs. The Department of Energy's Short-Rotation Woody Crops Program, begun in 1977, has conducted field trials to boost productivity and reduce costs of woody species managed under SRIC as an energy source. Its target is to achieve average productivity of 20 dry t/ha/yr (10 t C/ha) of biomass at a cost of \$2.25/GJ on optimal plots by 1995, and a competitive technology 5 years later.

By 1987, productivity reached 13 dry t/ha/yr (6.5 t C/ha) at a cost of \$55/dry t, or \$3.25/GJ (ranging from \$2.90 to \$5.10 delivered), on Soil Conservation Service (SCS) site class I-III soils (i.e., largely fertile Planting densities ranged from and flat). 2500-4000 trees/ha, on coppice rotations of 5-8 years. Ongoing research is focused on four species (silver maple, sweetgum, American sycamore, and black locust) and one genus (Populus, including cottonwood, poplar, and aspen). Collectively, average SRIC growth rates have reached about 9.5 dry t/ha, or 4.7 t C/ha. Rates as high as 12-14 t C/ha have been documented for exotic or hybrid trees (Ranney et al., 1987).

Other species with high potential for plantation biomass production include wood grass (*Populus*), grown at densities of about 1700 trees/ha for 4-year rotations, and 25,000 trees/ha for 2-year rotations (Shen, 1988). Kenaf, an African annual crop closely related to hibiscus, grows to 6 meters in 120-150 days after seeding, and can produce 3-5 times more pulp for paper than trees on an annual basis, which potentially frees forests for biomass production and carbon storage. Field trials in Texas by the U.S. Department of Agriculture (USDA) have found that kenaf grows well without pesticides in the Cotton Belt and with irrigation in the drier Southern states, and requires less chemical input than wood to produce and whiten pulp. Ninety percent of its original weight can be converted to usable fiber (Brody, 1988).

Working with tropical species in Espirito Santo, Brazil, the Aracruz Pulp Company has produced eucalyptus hybrids with 30% increased height and 80% improved diameter at breast height (dbh) compared to parent trees at four years through selection of parent tree seeds, breeding for desired characteristics, and planting into specific microsites. Average yields of 70 m³/ha/yr (18.2 t C/ha/vr) for 14 million trees per year grown from rooted cuttings of 54 species have been achieved, and yields of 100 m^3 (26 t C) or greater are projected. Stands are managed for bleached pulp and charcoal for steel making. The trees reach 20 meters in height in less than three years (OTA, 1984; IIED and WRI, 1987). Other trials with eucalyptus from 32 sites in 18 countries have generated productivity gains of several hundred percent simply by matching optimal seed characteristics with site soil and microenvironmental conditions (Palmberg, 1981).

Pine breeding for straightness, reduced forking, and drought resistance, coordinated by seed cooperatives in Latin America and Europe, is showing significant improvements. Other tree-improvement methods include seed orchards that rely on grafting and rooted cuttings to produce clones of trees, but these methods are limited to only a few species. Tissue culture (manipulating sprouts from germinating seeds) is still in its infancy in forestry, although the Weyerhaeuser Corporation in the U.S. Northwest soon plans to produce 100,000 clones of Douglas fir per Research on producing cell culture year. embryoids (microscopic infant trees) is underway in major developed countries on temperate species, and early work on teak and Caribbean pine is encouraging (IIED and WRI, 1987).

Table 5-22 surveys productivity increases from intensive management and applied genetics for selected species in the U.S. and in the tropics.

The implications for carbon fixing are clear. A 30% rise in biomass production allows 30% less land in forest, or a 30% offtake of fuelwood or timber to achieve the same results. Drought-resistant strains would encourage forest sector and donor community investment in arid and degraded land projects.

The potential benefits of productivity increases on plantation forests are currently limited by the slow pace of research and field trials on promising species and varying site conditions. Eighty-seven percent of plantation forestry in the tropics focuses on species of only 3 types: pine, teak, and eucalyptus (Vietmeyer, 1986). Obstacles to expanding plantations are reviewed below.

Option 3: Expand Current Tree Planting Programs in the Temperate Zone

Forested area in temperate and boreal zones is considered roughly constant in most studies but may be declining in this decade (Houghton, 1988a). The U.S. had an estimated 445 million ha (1.1 billion acres) of forest land circa 1630. By 1987, forest area had declined to 296 million ha (731 million acres), still 32% of our land area. However, forests were much larger temperate historically and could be expanded. Some European countries have increased their net forested area: France was 14% forest in 1789; today, 25% of France is forested (Postel and Heise, 1988).

According to the Forest Service, total U.S. tree planting by federal and state agencies revegetated 1.2 million hectares (3 million acres) in 1987 (USFS, 1987). Table 5-23 lists the five major tree-planting programs in the U.S. since 1935 and the number of acres planted in their highest 5-year period.

If current programs planted 1.2 million ha with existing financial and programmatic incentives geared to replacement levels of planting, then additional enticements on the order of \$220-345/ha (\$90-140/acre) would probably stimulate tree planting on hundreds of thousands of hectares. The Conservation Reserve Program of USDA (see below) paid an average of \$219/ha (average rental payment of \$125/ha or \$50/acre plus half of establishment costs at an average of \$94/ha) to plant 850,000 ha of trees (2.1×10^6 acres) from 1986 to mid-1988. Youth groups could be mobilized to plant trees annually on Arbor Day or during weekend or summer work camps.

Large-scale reforestation by individuals, companies, and/or government programs has been proposed as a possibility in temperate zones. However, this would be far less cost effective (by perhaps a factor of 3-10) than in the tropics because of higher land costs and slower tree growth. Recently, more targeted proposals for tree planting in the U.S. focus on use of croplands that are considered surplus during periods of diminished exports and high-cost land for farm support programs.

Option 4: Reforest Surplus Agricultural Lands

Reforestation of economically or environmentally marginal ("surplus") crop and pasture lands has been proposed as the quickest, most cost-effective way to stimulate tree planting at the scale necessary to partially offset CO_2 emissions (Dudek, 1988b; Postel and Heise, 1988; Andrasko and Tirpak, 1989; Moulton and Richards, 1990; USFS/EPA, 1989). Planting tree carbon sinks may be comparatively cheaper than other current CO_2 -limiting options, for example, planting short-rotation biomass energy plantations, investing in energy conservation measures, or scrubbing CO_2 from industrial emissions (Dudek, 1988a,b).

The most commonly suggested model for afforestation is the Conservation Reserve Program (CRP) administered by USDA. The CRP was established by the conservation title of the Food Security Act of 1985 to retire highly-erodible cropland, reduce production and boost prices of surplus food commodities, and reduce Treasury outlays. Participating landowners contract to retire cropland for 10 years. They are reimbursed for 50% of the costs of planting the necessary vegetative cover, and receive an annual rental payment.

Productivity Increases Attributable to Intensive Plantation Management

Management Technique	Maximum Mean Annual Yield (Tons carbon/ha/yr)
Douglas Fir in Washington	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
Natural stands	2.8
Silvicultural treatments	
Plantation establishment	3.6
Nitrogen fertilization	4.4
First-generation genetics	4.9
TÄRGET	12.5
Loblolly Pine in North Carolina Pocosins	
Natural stands	1.8
Silvicultural treatments	
Drain and plant	3.5
Bedding	4.3
Preplant phosphorus	5.3
Nitrogen fertilization	5.9
First- and second-generation genetics	7.2
TARGET	15.0
SRIC Hardwoods, Various Sites in U.S.	
Short rotation, genetics, site preparation, fertilizer, coppicing	6.5
TARGET for year 1996	10.0
Energy Crop Plantations, Temperate Zone Intensive management, mixed species;	
TARGET for year 2025	24.7
Eucalvotus Hybrids in Espirito Santo. Brazil	
Seed selection, breeding, microsite planting	18.2
TARGET	26.0

Source: Based on Farnum et al., 1983, and Marland, 1988 (Douglas fir and loblolly pine); Ranney et al., 1987 (SRIC hardwoods); Walter, 1988 (energy crop plantations); WRI and IIED, 1988 (Eucalyptus).

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TABLE 5-23

Land Planted (x 10⁶) Period (Highest 5 years) (hectares) Program (acres) Civilian Conservation Corps (CCC) 1935-39 1.4 0.6 1957-61 2.0 0.8 Soil Bank **USDA-Forest Service Reforestation** 1979-83 1.5 0.6 Forestry Incentive Program (FIP), Agriculture Incentive (ACP) 1978-82 0.4 1.1 1986-90 projected Conservation Reserve Program (USDA) 5.6 2.3 1986-89 actual 2.0 0.8

Summary of Major Tree Planting Programs in the U.S.

Sources: Conrad, 1986; USDA, Land Retirement and Water Quality Branch statistics on conservation Reserve Program enrollment, November, 1988.

Participation in the tree-planting program was targeted at 12.5% of projected total retired acreage (16.2-18.2 million ha, or 40-45 million acres by 1990), or about 2.3 million ha (5.6 million acres). However, treeplanting enrollment totals only 0.40 million ha (of 10.5 million ha enrolled in CRP by November 1988), mostly in Southern states already producing plantations of loblolly pine in favorable soils and climate. Planting rates have been low due to low bid prices, reluctance of farmers to lose base acreage in programs, federal crop support and inadequate support for tree planting by extension offices. Better financial incentives (i.e., higher bid prices, higher share of planting costs paid) and open, continuous enrollment opportunities may greatly increase tree acreage enrollment.

For example, all new CO_2 emissions from fossil-fuel electricity plants projected for 1987-96 could be offset by planting trees (see Table 5-24). Estimates of planned increases in fossil-fuel electric generating capacity for 1987-96 total 25,223 MW, producing 45.5 Tg C (equivalent to 166.7 million tons CO_2) (NAERC, 1987).

The uptake of CO_2 varies by species. Silver maple, for example, a relatively inefficient species, absorbs 5 t C/ha/yr under optimal conditions, while American sycamore absorbs as high as 7.5 t C/ha/yr (Steinbeck and Brown, 1976; Marland, 1988). Depending upon the species chosen, it would take between 4.5-13 million ha of short-rotation (4-5 years) monocultural plantations on good sites to offset the planned 25,223 MW of additional fossil-fuel electricity.

Mixed stands of numerous tree species are more desirable to prevent ecological problems associated with monocultural stands such as increased pest populations, low species diversity, and vulnerability of evenaged stands. The acreage requirements for mixed stands to offset 45.5 Tg C could rise to 13 million ha (32 million acres), or about 70% of the total enrollment target for the 10year CRP program. Further analyses are underway to consider availability of productive soils, variations in actual site characteristics, and mixed-stand productivity rates (e.g., AFA, in press).

USDA's share of costs for establishing trees on CRP acres averages \$94 per hectare, plus rental payments averaging \$125 per ha per year for the 10 years of the current CRP. If the full costs of the planting are assumed to be \$370/ha, and fertilizer costs are \$62/ha, then the mid-range estimate of 9.1 million ha of trees added to the CRP would cost \$3.9 billion to establish (\$3.1 billion if current average USDA cost-share expenditures continued). Rental payments by USDA or utilities, estimated to rise to about \$250/ha/yr, would need to continue over the 50-year life of the electricity plants whose emissions would be offset. Some lands not presently producing timber or crops might be available for afforestation. In 1976, the U.S. had 70 million ha (173 million acres) of land out of production with average rainfall greater than 50 cm/yr. Although the land was used for recreation or other purposes, it may offer suitable (although not optimal) habitat for tree planting (Fraser et al., 1976). Any additional lands required would have to be diverted to forestry from other competing land uses.

U.S. EPA developed a national plan to offset 10% of current U.S. emissions of CO_2 in June, 1989, called "Reforest America" (Andrasko and Tirpak, 1989) that identified five program components: 1) federal lands (planted with new trees or more intensively managed), 2) rural surplus agricultural lands (planted), 3) urban parks, residences, and commercial buildings (planted), 4) private timberlands (more intensively managed), and 5) Conservation Reserve Program lands (private croplands enrolled in a USDA program, and planted). The plan estimated that 10-20 billion trees would need to be planted on 5.7-10.5 million ha (14-26 million acres), and 13.8-23.5 million ha (34-58 million acres) of forest managed more intensively to fix 81-127 million t C/yr at a federal sector cost of \$146-193/yr (plus private sector costs).

Moulton and Richards (1990) have performed the most sophisticated analyses thus far to estimate the cost per ton of carbon sequestered by tree growth in largescale afforestation programs for lowest-cost pasture and crop lands in the U.S., summarized in Figure 5-13. "Trees for U.S.," a federal government executive branch

Estimates of CRP Program Acreage Necessary to Offset CO₂ Production from New Fossil Fuel-Fired Electric Plants, 1987-96, by Tree Species or Forest Type

Tree Species/Forest Type	Carbon Fixing Rate Used (t C/ha/yr)	Land Requirements Hectares	for Offset (million) Acres
Average growth U.S. commercial forests 1977 (USFS, 1982)	0.82	55.5	137.1
Average growth US commercial forests fully stocked (USFS, 1982)	1.35	33.7	83.2
Estimate for large mixed stands of moderate-growth species	3.5	13.0	32.1
Silver maple (Ranney et al., 1987)	5.0	9.1	22.5
SRIC program average productivity by 1987 (Ranney et al., 1987)	6.5	7.0	17.3
American sycamore (Marland, 1988)	7.5	6.1	15.1
SRIC program target for 1996 (Ranney et al., 1987)	10.0	4.5	11.1
SRIC program, highest documented from exotics (Ranney et. al., 1987)	13.0	3.5	8.6
Loblolly pine, target after genetics (Farnum et al., 1983)	15.0	3.0	7.4

Notes:

1. New fossil fuel-fired electric utility plant emissions are assumed to be 166.7 million tons CO_2 total for period 1987-1996 (or 45.5 Tg C) (Dudek, 1988a; NAERC, 1987). 1 metric ton $CO_2 = 0.27$ ton carbon.

2. 1 ton biomass = 0.50 ton carbon. 1 hectare = 2.47 acres. Units are expressed as metric (not English) tons/acre for comparison.

3. Rotations for all estimates are assumed to be 4-5 years.

4. The carbon fixation rates for silver maple and American sycamore differ from those cited in Dudek (1988a), following personal communication with Dudek.







proposal prepared by USFS and U.S. EPA in the fall of 1989, was built on "Reforest America" and work by Moulton and Richards. The proposal consisted of a four-component plan to (1) offset 1%, 2%, 5%, or 10% of U.S. CO₂ annual emissions through increased cost-sharing for the existing USFS Forest Incentives Program (FIP) and Agricultural Conservation Program (ACP), (2) plant community forests, and (3) use surplus lowcost pasture lands (theoretically available at 25-35% of the cost of rental payments for surplus crop lands). Total cost estimates are \$1-12.9 billion over 20 years (roughly \$50-210 million/vr, on average) for the 1-10% options, (USDA/U.S. respectively EPA, 1989). Analyses of options to use economic incentives to accomplish the program, impacts of such national afforestation programs on food and fiber supplies and prices, ecological implications, and the role of volunteerism in tree planting and maintenance have been undertaken or are in progress. Table 5-25 compares these recent estimates to other studies of costs and acreage requirements.

President Bush announced a major reforestation program as part of a broader conservation initiative (America the Beautiful) in January, 1990, based on the USFS/U.S. EPA analyses. The new tree plan calls for planting 1 billion trees per year for about 10 years, on 600,000 ha of private land. In addition, 30 million trees/yr would be planted in communities, and 73,000 ha/yr of private forest land would be more fully stocked or undergo timber stand improvement via a 50/50 federal/private cost-share arrangement. Total estimated cost of the program would be \$175 million/yr, beginning in the fall of 1990, approved by Congress. If fully if implemented, the plan would offset 1-3% of current U.S. CO₂ emissions after all trees are planted and mature -- a small but significant first step by a major greenhouse gas emitter to use forestry to slow CO_2 accumulation.

Australia announced its One Billion Trees plan in 1989, to restore its degraded subtropical and temperate forests, offset climate change, and conserve biodiversity. The plan entails planting 1 billion trees on 1 million ha by 2000, including 400 million in community planting, and 600 million in natural regeneration and direct seeding, plus a National Afforestation Program to establish hardwood plantations. Establishment costs are estimated at A\$300-2,000/ha, with a total of A\$320 million over 10 years. Carbon benefits are expected to be 6-10 million tons of carbon per year, and 300-500 million tons of carbon over the 50-year lifetime of the program (Eckersley, 1989; Hawke, 1989).

The stream of direct and indirect benefits that would accrue from afforestation, including timber harvest, reduced soil erosion and nonpoint source water pollution, increased recreational use, and increased wildlife have not been considered yet, and would tend to reduce costs attributed to climate change programs if utilities or farmers managed forested land for multiple uses. Quantification of these potential benefits is needed.

CO2 uptake rates might be increased through biotechnology improvements to perhaps 10 t C/ha/yr within 10-15 years (Ranney et al., 1987). Higher uptake rates would reduce both offset acreage requirements and costs. If economic hardwood species like American sycamore (used in flooring and millwork) and silver maple (for furniture and box and crate production) or softwoods (for lumber) are harvested for durable products, carbon storage would continue after harvest.

Option 5: Reforest Urban Areas

Urban areas, which currently contain 75% of the U.S. population on 28 million ha, are increasing by 0.53 million ha (1.3 million acres) per year (USDA, 1982). A study of urban forests in 20 cities found that for every four trees removed only one tree is planted, and for one-third of the cities, only one in eight trees lost is replanted (Moll, 1987). The total number of trees in Chicago dropped by 43,853 between 1979 and 1986. Trees planted per year declined from 24,675 in 1979 to 9,380 in 1980 (NASF/USFS, 1988; Open Lands Project, 1987).

An urban tree is about 15 times more valuable than a forest tree in terms of reducing CO_2 emissions. Trees break up urban "heat islands" by providing shade, which reduce cooling loads (air conditioning) in

Estimates of Forest Acreage Required to Offset Various CO₂ Emissions Goals

Estimate	Location	Carbon Sequester Rate Assumed (t C/ha/yr)	Offset Goal	Hectar es (million)	Total Planting Cost (\$ billion)	Average Cost/ha (\$)
		-				•
Dyson and Marland (1979)	Temperate Zone	7.5	5 Pg C (total annual fossil fuel use)	700		
Marland (1988)	Tropics	9.6	5 Pg C (total annual fossil fuel use)	500		
Myers (1988) ^a	Tropics	10.0	2.9 Pg (net annual increase C)	300	120	398
Sedjo and Solomon (in press)	Tropics or Temperate	6.2	2.9 Pg (net annual increase C)	465	186 tropics 372 temperate	395 800-1400 ^b
Woodwell (1987)	Tropics	5.0	1-2 Pg (net annual increase C from tropics)	200-400		
Postel and Heise (1988)	Tropics	6.8	0.7 Pg (C benefits from new fuelwood plantations and restored forests)	110		
Dudek (1988a,b)	U.S.	10-12	0.05 Pg (1987-96 new electric plant C)	3.4-4.5	1.6-1.9 ^c	432 ^c
EPA (this study)	U.S.	3.5-10	0.05 Pg (1987-96 new electric plant C)	4.5-13	1.9-5.6°	432 ^c
Andrasko and Tirpak (1989)	U.S.	4.4	0.12 Рд/ут	10.5 ^d	6.4	
USFS/U.S. EPA (1989)	U.S.	5.7 5.7	0.06 Pg/yr 0.12 Pg/yr	8.1 ^e 15.0 ^f	9.4 19.2	

a See also Booth, 1988.

b Includes \$400/ha land purchase cost.

c Assumes no cost-sharing of establishment costs and no annual rental payments (see text).

d Assumes 10.5 million ha planted and 23.5 million ha more intensively managed.

e Assumes 8.1 million ha planted and 4.3 million ha intensively managed.

f Assumes 15.0 million ha planted and 10.8 million ha intensively managed.

warm weather by reducing the building's heat gain, and cuts heating loads in cool weather by slowing evaporative cooling and increasing wind shielding. Three strategically placed trees per house can cut home air conditioning energy needs by 10-50% (Akbari et al., 1988). Trees planted as windbreaks around houses and buildings also can reduce winter heating energy use by 10-50% (Robinette, 1977). Thus, urban trees both sequester CO_2 and reduce consumption of fossil fuels, making strategic planting around buildings a small but efficient response option (Meier and Friesen, 1987). The American Forestry Association (AFA) recently conducted a survey of urban forest needs and launched in the fall of 1988 Project ReLeaf, which intends to plant 100 million trees in city streets, parks, and rural areas. Akbari et al. (1988) estimate savings of 40 billion kilowatt-hours of energy from these new trees, which would provide a carbon cycle benefit equivalent to 4.9 Tg C annually. This benefit would accrue from a combination of CO_2 absorption and reduced emissions from electricity generation.

Option 6: Pursue Afforestation for Highway Corridors

Highway corridors offer significant opportunities for tree planting, along 6.2 million kilometers (km) (3.9 million miles) of roads in the U.S. In 1985, 11.9 million ha (29.5 million acres) of land totalling 1.3% of the contiguous U.S. were in use as highways, including right-of-ways and buffer strips with 9.9 million ha in rural areas, and 2.0 million ha in urban areas (calculations based on average municipal right-of-way as 50 feet, reported in U.S. EPA, 1987; data from U.S. DOT. 1985). The North-Central states have 4.2 million ha (10.3 million acres) in roads, the South has 3.9 million ha, and the Northeast, 1.1 million ha, all regions with generally good site characteristics for tree planting. If, for example, an additional 10% of the 9.2 million acres of interstate, state, and local highway corridors in these regions were planted with trees, 0.9 million ha would be available -- about 10% of the roughly 9 million ha in trees necessary to offset new CO₂ emissions from powerplants from 1987-At average costs of 1996 (see above). establishment and fertilization of \$432/ha, total costs would approach \$390 million. If 20% of highway corridors were planted, 1.8 million ha (4.52 million acres) would be produced, at a cost of \$777 million.

Obstacles to planting highway corridors include safety and visibility concerns of state and federal departments of transportation, establishment costs (which should, however, be less than regular grass maintenance costs), and existing regulations.

Option 7: Reforest Tropical Countries

Numerous estimates have been made for tree planting desirable for economic, social, and environmental reasons unrelated to climate warming. One authority concludes that "at least 100 million hectares of tree planting worldwide appears necessary to restore and maintain the productivity of soil and water resources," an area equivalent to the size of Egypt (Postel and Heise, 1988). Major tree-planting programs are being promoted in many parts of the world, partly in response to a 1985 international initiative, the Tropical Forestry Action Plan (TFAP), jointly sponsored by the Food and Agriculture Organization (FAO), the United Nations Development Programme (UNDP), The World Bank, and World Resources Institute (WRI) (see CHAPTER VIII). In response to TFAP, global funding for forestry by multilateral development banks and bilateral agencies is expected to rise from \$600 million in 1984 to \$1 billion in 1988. In a parallel effort, China doubled tree planting to 8 million hectares by 1985, and planted 3.3 million ha of seedlings in 1986 alone (Houghton, 1988a, quoting FAO data), although the survival rates initially hovered around 30%. China has set a goal of 20% forest cover by the year 2000 (up from 12.7% forest in 1978) (Postel and Heise, 1988).

The carbon benefits achieved from afforestation, which reduce emissions of CO_2 to the atmosphere, are not likely to be realized solely on the basis of slowing global warming. Instead, social forestry projects designed to integrate the provision of human needs with economic incentives and environmental stabilization, with carbonreduction goals piggybacked on top, provide the most feasible approach.

Forest plantation planting in the tropics to date has focused on establishing commercial hardwoods (722,000 ha/yr) (WRI and IIED, 1988), and on providing fuelwood (550,000 ha/yr) (Postel and Heise, 1988). The gap between fuelwood supply and demand in the rapidly expanding developing countries could reach 1 billion m³ by the year 2000 (Marland, 1988). World Bank tallies suggest that 55 million ha of high-yielding fuelwood plantations will need to be established by 2000 to close this projected deficit -- fully 2.7 million ha/yr, or 5 times current fuelwood rates. Thus, allowing for overlap, Postel and Heise (1988) calculate that a total of about 110 million ha of planting is necessary both to restore degraded lands and to provide fuel requirements in 2000, which would sequester approximately 0.7 Pg C/yr for the roughly 40year life of the forest.

Several crude estimates have explored the possibility of very large reforestation efforts in tropical regions to provide a sink for fossil-fuel emissions. For example, Sedjo and Solomon (1989) have proposed that the current annual atmospheric net increase in carbon (approximately 2.9 Pg C) could be about 30 sequestered for years in approximately 465 million ha of plantation forests, at a cost possibly as low as \$186 billion in the tropics or \$372 billion in the temperate zone, a large but not inconceivable sum. This area would also produce as much as 4.7 billion m³ of industrial wood annually, three times the current annual harvest. The opportunity cost to society to offset carbon production from global annual deforestation of 11.4 million ha in the tropics can be calculated from Sedjo and Solomon's replacement cost figures and equals \$400 per hectare, or \$4.6 billion per year, a sum the world community should be willing to pay for forest preservation in order to avoid paying carbon offset replanting costs. Myers (1988) has suggested that 300 million ha of plantation eucalyptus or pine (a landmass the size of Zaire), which absorbs about 10 t could offset the 2.9 Pg C/ha/yr, С accumulating in the atmosphere annually (see also Booth, 1988). Dyson and Marland (1979) and Marland (1988) have suggested that 700 million ha of land, an area about the size of Australia or equal to the total global forest cleared since agriculture began

(Matthews, 1983), in short-rotation American sycamore, fixing carbon at a rate of 7.5 t/ha/yr would be required to offset total global production of 5 Pg C per year.

For all of these estimates some of the highest growth rates observed on selected sites have been assumed for vast tracts of land characterized by very different site conditions. Also, global reforestation estimates thus far have focused on the potential for using forest growth to completely offset total or net global carbon emissions. New estimates are needed that consider more feasible offset goals and growth rates. More complete analyses, based on better field estimates of carbon fixation rates for a range of mixed-species stands and agrosilvicultural systems, are underway to identify available acreage with adequate soils for potential planting programs in specific generate inductive countries, i.e., to assessments of the potential of this approach rather than the deductive approaches utilized Table 5-25 gives a summary of thus far. preliminary estimates of forest acreage required to offset global CO₂ emissions.

Is there adequate idle land to seriously entertain the notion of massive tree planting? Houghton (1988b) has roughly calculated for tropical Asia and Africa the availability of tropical land climatically and edaphically suitable for forest growth (i.e., climate and soils that previously supported forest). Crude measures of land formerly in forest but presently degraded or in pasture, and not in use for crops or development, suggest that about 100 million ha are available for reforestation in South and Western Southeast Asia (excluding arid lands in India and Pakistan). For tropical Africa, ratios of land once forested and land currently in "other land" categories in FAO estimates (FAO, 1987) are less reliable, but create a range of 20-150 million ha available. Human-initiated fires set to create and maintain savanna for cattle grazing and other uses hypothetically could be suppressed (although difficult to manage in practice), potentially allowing another 191 million ha of savanna to revert to closed forest along the northern savanna and in Western Africa, thus providing an upper limit of 340 million ha with potential for reforestation (Houghton, 1988c; FAO/UNEP, 1981).

Option 8: Restore Degraded Lands

Restoration of lands formerly forested but degraded by anthropogenic practices such overgrazing, logging, swidden and as inappropriate agricultural methods could increase reforestation and carbon fixation rates. Forest fallow in swidden agriculture, often with low volumes of standing biomass. totals one billion ha globally, with another one billion in some form of degradation. Desertification (the reduction of biological productivity, primarily from human activities, usually in dry forests or rangelands) has moderately or severely affected 1.98 billion ha globally, especially in the African Sahel, Southern Africa, Southern Asia, China and Mongolia (IIED and WRI, 1987; OTA, 1984). Sedjo and Solomon (1989) stress the low purchase price of degraded lands, while recognizing that low-productivity soils on degraded sites are likely to greatly increase acreage requirements for a given offset goal. Grainger (1988) concluded that 758 million ha of degraded tropical land, including the 203 million ha forested in the past, could be restocked with forest.

The substitution of sustainable resource use practices and active reforestation on these lands can reduce further loss of woody biomass and increase rates of carbon fixing and fuelwood production. The price of establishing plantations on degraded grasslands in Indonesia has hovered around \$400 per hectare (JICA, 1986). For example, Houghton (1988b) estimates that by replacing swidden cultivation with permanent, low-input agriculture, about 365 million ha of fallow land would be available for reforestation during the period 1990-2015. Managed reforestation of arid lands has been successful in some sites where natural mulch or commercial fertilizers were applied to seedlings, and native species well-adapted to local pest and environmental conditions were planted. These lands were supplemented by cautious use of fast-growth or nitrogen-fixing leguminous exotic species, like Leucaena, Pinus, Acacia, and Eucalyptus, which tend to be more susceptible to pest invasions. Research and field tests on leguminous trees inoculated with Rhizobium fungi, which produce nitrogen-fixing nodules on legume roots, have shown that damaged tropical soils

depleted of essential mycorrhizal fungi can be replanted effectively and inexpensively (less than \$0.01 per tree) (Janos, 1980).

Subtropical dry forests in the Western Hemisphere have been reduced by 98%. Botanist Daniel Janzen has organized an ambitious plan to restore dry forest cut for agriculture and to manage remaining habitat fragments in order to expand Guanacaste National Park in Costa Rica (Jansen. 1988a,b). The plan calls for establishing a local and international environmental educational and research program, suppressing human fire activities, cattle ranching, agricultural clearing, purchasing intact remnant dry forest habitat adjacent to moist forest tracts or protected areas to provide seed sources, and developing a management plan stressing species diversity and zoning for habitat use, including provision of economic opportunities. A closed-canopy dry forest with significant representation of its previous fauna is expected to evolve within 10-50 years. This natural regeneration may sequester an estimated 8.6 million t C, at a rough cost of \$11.8 million (Jansen, 1988c). Expansion of this innovative approach throughout the dry tropics may be feasible, if stable land tenure and managed use can be attained.

Nyabisindu, Rwanda, hillsides In denuded by intensive swidden agriculture including rapid deforestation, soil erosion, and overgrazing, are being restored to productivity by strips of densely planted trees positioned across steep slopes to catch soil and create terraces for crops, and to produce fruit and fuelwood. The restoration project stocks these hedges from a tree nursery producing five million seedlings per year for farm fruit trees, shade trees lining roads, and hilltop woodlots. A typical farm family can produce 25-50% more fuelwood than it consumes with this mixed crop-tree system (Dover and Talbot, 1987).

Option 9: Increase Soil Carbon Storage by Leaving Slash After Harvest and Expanding Agroforestry

Forest soils store about 1030-1630 Pg of carbon, about twice the total amount of carbon stored in terrestrial biomass, and fully 73% of the total carbon stored in soils (Olson et al., 1983; Bolin, 1983). The annual flux of carbon into soils is 40-100% of the carbon emitted by fossil-fuel combustion, but this flux is offset by an equivalent release of carbon by microbial activity and root respiration in soils (Bolin, 1983; Johnson, 1989). Potentially, soil carbon storage pool size and residence time could be increased through forest and landuse management practices that recognized this new objective.

Carbon enters soil via three main methods: 1) deposition of biomass debris on the surface, which is decomposed by heterotrophic organisms into CO_2 and amorphous organic matter or humus that is mixed or leached into the soil, 2) plant root respiration releases carbon into soils, and root biomass is roughly half carbon, and 3) agroecosystems often employ the direct introduction of plant residues into soils during preplanting and post-harvest plowing. Organic matter accumulation in soils is inversely proportional to mean annual air temperature. Prolonged waterlogging of soils also facilitates storage of carbon in soils; both low annual temperatures and waterlogging prevent carbon volatilization (Johnson, 1989).

Changing agricultural and forestry management practices to lengthen soil carbon retention times offers one of the most promising ways to store additional carbon. Retention times range from lows on the order of 4 years for equatorial forests, to 100 years for tundra soils, and up to around 2,000 years for peats, with a global mean time of 30-40 years (Oades, 1988). Alternative agricultural practices like no-till and low-till, which minimize soil disturbance due to plowing, are being widely encouraged for conservation and economic reasons (National Research Council, 1989). These practices could also reduce soil carbon loss and facilitate carbon storage; however, there has been little research on low-input sustainable agriculture systems from a greenhouse gas balance perspective.

For tropical agroecosystems, the soilagroforestry hypothesis has been stated by Sanchez (1987) as follows: "appropriate agroforestry systems improve soil physical properties, maintain soil organic matter, and promote nutrient cycling." This hypothesis is currently the subject of a series of studies at the International Council for Research in Agroforestry in Nairobi and elsewhere. Field work and simulations underway on changes in soil carbon storage for an alley cropping system in the Machokos District in Kenya show that its introduction on degraded soils leads to recovery of carbon storage averaging 100 kg/ha/yr for the initial 20 years (see Figure 5-14). Thereafter, annual net carbon storage falls off asymptotically and after 108 years reaches zero, but averages 28 kg/ha/yr for the entire 108-year period (Franz, 1989).

The Southeastern U.S. lost huge quantities of soil carbon from 1750 to 1950 due to conversion of forest to agriculture (Delcourt and Harris, 1980), although reforestation from natural regeneration of forest and commercial plantations has reversed that trend over the past 30 years (Schiffman and Johnson, 1989). Natural regeneration on old fields increased carbon storage over 50-70 years by 235%, from 55,000 to 185,000 kg/ha, including a 10% increase in soil carbon. Soil carbon storage in surface soils of old field plantations and natural forests has been found to be double that of adjacent croplands, totalling 10.4-12.9 t C/ha (Schiffman and Johnson, 1989). Hence, widespread reforestation of surplus crop and pasture lands has the added advantage of increasing soil carbon storage significantly.

Forest harvest practices could be altered to increase the storage of soil carbon by leaving more slash on the ground after cutting, allowing slow decay and more incorporation of biomass into soils instead of burning slash, which adds a sudden flux of carbon to the atmosphere. The amount of slash burned might be minimized, and the period between burns of slash might be lengthened as well. Harvest techniques and equipment that minimize disturbance and degradation of soil organic matter could be introduced, especially on steep terrain and during rainy seasons. Timber selection systems, rather than clearcut methods, would leave more standing biomass to absorb rainfall and reduce erosion and soil carbon volatilization. Similarly, even-age management techniques that utilize harvest of virtually all trees in a stand because they are ready for harvest simultaneously could be replaced by all-age management.



ALLEY CROPPING IN MACHAKOS, KENYA

FIGURE 5-14

Source: Franz, 1989.

Obstacles to Large-Scale Reforestation in Industrialized Countries

Economic and institutional obstacles to widespread reforestation center on the high costs of site preparation, planting, forest management, and necessary financial incentives to private landowners. However, 1.2 million ha of trees were planted in 1987 without strong incentives (USFS, 1988). U.S. state foresters maintain that financial incentives on the order of \$125-250/ha (\$50-100/acre) would be sufficient to bolster reforestation of harvested woodland and surplus croplands in most states. With about three years of lead time, existing tree nurseries could accelerate production of seedlings enough to plant 3-10 times current acreage per year (NASF, 1988).

Ecological drawbacks to massive reforestation schemes include the low levels of genetic variability that characterize vast tracts of monocultural stands and their reduced resistance to pest infestations (e.g., gypsy moth, pine bark beetles), which can lead to widespread forest decline and mortality. Large-scale plantations may strain surfacewater and ground water resources in areas already experiencing overdrafts of and escalating demand on aquifers, for example, the Ogallala aquifer in the southern Great Plains, and Southeast coastal plain ground water (Los Alamos National Laboratory, 1987).

pollution, such as acid Air precipitation, ozone, and other photochemical oxidants, is already affecting the health of forests in the U.S., Europe (e.g., see Kairiukstis et al., 1987; UNECE/FAO, 1989), and China. Since 1979 there has been documented decline in at least seven important coniferous and four important broadleaf species in European forests, and in at least eight important species in North American forests. Fifty-two percent of West German and 36% of Swiss forests were in decline by 1986. In the Southeast U.S., natural-stand diameter growth rates for yellow and loblolly pines have declined 30-50% in the past 30 years (WRI and IIED, 1986; IIED and WRI, 1987).

pollution Air impacts mav be exacerbated by the combined effect of warming due to climate change and increased ultraviolet radiation due to ozone depletion. The long-term process of climate change is likely to complicate the task of actively expanding net forest area, a topic explored in Smith and Tirpak (1989). The increase of carbon dioxide, through the effect of CO_2 fertilization, may spur tree growth rates, but the net result of climate change on forest growth under changing temperature and precipitation conditions is difficult to predict. Early studies suggest that Southern bottomlands hardwood, oak, and pine forests, and Northern conifer forests are likely to advance northward as temperatures increase. The natural rate of forest migration -- about 100 to perhaps 400 km per 1000 years -- appears unlikely to keep up with the likely rate of forest decline (Davis and Zabinski, in press; Shands and Hoffman, 1987; Smith and Tirpak, 1989). Technical methods of speeding seed dispersal to favorable soils (e.g., seeding from aircraft) are not complex but may be costly, with potentially low seedling survival rates (WWF, no date).

Forests under the stress of climate change may have difficulty maintaining current productivity rates, let alone increased rates and expanded geographic range, as envisioned under reforestation policies. Forests migrating north in response to rising temperatures will tend to encounter poorer soils, slow natural seed dispersal methods, stresses on ecosystems, competition from other land use sectors and ecosystems also responding to climate change, and either reduced or increased precipitation and water supply conditions, depending on the region. While global boreal forests are likely to increase in total area and tree density (Shugart and Urban, no date), they probably will contain, on average, lower standing biomass volumes and carbon fixation rates than current boreal forests. Sedio and Solomon (1989) estimate a net loss of 24 Pg C storage in global forests under a $2xCO_2$ scenario (doubling of pre-industrialized CO₂ concentration levels), largely due to declines in total biomass in boreal forests.

Forest decline presents a major obstacle to forest management to mitigate climate change in all forest zones (i.e., reports of decline are emerging in the subtropics and tropics). According to one source, decline is "a complex disease caused by the interaction of a number of interchangeable, specifically ordered abiotic and biotic factors to produce a gradual general deterioration, often ending in the death of trees" (Manion, 1981, in Auclair, 1987). Significant modelling of stress and decline have taken place (e.g., Kairiukstis et al., 1987), and may have potential for application to climate stress on forest and tree growth and regeneration, migration of forests, and afforestation. "In large areas, the silvicultural regimes are at least partly increasing the forest damages" (Kuusela, 1987).

Aggressive silvicultural and management responses to decline may offset losses and facilitate evaluation of mitigation options for climate change under intensifying conditions of air pollution. Responses include increasing diversity of stands; thinning younger stands to maximize tree vitality (Rykowski, 1987); keeping stands densely planted in order to avoid physiological wind damage observed in stand borders and to provide a selection reserve for further thinning; and applying fertilizers to stands liable to pollution stress and decline, as practiced in Duben-Forest and Lower Lusatia pine stands on nutrient-poor soils in Eastern Europe, while avoiding overfertilization that leads to growth depressions (Thomasius, 1987).

Climate change, therefore, may affect the viability of reforestation strategies as a mitigation measure. Further research is needed.

Obstacles to Reforestation in Developing Countries

Tropical reforestation schemes face many obstacles. Pest management in monocultural plantations (e.g., rats, fungus, nematodes for *Leucaena* in the Philippines) and loss of genetic diversity, which might allow adaptation to pest or viral infestations, have proved major deterrents to large-scale plantation projects in the Philippines, at Jari, Brazil, and elsewhere. Other issues include

rapid removal of soil nutrients by fast-growth species, reduced growth rates at altitudes as low as 450 meters and in frost belts for some species. and sheet erosion. Practical limitations of plantations include the large areas of land necessary, limited transportation infrastructure to move biomass to users. plantation security (fencing to prevent poaching of trees in northern Nigeria in 1976 costs \$160-200 per ha), costs of establishment, and limited availability of skilled technicians (Villavicencio, 1983).

Pastures cut from tropical forests have been invaded by resilient monocultural grasses like *Imperata cylindrica*, which must be suppressed before trees can survive. Research into recolonization of large, highly degraded pastures in the Amazon (Uhl, 1988) suggests that three factors inhibit reforestation: few seeds of forest species are being dispersed into pastures because 85% of tree seeds are transported by animal pollinators that do not frequent pastures; most seeds dispersed to pastures are eaten by predators; and moisture and energy conditions near the ground surface in pastures are radically different from forest conditions.

Economic and population pressures in many regions make net afforestation difficult to achieve. China, for example, is experiencing rapid economic development, which has led to housing construction that consumed 195 million cubic meters of wood (0.05 Pg C) between 1981 and 1985, equivalent to the total annual growth of all China's forests (Postel and Heise, 1988). Cost estimates for plantation establishment in the tropics (80% of costs are for labor) are summarized in Table 5-26. These costs range from about \$100-200/ha/yr for dry areas with less than 1100 millimeters (mm) of rainfall per year, to over \$1000/ha/yr in wetter areas receiving over 1800 mm/yr (FAO, 1989).

Other environmental stresses on extant forests, including seasonal climatic variations and human-induced stresses, reduce the ability of forests to meet current and projected demand for forest products, let alone supply new large increases in productivity and plantation acreage. Persistent drought already plays a prominent role in the migration of environmental refugees from traditional

Rainfall (mm)	Species	Country	Number of Plants	Cost (year \$)	Man-Days
1. PLANTA	TION (approximately 80% of	of costs are lab	Dr)		
<500	Acacia tortilis, Albizia lebbeck, Prosopis cineraria, Prosopis juliflora	India India	400 1,000	100 US\$ (78) 200 US\$ (78)	160 320
500-1,100	Leucaena leucocephala	India	1,000	200 US\$ (78)	320
1,200-1,800	Tropical pines	Honduras Madagascar Zambia	1,600 2,000	400 US\$ (84) 15,000 CFA (71) 238 US\$ (78) 238 US\$ (78)	50 100 N/A
	Eucalypts	Burkina Faso Senegal Togo Benin Cote d'Ivoire	2,500 2,500 2,500 1,600	228 039 (78)	255-330 345 185 250 145-210
	Some species, but with Taungya system Bamboo Enrichment planting,	Cote d'Ivoire Togo India Madagascar			100-150 145 150 260
	various species	Zaire	250 400		80 124
>1,800		Zaire Congo Gabon	4,500 950 400		468 80 264
	Gmelina	Brazil Gambia		955 US\$ (79) 600 US\$ (79)	N/A N/A
	Eucalypts	Brazil Gambia		1,700 US\$ (79) 1,200 US\$ (79)	N/A N/A
	Schizollobium parahybum; Condia alliodora	Ecuador	2,000	640 US\$ (88)	150
2. DIRECT	SOWING				
By hand, spo By air, pelle	ot sowing tized seed	Honduras, 198 India, 1986 (tr	0 ials)	50 US\$ 15-50 US\$	

Costs of Afforestation: Stand Establishment and Initial Maintenance (per hectare basis)

Source: FAO, 1989.

agricultural areas such as the Sahel, forcing relocation to areas of marginal dry forest that introduces new pressures (Houghton, 1988a; Postel and Heise, 1988).

Comparison of Selected Forestry Technical Control Options

Slowing tropical deforestation, and rapidly expanding temperate and tropical reforestation, may offer two of the most costeffective policy responses to increasing CO₂ emissions. However, only rudimentary estimates of the feasibility, costs, and consequences of large-scale reforestation have Table 5-27 summarizes been performed. All calculations these options. are preliminary estimates of planting costs only. Total costs of these measures are not estimated, and would vary greatly depending on land costs and management costs. These estimates are provided to give a general sense of the relative costs of these options. Few viable, global-scale plans to slow forest loss in the tropics have been advanced. Most are policy options rather than technical fixes, and these are discussed in Chapters VII and VIII. Replacement of swidden agriculture with permanent low-input, sustainable agricultural systems offers particular promise.

Integrated natural resource management and social forestry projects such as provision of the full spectrum of forest and food products in demand; forest protection from swidden agriculture, logging, and fire; economic opportunities and reasonable rates of return; and cooperative management by local people and resource professionals are likely to be the most successful in addressing climate change effects and offset goals. Examples of three such projects are displayed in Table 5-28. These projects were proposed to offset the lifetime CO_2 emissions of a 180 MW coal-fired electric plant planned by Applied Energy Services in Uncasville, Connecticut, by planting and managing forests, or protecting former forest converted into pasture to allow natural regeneration into secondary forest (to be protected in a national park in Guanacaste, Costa Rica [Jansen, 1988c]).

Obstacles to slowing deforestation and to planting and maintaining reforested lands in the tropics include degraded soils, limited research on appropriate species and systems, limitations in institutional capabilities, government incentives that hasten deforestation, and soaring population growth rates.

Comparison of Selected Forest Sector Control Options: Preliminary Estimates

	the second se	the second se				
Option	No. ha Required (million)	Planting Cost/ha (\$)	Total Planting Cost (million \$)	Fixation Rate (t C/ha)	Carbon Offset Goal (Pg C/Sequestered)	Planting Cost Per Pg C (billion \$)
		D	DMESTIC U.S. OPTIO	NS		
Plant trees to offset annual CO ₂ emissions U.S.	240.0	432	104,000	5	1.2 Pg C/yr	10
Plant 100 million urban trees	0.0		100	5	0.052 Pg C/yr	0.2
Reforest 20% of highway corridors	1.8	432	778	5	0.009 Pg C/yr	10
Plant trees to offact new U.S. electric plant CO ₂ (1987-96)	9.1	432	3,930	5	0.045 Pg C/yr	10
Implement current forest economic opportunities at 4% ROR	58.3		0		0.164 Pg C/yr	0
		INTERNATION	AL FORESTRY OPTIC	ONS (TROPICS)		
Plant trees to offset new U.S. electric plant CO ₂ (1987-96) in LDCs	6.0	400	2,400	7.5	0.045 Pg C/yr	6
Plant trees in Guatemala to offset CO_2 emissions of 180 MW electric plant in U.S.	0.1		14ª		0.16 Pg C total over 40-year períod	0.9
TABLE 5-27 (continued)

Comparison of Selected Forest Sector Control Options: Preliminary Estimates

Option	No. ha Required (million)	Planting Cost/ha (\$)	Total Planting Cost (million \$)	Fixation Rate (t C/ha)	Carbon Offset Goal (Pg C/Sequestered)	Planting Cost Per Pg C (billion \$)
Substitute sustainable agriculture for all swidden agriculture	41					
Restore degraded lands and provide fuelwood for year 2000 and reduce tropical C release by 40%	110	400	44,000	7.5	0.7 Pg C/yr over 40 yrs.	6
Reforest tropical lands to offset global annual net increase in C	465	400	186,000	6.2	2.9 Pg C/yr	8
Replant tropical forest cut or burned each year	11.3/уг	400	4500/yr		1.0 Pg C/yr	4.5

^a Total project cost, including forest protection, plantation establishment, and agroforestry.

Note: All calculations made from estimates and references listed in this section; and all calculations are preliminary estimates of planting costs only, without management, harvest, rental or purchase costs included.

TABLE 5-28

Overview of Three Social Forestry Projects Proposed to Offset CO_2 Emissions of a 180-MW Electric Plant in Connecticut

Forest Attribute	CARE/WRI/Guatemala	WWF/Costa Rica	Guancaste/Costa Rica
Total area of project	101,000 ha	122,000 ha	70,400 ha
Protected in forest reserves	19,740 ha	72,000 ha	70,400 ha
Logged or managed forests	38,000 ha		
Newly established woodlots (plantations)	13,140 ha	12,000 ha	
Agroforestry lands	68,350 ha		
Carbon sequestered over 40-year life of plant	18.1 Tg C	11.0 Tg C	8.6 Tg C
Cost estimate (cash or in-kin	nd) \$14 million	\$9.6 million	\$11.8 million
Cost per ton C sequestered	\$ 0.77	\$ 0.87	\$ 1.37

Note: Offset goal = 0.39 Tg C/yr.

Sources: Turner and Andrasko, 1989 (all projects); Trexler et al., 1989 (Guatemala); WWF, 1988 (Costa Rica); Jansen, 1988c (Guanacaste).

PART FIVE: AGRICULTURE

Agriculture contributes to the emissions of greenhouse gases through several means: rice cultivation, nitrogenous fertilizer use, enteric fermentation in domestic animals, and decomposition of animal manure. Estimates place the annual contribution of rice cultivation and domestic animals at approximately 20 and 15%, respectively, of global methane (CH_4) production. The use of nitrogenous fertilizers is estimated to account for between 1 and 17% of the current global source of nitrous oxide (N_2O) (see CHAPTER II). Land clearing for agriculture, and the intentional burning of agricultural wastes, grasslands, and forests make a significant contribution to the global emissions of carbon dioxide (CO_2) , CH_4 , and N_2O , as well as carbon monoxide (CO) and nitrogen oxide (NO_x). Also, energy use in agriculture is significant, particularly in developed countries, where the requirements for irrigation, field operations and agrochemicals are high. Figure 5-15 illustrates the net effect of these agricultural sources on current greenhouse warming.

Both the magnitude of agricultural source emissions and the potential effectiveness and costs of possible reduction measures are very uncertain. While considerable research has been done on the agricultural activities of interest, relatively little attention has been focused on agriculture-related emissions of greenhouse gases and how various changes in agricultural practices affect these emissions. Many fieldlevel measurements across a wide range of cropping situations, in addition to whole systems evaluation (across the range of greenhouse gases), will be required in order to develop a rational control strategy.

For each of the three major trace-gasproducing agricultural practices, we discuss existing technologies and management practices, emerging technologies, and areas that require additional research. Technical options for reducing greenhouse gas emissions are discussed under each of these subsections.

RICE CULTIVATION

Methane is produced by anaerobic decomposition in flooded rice fields. Some CH_{4} reaches the atmosphere through ebullition (bubbling up through the water column), but most of it (about 95%) passes through the rice plants themselves, which act as conduits. Methane production is affected by the particular growth phase of the rice plant, temperature, irrigation practice, fertilizer usage, amount of organic matter present, rice species under cultivation, and number and duration of rice harvests (Fung et A limited number al. 1988). of measurements have been performed in California, Italy, and Spain to evaluate CH_4 production in flooded rice fields. No measurements have been published for the major rice-producing areas of Asia, however, where environmental conditions and cultivation practices differ significantly from those in these more temperate regions (Cicerone and Shetter, 1981). This data limitation makes it difficult to evaluate emissions and potential greenhouse gas reductions strategies for Asia. Measurements of CH_{4} from rice are currently being performed in China and Japan.

Rice cultivation is currently estimated to contribute between 60 and 170 Tg CH₄ per year (Fung et al., 1988), and with riceharvested area increasing between 0.5 and 1.0% per year (IRRI, 1986), rice cultivation will continue to be a significant source of CH₄ emissions.

Rice cultivation practices around the globe vary widely. With over 60,000 varieties of rice, there is great variation in water requirements, fertilizer response, pest and disease resistance, growing season, plant height, and yield potential. Traditional rice varieties are generally tall plants with a low grain-to-straw ratio that have a good resistance to endemic weeds and pests and a high tolerance for moisture, including flooded monsoon conditions. Cultivation of FIGURE 5-15



traditional varieties of rice does not involve heavy fertilization because these plants tend to lodge (fall over) at high levels of fertilization. The highest most stable rice yields are achieved with irrigation.

Research of the 1960s led to the Green Revolution, which radically changed the nature of rice production in Asia. This research produced a high-yielding rice cultivar that is short, stiff-stemmed, and very fertilizer responsive. These modern, high-yielding varieties also have a short growing time, which allows for multiple plantings during the year. The first of these modern varieties, IR8, established a maximum yield potential of 10 million tons per hectare (mt/ha) under ideal conditions, and reduced the average growing time from 160 to 130 days (Barker et al., 1985).

Existing Technologies and Management Practices Affecting Methane Production

No currently-available technology can inhibit the production of CH_4 in rice paddies, but cultivation practices and plant variety affect the amount of CH_4 produced.

Nature of Rice Production System

The nature of the rice production system has a substantial effect on the amount of CH_{4} produced. Wet paddy rice produces CH_4 , while dry upland rice does not. Wetland rice comprises about 87% of rice area worldwide. Of global rice area, about 53% is irrigated, 22.6% is shallow rainfed, 8.2% is deepwater, and 3.4% is tidal wetland. The remaining 13% is dry upland rice (Dalrymple, 1986). The majority of upland rice area is in Africa and Latin America. Rice paddies are inundated to varying depths and for different lengths of time depending on production system used, which affects the rate of CH₄ generation. How these rates differ has yet to be quantified.

Fertilization With Organic Matter

The kind and volume of organic matter added to the rice paddy has been shown to affect CH_4 production. Laboratory experiments have shown that adding organic matter leads to an early peak in CH_4 production and an overall increase equivalent to 2-5% of the added organic matter (Delwiche, 1988).

Organic fertilizers are often used in rice cultivation in Asia. Sources include animal manures, composted garbage, night soil (human feces), and plant residues. After harvest, rice plant residue is often incorporated into the soil as a source of organic material -- a practice that appears to increase CH_4 emissions significantly. In addition, it is not known whether and to what extent the introduction of manure from domestic animals during plowing and harrowing affects CH_4 production.

Disposition of Crop Residues

Crop residues can be burnt, buried, incorporated into the rice paddy, or used for some other activity. Burning the residue releases CO_2 . Buried residue partially decomposes and produces CH_4 , but less than the amount produced by incorporating the residue into the paddy.

In southern India and Sri Lanka, there is a preference for intermediate height varieties of rice, which produce more straw for fodder and fuel (Barker et al., 1985). Finding additional uses for rice straw, such as for fiber or building materials, is necessary in order to reduce the incentive for plowing crop residue back into the field.

Type of Rice Variety Planted

The shift to high-yield varieties of rice has helped to reduce the amount of CH_{4} produced per unit of rice. Modern, shortstemmed varieties have a grain-to-straw ratio that is about 50% higher than traditional varieties, which means less organic material (straw) is left to decompose, assuming it is not burned. In addition, the shorter growing season of high-yield varieties results in a reduction in CH₄ emissions. However, the shorter growing season also allows multiple plantings during the course of a year. Overall, CH₄ emissions could increase as a result of multiple planting, particularly if more organic material is incorporated into the paddies to support the greater number of plantings.

High-yield varieties of rice are largely limited to irrigated areas where yield response is the highest. These modern varieties show the highest fertilizer response and overall yield in irrigated areas during the dry season, when water levels are best controlled and solar energy is at its peak. The yield response is lower and highly variable under the summer monsoon conditions when flooding, pests, and diseases are most Some farmers in India and common. Bangladesh cultivate modern varieties in the dry season and traditional varieties in the wet season (Barker et al., 1985).

The uncertainty of adequate moisture in many areas, and flooded conditions in others, discourages the use of modern fertilizerresponsive varieties in non-irrigated production regimes. But, in some countries, the use of modern varieties has expanded well beyond the irrigated zones. In the Philippines, modern varieties are grown extensively in rainfed lowlands. In Burma, modern deepwater and upland varieties now cover an area three times that which is irrigated (Dalrymple, 1986; see Table 5-29).

Further dissemination of the short, stiffstemmed, fertilizer-responsive modern varieties of rice has potential for decreasing emissions of methane. World rice yield is currently at about one-half of genetic potential, which is as much as 14-16 mt/ha (Mikkelsen, 1988). There is considerable room for efficiency improvements in rice production, which would lead to a relative decrease in CH_4 production.

Fertilizer Use

Widespread adoption of modern varieties has been somewhat impeded in developing countries because of the capital required for new seed and fertilizer. Switching to modern varieties has resulted in an increase in the use of both organic and chemical fertilizers. Research indicates that a significant increase in production could be achieved through more efficient application of chemical fertilizer. Asia currently has a fertilizer-use efficiency of between 30 and 40%. Direct placement of fertilizer into the soil when rice is transplanted could double fertilizer-use efficiency and would increase yield (Mikkelsen, 1988).

The use of chemical rather than organic fertilizer may, at least temporarily, reduce CH_4 production in the rice paddy. The interaction of such soil amendments on CH_4 production and rice yield needs to be thoroughly examined.

Fertilizer use on rice is a significant source of N_2O . Intermittent flooding and drying of the paddy results in a high rate of N_2O evolution through denitrification (Eriksen et al., 1985). Methane control strategies for rice must also consider the effect on N_2O evolution (see **NITROGENOUS FERTILIZER USE AND** SOIL EMISSIONS).

Emerging Technologies

Current research at the International Rice Research Institute (IRRI) and other rice research centers is focused on the development of varieties better suited to a wide range of environmental conditions (Dalrymple, 1986). The development of highyield varieties that can withstand the drought conditions of upland and shallow rainfed systems, as well as the flooded conditions associated with lowland and tidal rice cultivation, would increase the dissemination of high-yielding varieties in these areas.

Greater emphasis is being placed on efforts to understand the complexities of the farming system by conducting research in farmers' fields and encouraging farmer involvement. This so-called farming-systems style of research combines the knowledge of researchers with the direct experience of farmers (Barker et al., 1985). Research that focuses on developing cultivars that consistently produce a good yield under a wide range of conditions, rather than a high yield under ideal conditions, holds the most promise for improving food supply stability and decreasing CH_4 emissions from rice cultivation in Asia.

There are likely to be further shifts to irrigated rice production in the future. However, improving the potential of modern

TABLE 5-29

Water Regime and Modern Variety Adoption for Rice Production in Selected Asian Countries

To Country (O	Total Rice	Irrigated Season		Rainfed				
	Area			Shallow	Deep Water	Floating		Percentage Cropped
	Country	(000 ha)	Dry	Wet	(0-30 cm)	(30-100 cm)	(>100 cm)	Dryland
Bangladesh	10190	10	2	42	26	11	9	25
Burma	4751	2	15	43	21	4	15	53
China (a)	34288	(b)	95	5	(c)	-	•	20 (d)
India	39515	Ìή	32	28	12	6	15	53 `
Indonesia	8913	30	51	6	3	2	8	64 (d)
Korea Rep	1229	(b)	100		•	-		34
Malaysia	680	29	29	29	•	-	13	44
Nepal	1261	-	23	54	15	4	4	36 (d)
Pakistan	1999	-	100			-		46
Philippines	3535	17	26	34	11	-	12	85
Sri Lanka	818	27	40	27	-	-	6	89
Thailand	8679	6	14	53	12	4	11	13

a Allocations based on impressions rather than data.

b All rice grown during the summer months and shown under wet season.

c A dash (-) indicates magnitude zero.

d Number of MV adoption in disagreement with "Development and Spread of High-Yielding Rice Varieties in Developing Countries." U.S. AID numbers: for China - 91%; Indonesia - 82%; Nepal - 53%.

Source: IRRI, 1986.

varieties to perform well under rainfed conditions would reduce the incentive to shift to irrigated production systems, which are large producers of CH_4 .

Research Needs and Economic Considerations

Before a comprehensive strategy to reduce CH_4 production in rice can be developed, research in several areas is needed. There is a need for experiments in Asia, where the majority of the world's rice is grown, and no data is currently available. In particular, to estimate the amount of CH_4 produced per unit of rice we need to quantify the amount of CH_4 produced from different cultivars, under various cultivation practices, particularly under different water management regimes. Additionally, the effect of adding chemical rather than organic fertilizer on CH_4 production needs to be further examined and quantified.

The increased temperatures and changes in precipitation patterns associated with climate change could have major implications for global rice cultivation. Particularly in the tropics, heat stress could present a problem for rice, where high temperatures could increase sterility, impair growth, and decrease yield (IRRI, 1981). Increased temperatures could also increase microbial activity and CH_4 production within the rice paddy. Such feedbacks need to be examined.

Rice is the cornerstone of the Asian economy. Economic and cultural considerations must be at the root of any CH_4 control strategy. The sheer number of small-scale rice farmers in Asia will make implementation of a control strategy difficult. Practices that are low-cost, beneficial, and attractive to small farmers will need to be identified and disseminated through existing and expanded agricultural research networks.

Many Asian countries are striving for self-sufficiency and have protected internal markets against the price fluctuations of the international market. Some countries have initiated price floors and others price ceilings. Price supports in countries such as the U.S. and Japan cause an increase in the production of rice.

NITROGENOUS FERTILIZER USE AND SOIL EMISSIONS

Denitrification and nitrification are the primary processes that lead to the evolution of N_2O from soils fertilized with nitrogenous fertilizers. In well-aerated soils, nitrification is the primary process producing N_2O (Breitenbeck et al., 1980). Denitrification is prevalent in poorly drained, wet soils. Rice cultivation is the largest agricultural contributor to denitrification losses (Hauck, 1988). Soil erosion and leaching of fertilizer into ground water and surface water is an additional source of N_2O : between 5 and 30% of fertilizer leaves the soil system via leaching or runoff (Breitenbeck, 1988). Researchers need to derive a more precise estimate of N_2O from this source.

Fertilizer-derived emissions of N_2O are estimated to be 0.14-2.4 teragrams of nitrogen (Tg N) annually (Fung et al., 1988), based on global consumption of 70.5 Tg of nitrogenous fertilizer in 1984/1985 (FAO, 1987). Nitrogenous fertilizer use is increasing at an estimated 1.3% per year in industrialized countries and 4.1% per year in developing countries (World Bank, 1988). By 2050, global fertilizer consumption is estimated to increase by a factor of 3.5 over the 1990 level (Frohberg et al., 1988).

Anthropogenic factors affecting the fertilizer-derived emissions of N_2O include the type and amount of fertilizer applied, application technique, timing of application, tillage practices, use of chemicals, irrigation practices, vegetation type, and residual nitrogen in the soil. Natural factors such as temperature, precipitation, organic matter content, and pH of soil also affect N_2O emissions (Fung, 1988).

 N_2O emissions are difficult to estimate because of the complexity and variability of fertilized soil systems. Estimates suggest that fertilizer-derived emissions of N_2O are highest for anhydrous ammonia (between 1 and 5% of N applied), followed by urea (0.5% of N applied), ammonium nitrate, ammonium sulfate, and ammonium phosphate (0.1% of N applied), and nitrogen solutions (0.05% of N applied) (Fung, 1988). Anhydrous ammonia is only used extensively in the United States, where it comprises about 38% of nitrogenous fertilizer consumption. Urea is used extensively in Asia and South America, where it accounts for 69% and 58%, respectively, of nitrogenous fertilizer consumption.

Existing Technologies and Management Practices Affecting Production of Nitrous Oxide

The wide variety of agricultural systems and fertilizer management practices produces very different quantities of N_2O emissions. These emissions can be reduced by improving the efficiency of fertilizer use, which can be achieved through changes in management, such as better placement in the soil, or in technology, for example, introducing nitrification inhibitors and fertilizer coatings, which both improve the efficiency of fertilizer applied and reduce the amount required.

Adoption of more efficient fertilizer management practices and technologies by farmers has been slow, however, particularly in developing countries. Traditional agricultural practices have proven to be difficult to dislodge. Immediate benefits of alternative practices must be made apparent or incentives provided in order to achieve widespread adoption of these more efficient practices and technologies.

Type of Fertilizer

Nitrous oxide emissions vary by one to two orders of magnitude between nitrogen solutions, urea, and anhydrous ammonia. The feasibility of using fertilizers with lower N_2O emission rates for different cropping situations needs to be examined and encouraged.

Fertilizer Application Rate

Typical fertilizer application rates vary depending upon crop type, soil conditions, fertilizer pricing, and environmental policies. Fertilizer application is often in excess of crop and soil requirements. Increased fertilizer application results in increased emissions of N_2O . Adjusting fertilizer application in accordance with plant requirements would improve fertilizer-use

efficiency. Currently, fertilizer subsidies and pricing encourage a higher than optimum level of fertilizer use.

Efforts to provide adequate nutrition to crops continue to be hindered by inadequate understanding and forecasting of factors that influence nutrient storage, cycling, accessibility, uptake, and use by crops during the growing season. Testing of soil and plant tissues could allow farmers to apply nutrients more in accordance with crop requirements, rather than following broad guidelines that often recommend excessive fertilization.

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Fertilizer application rates vary widely by crop type. For example, in the U.S. in 1985, average fertilizer application rates (in lb N per acre) were 134 for corn, 64 for wheat, and less than 20 for soybeans (NRC, 1989). Within the U.S., corn alone accounts for 44% of all directly applied fertilizers in agriculture, while wheat, cotton and soybeans receive 18% combined (NRC, 1989).

Corn, being a row crop, is susceptible to high rates of soil erosion, increasing the potential nitrogen losses. After the harvest of corn, substantial amounts of nitrogen generally remain in the soil, available for evolution as N_2O . The surplus nitrogen can be captured by inter-cropping with a grain crop such as rye, which could then be plowed back into the soil (see Alternative Agricultural Systems).

Overall, N_2O emissions could be reduced through less cultivation of crops with high fertilizer requirements. Within the U.S., reducing price supports for corn, or zoning against row crops in high erodibility areas or in nitrate-contaminated watersheds could achieve this goal.

Timing of Fertilizer Application

The timing of fertilizer application is likely to affect the evolution of N_2O from the soil. Limited studies on the subject suggest that emissions from fertilizer applied in the fall exceed those from fertilizer applied in the spring (Bremner et al., 1981).

Placement of Fertilizer

Proper (deep) placement of fertilizer can improve fertilizer efficiency by curbing nitrogen losses and thus N_2O emissions. Broadcasting and hand placement of fertilizer results in higher nitrogen losses than does deep placement. Deep placement is particularly important in flooded fields where fertilizer is used inefficiently. In Asia, only about one-third of the nitrogen applied benefits rice crops. Placement of fertilizer into the reduced zone, which prevents microbial action, can double fertilizer-use efficiency (Stangel, 1988). This technique improves efficiency regardless of the water regime (Eriksen et al., 1985).

Rice can either be grown from seeds or transplanted. Transplanted rice may reduce denitrification losses by allowing more efficient fertilizer application. A simple tool that allows for proper fertilizer placement at the time of transplanting greatly improves fertilizer efficiency; however, this tool has not been widely adopted in Asia (Stangel, 1988). Rice farms in Asia average 3 ha or less and labor-intensive are very operations. Consequently, there has been little incentive to develop and disseminate fertilizer technology.

Water Management

Intermittent flooding of rice paddies increases nitrogen loss and the creation of N_2O (Eriksen et al., 1985; Olmeda and Abruna, 1986). In paddy rice, the trade-off between CH_4 and N_2O production must be evaluated.

Tillage Practices and Herbicide Use

A few preliminary measurements suggest that denitrification activity and N_2O emissions are higher under no-till systems than under conventionally tilled systems (Groffman et al., 1987). This increase could be the result of fertilizer placement or the increased use of herbicides associated with notill systems. Preliminary observations indicate that application of post-emergent herbicides leads to significant, but short-lived, increases in N₂O emissions (Breitenbeck, 1988). The influence of tillage practices and herbicide use on N_2O emissions merits further study.

Legumes as a Nitrogen Source

Few studies have been done to determine the role of nitrogen-fixing crops in the emission of N_2O . Estimates of N_2O emissions from legumes cover a wide range: some are similar to those from fertilized crop systems (Groffman et al., 1987), while others are similar to emissions from fallow unfertilized soil (Blackmer et al., 1982). If N_2O emissions from legumes as a nitrogen source were comparable to emissions from nitrogenous fertilizer, the use of legumes would be superior from an overall greenhouse gas perspective because of the great energy requirement for production of ammonia-based fertilizers. Further quantification of N_2O from legumes per unit of nitrogen supplied to the soil is required.

Technologies that Improve Fertilization Efficiency

Nitrification Inhibitors

Nitrification and urease inhibitors are fertilizer additives that can increase efficiency by decreasing nitrogen loss through volatilization. Nitrification inhibitors can increase fertilizer efficiency by 30% (Stangel, 1988).

Reduced Release Rate

Techniques that limit fertilizer availability, such as slow-release or timedrelease fertilizers, improve nitrogen efficiency by reducing the amount of nitrogen available at any time for loss from the soil system.

Coatings

Limiting or retarding water solubility through supergranulation or by coating a fertilizer pellet with sulfur can double fertilizer efficiency (Stangel, 1988).

Emerging Technologies

No breakthrough in chemical fertilizer technology is anticipated in the near future, but there are likely to be improvements in fertilizer production and application efficiency. The development of a subsurface fertilizer application method for no-till, for example, could have a significant effect on N_2O emissions from that source.

Advances in biotechnology are likely to affect N_2O emissions from agriculture. Engineering of crop varieties that are more resistant to weeds could reduce herbicide use, and in turn, decrease the emissions of N_2O .

Nitrogen-fixing cereal crops, which could be available by 2000, would decrease the use of fertilizer on those crops. The potential for reduced N_2O emissions needs to be examined (OTA, 1986).

Technological advances that increase crop yield will help reduce the amount of land and other inputs needed to produce the goods required to support the population. Improved yield and other efficiency improvements hold potential for reducing N_2O emissions.

Alternative Agricultural Systems

Environmental concerns regarding pollution of ground and surface water and soil degradation from intensive agriculture have renewed interest in alternative agricultural systems. Such systems, sometimes referred to as sustainable, alternative, or low-input, strive to achieve a style and level of agricultural production that has long-term sustainability on the resource base. As compared with conventional agriculture, such systems utilize more thorough incorporation of natural processes such as nutrient cycling, nitrogen fixation, and pest-predator relationships; reduce the use of off-farm inputs with the greatest potential to cause environmental or health effects; and seek to achieve profitable and efficient production with emphasis on conservation of soil, water, and biological resources (NRC, 1989). The potential of alternative agricultural systems to reduce greenhouse gas emissions, while maintaining food security and satisfying farm income needs, needs to be evaluated holistically.

Alternative Agriculture and Nitrous Oxide

Alternative, low-input sustainable agricultural systems frequently utilize crop rotations, soil-conserving tillage practices, onfarm nutrient sources, green manures (leguminous crops), and integrated pest management (IPM) techniques. Such systems achieve energy savings by reducing the need for plowing and lowering the fertilizer requirement.

Crop Rotation. Rotating crops serves to increase soil moisture, provide pest control, and increase the availability of nutrients in the soil. Rotating crops, rather than leaving land fallow, can reduce N_2O losses (see Crop Type above). Crop rotations can reduce the establishment of root pests and diseases, leaving root systems better able to absorb nutrients, thereby reducing the fertilizer application requirement (NRC, 1989).

Conservation Tillage. Practices such as low-till, no-till, and ridge-till reduce soil losses and associated loss of nitrogen contained in the soil. Tillage practices may reduce the efficiency with which the fertilizer can be applied. The overall effect on N_2O emissions (on and off the field) needs to be evaluated.

Organic Nitrogen Sources. Using leguminous crops or animal manure as a nitrogen source reduces the need for additional nitrogen fertilizer, but may result in similar or enhanced N_2O emissions. The energy savings and environmental benefits associated with reduced use of nitrogen fertilizer make this option appealing, but better estimates of N_2O from each type of system is required.

Sustainable Agriculture and Land Conversion

Agricultural practices affect greenhouse gas emissions in a large way through land conversion, disturbance, and biomass burning. Particularly in the tropics, the conversion of forest to cropland, pasture, or fallow results in a net loss of stored carbon (see PART FOUR: FORESTRY). Much of the reduction in stored carbon will come from the soil, evolving over time after clearing (Houghton et al., 1983). Land clearing also results in a net loss of N₂O from the soil (Matson, pers. communication). Slash and burn agriculture (as discussed in PART FOUR) promotes high levels of land conversion, and hence, a net loss of carbon and nitrogen sinks. Additionally, biomass burning associated with slash and burn agriculture results in emissions of CO_2 , CH_4 , N_2O_1 , CO_1 , and NO_2 . Sustainable agricultural practices can do much to reduce greenhouse gas emission by reducing the demand for agricultural land and by increasing organic nutrient storage in the land. Carbon storage in these systems is high as compared with conventional systems (Lal, 1989).

Research Needs and Economic Considerations

Many uncertainties surround the factors influencing N_2O emissions from fertilizer. Cultivation practices and environmental practices that affect the fertilizer-derived emissions of N_2O have not been well quantified. Additional research in the following areas is needed:

• N_2O emissions by fertilizer type;

• the effect of crop type on emissions;

• the effect of water management practices on emissions;

• N_2O release from drainage and ground water;

• N_2O emissions from legumes and manure;

• the effect of tillage and herbicide use on N_2O emissions;

• how the rate of fertilizer application affects emissions;

• the effect on emissions of different fertilizer management practices, including fertilizer placement;

• how overall emissions from conventional and alternative cropping systems compare; and • the contribution of tropical agriculture to N_2O emissions.

Most fertilizer use in Asia is for rice cultivation. Rice is a significant source of both CH_4 and N_2O . Fertilizer management practices can affect the level of both CH_4 and N_2O production. The production of the two gases under different management regimes needs to be explored, and trade-offs evaluated. There is room for significant efficiency improvement in this area.

Agricultural policies in the U.S. dissuade the adoption of alternative agricultural practices and systems by economically penalizing those who adopt rotations, apply certain soil conservation systems, or attempt to reduce pesticide application. Federal policies have made high production levels a higher priority than protection of the resource base, sometimes encouraging inefficient fertilizer and pesticide use and unsustainable use of land and water.

Fertilizer subsidies, target prices, and loan levels encourage a level of fertilizer use that is above the economic and environmental optimum. Such policies also reduce the attractiveness of more efficient fertilizer application and use. Increased fertilizer prices and the threat of shortages in fossilfuel-based fertilizers should increase interest in fertilizer efficiency in the future.

ENTERIC FERMENTATION IN DOMESTIC ANIMALS

Livestock play a vital role within the agricultural sector, producing meat, dairy products, and fiber. Ruminant animals, including cattle, dairy cows, buffalo, sheep, goats, and camels have the capability of converting roughage into usable nutrients through microbial fermentation. This unique capability allows them to convert cellulosic plant material to milk, meat, and fiber that would otherwise be unavailable for human consumption. Some non-ruminant animals (e.g., horses and pigs) also produce CH4, although in much smaller quantities. Currently, ruminants contribute approximately 97% of the annual CH, emissions from domestic animals; non-ruminants contribute approximately 3%.

Protein of animal origin has the highest biological value of all sources of protein. Within the United States, animal products supply 53% of all foods consumed, including 69% of the protein, 40% of the energy, 80% of the calcium, and 36% of the iron in our diets (English et al., 1984). In developing countries, there is a continued and growing demand for animal proteins.

About 24% of the world's land area is in permanent pasture. Rangeland and pastureland combined account for over 50% of total land area in the world. Within Africa and Oceania (Australia and New Zealand), rangeland and pastureland comprise 65% and 75% of the land area, respectively (IIED and WRI, 1987). These areas are typically too steep, arid, rocky, or cold to be suitable for crops, but they provide forage for about 3 billion head of cattle, buffalo, sheep, and goats (FAO, 1986).

The type and function of livestock systems vary considerably around the globe. Within developed economies in which meat is a major export commodity, livestock are intensively managed for either meat or dairy production. Ranches within these economies are typically large and use management techniques such as selective breeding, rangeland management, feed enhancement, and the use of antibiotics to increase cattle production.

Livestock within these systems are typically larger animals, fed at least part of the time on a high-quality grain diet. Fodder crops are grown specifically for feeding cattle. Most beef cattle are fed a high-quality, lowcellulose diet in a feedlot for several months prior to slaughter. These animals have a much higher yield of meat or dairy product than similar animals in developing countries. Table 5-30 shows average meat production per animal in several regions of the world.

Within less developed economies, livestock are usually more integrated into the whole agricultural system, frequently as a part of a crop/livestock or pasture-based system. These animals are not always managed to maximize reproductive efficiency or slaughtered at the most efficient stage for optimal productivity. They are frequently maintained as scavengers and live on a lowquality forage diet.

Livestock serve as a buffer within agricultural systems by helping to stabilize cash flows and food supplies. Livestock production can serve to level out the effect of climate variability and the seasonality of rainfall in crop/livestock systems. Ruminant livestock can salvage energy and nitrogen from what otherwise could have been complete crop failures. In a grain crop failure, for example, vegetative matter suitable for livestock consumption is still produced. Livestock are convenient disposal systems for crop residues and provide a sink for surplus and damaged crops not suitable for human consumption (Raun, 1981).

In Tanzania and other Central African countries, tribal groups regard an increase in animal numbers as the best insurance against economic and social risk. The animals afford protection against the uncertainties of climate and destruction of crops by pests (Winrock, 1977). Livestock ownership enhances social status in many developing countries.

In addition to the production of meat, dairy products, and fiber, livestock are a source of fertilizer, fuel, and provide most of the tractor power in many developing countries. Animals are used for plowing, threshing, and providing power for irrigation. Draft animals can increase farm output several times by increasing the area that a farm family can cultivate. Within Africa and the Far East, over 80% and 90%, respectively, of all draft power is provided by animals (Raun, 1981).

Animal manure is used by about 40% of the world's farmers to enhance soil fertility. Dried dung can also be used as fuel. It is estimated that over 200 million tons of manure are used each year as fuel in developing countries (Winrock, 1977).

Management Practices Affecting Methane Emissions from Livestock

Enteric fermentation, the digestive process that makes livestock so useful, causes them to emit CH_4 into the atmosphere. The 1272 million cattle, 1140 million sheep, 460

TABLE 5-30

Average Meat Yield per Animal

(kilograms)

Region	Beef & Veal	Mutton & Goat
North America	87.7	11.1
Europe & USSR	59.7	6.6
Oceania	45.8	5.7
Latin America	29.4	2.7
Near East	17.3	4.4
Far East & China	8.2	4.0
Africa	13.6	3.5
World Average	31.2	4.7

Source: Stoddart et al., 1975.

million goats, 126 million buffalo (FAO, 1985), and assorted other domesticated animals contribute an estimated 65-100 Tg of CH₄ to the atmosphere annually. Of this amount, approximately 57% comes from beef cattle, 19% is from dairy cattle, and 9% is from sheep (Lerner et al., 1988). With the global cattle population increasing at 1.2% per year (see CHAPTER IV), livestock will continue to be a significant source of methane.

Livestock cannot metabolize CH_4 . It is lost energy, which neither contributes to the animal's maintenance, nor to the production of a product. Estimates of gross energy intake lost as CH_4 for cattle have ranged from 3.5% (Johnson, 1988) to 8.3% (Blaxter and Wainman, 1964).

Methane emissions from livestock are affected by differences in quantity and quality of feed, body weight, age, energy expenditure, and enteric ecology. All other things being equal, emissions are higher for animals that are heavier, have higher feeding levels and high-cellulose forage diets, and are ruminants. Emissions are also higher for work animals because some of the additional feed required to supply this energy is converted to CH_4 (Lerner et al., 1988). Manure is an additional, unquantified source of CH_4 (Winrock, 1977).

Although we know that animal type, feed type, and management practice affect the amount of CH_4 generated by an animal, few modifications to current practices are certain to reduce CH_4 production significantly.

Livestock System Productivity

Intensively managed, high-productivity livestock systems -- those with fewer, larger, and more productive animals -- produce more animal product per unit of CH_4 (Moe and Tyrell, 1979). In these highly managed livestock systems, as the feeding level is increased, the level of CH_4 production increases, but the energy loss in relation to gross energy intake decreases (Thorbek, 1980). An animal fed at maintenance level, however, loses a larger percentage of its gross energy intake to methanogenesis than does an animal fed at a higher level and has no increase in animal product.

The vast differences between livestock systems in developed and developing countries make variances in productivity difficult to compare. Additional benefits, such as the work output of draft animals, must be considered, but intensively managed, highproductivity livestock systems are the most efficient in terms of animal product yield.

Diet

At low levels of feed intake, or at slightly above maintenance, a high-cellulose forage diet results in lower CH_4 production per unit of feed than a high-nitrogen grain diet. Conversely, at high levels of feed intake, approaching three times maintenance, a highquality grain diet results in lower CH_4 production per unit of feed (Blaxter and Clapperton, 1965). Overall, CH_4 emissions from an animal at any level of feed intake seem to decline with increased digestibility of the feed (Gibbs et al., 1989).

This information suggests that feeding practices could be modified for some feedlot animals to reduce overall CH_4 emissions. Gibbs et al. (1989) suggest that "low-CH₄" diets could be identified that reduce CH₄ without sacrificing emissions animal The use of oils as a feed productivity. supplement also has potential for reducing CH_4 emissions. The implications of modifying feeding strategies on feed costs, animal productivity, and CH₄ emissions need to be thoroughly evaluated. Such analysis needs to consider energy inputs and N_2O emissions resulting from production of the feed. For example, the CH_4 reduction achieved from switching from a forage diet to corn could be largely offset by the N₂O production and energy consumption associated with the row crop. Once again, the whole system needs to be evaluated as a unit.

Nutritional Supplements

In developing countries, animals are generally living near maintenance levels and subsisting on a high-cellulose diet of forage and agricultural by-products such as wheat straw, rice straw, and sugar cane tops. Methane yields in these animals may be as high as 9-12% of gross energy intake due to low digestibility of the diet and ammonia deficiency in the rumen (Preston and Leng, 1987). If this is the case, providing nutrient supplements of urea or poultry litter to these animals could increase animal productivity and reduce CH_4 emissions. However, further research is needed in this area since no measurements of CH_4 generation have been done on livestock within farm conditions of developing countries.

Feed Additives

Feed additives, which increase feed use efficiency and reduce CH_A generation by modifying rumen fermentation, are currently available for beef cattle. These feed additives, known as ionophores, are fed to most feedlot cattle to improve the efficiency of beef production during finishing for market. lonophores reduce the amount of CH₄ produced by a ruminant by improving digestive efficiency (less is produced) and by causing the animal to eat less, which leaves less food in the gut to ferment. Ionophores improve the efficiency of beef production by 6-8%, while reducing CH_4 production by approximately 5% for animals on a forage diet, and by approximately 20% for animals on a high-grain diet (Johnson, 1988).

Ionophores have been shown to lose methane-suppressing effectiveness over time as the bacteria in the gut develops a tolerance to them (Johnson, 1974). A feeding program that alternates different ionophores has been suggested to improve overall efficiency by impeding bacterial adaptation (Hubbert et al., 1987).

The use of ionophores is predominately limited to feedlot cattle because of the difficulties associated with administering a drug to range cattle. Range cattle can be fed ionophores using a mineral block lick, but few range cattle receive this drug.

Feed additives are not currently available for dairy cattle, and are unlikely to become available because of problems with efficiency and chemical residues in the milk. In developing countries, where cattle are generally used for milk and meat production, ionophores cannot be used.

Methane from Manure

Under anaerobic conditions, microbial decomposition in manure generates CH_4 . The amount of CH_4 produced depends upon the waste management method used and temperature and pH of the system. The waste of livestock managed in confined feedlots or dairies is frequently piled or flushed into waste lagoons. Disposing of manure in lagoons or flooded fields creates anaerobic conditions conducive to the generation of CH_4 .

Overall CH_4 production from this source is uncertain, largely due to a lack of information on manure disposal by method, and lack of data on CH_4 production across a range of lagoon systems. Measurements of CH_{4} generation from waste lagoons and anaerobic digesters have been on the order of 0.14 to 1.0 cubic meters of volatile solids added to the lagoon (Safley and Westerman, 1988), which translates into about 12-85 kg of CH_4 per ton of manure (wet weight). Because a 600-kilogram (kg) dairy cow produces about 15 tons of manure per year (wet weight), the disposal of this manure in a lagoon could result in 120-825 kg of CH₄ emissions per head per year (Gibbs et al., 1989). This amount of CH_4 production is on the order of ten times that which originates in the animal's rumen, but this level is often not realized due to variability in disposal methods. Swine and poultry wastes produce a similar amount of CH₄ emissions per ton of waste (Gibbs et al., 1989).

Methane from manure can be captured and used as an energy source. Techniques are being developed and are in use for covering waste lagoons and capturing the CH_4 , which can then be used to generate electricity for use on the farm or can be sold to an electricity grid. Energy from manure can also be captured in the form of CH_4 in biogas plants. Manure produced by ruminants, particularly cattle and buffalo, is an ideal substrate for anaerobic fermentation in biogas plants. Methane from manure has a value of 5 kilocalories (kcal) per cubic meter (about 70% of the energy value of natural gas). In the U.S., the dung from about 40 cows could provide all of the non-mobile fuel for a farm family, including electricity. Disposal of manure in biogas plants can reduce CH_4 generation, while still providing a fertilizer source from the residue (Winrock, 1977).

Emerging Technologies

Efficiency improvements and advances in biotechnology have resulted in considerable productivity increases for beef cattle, dairy cattle, and sheep. Since 1940, dairy production in the U.S. has remained relatively constant while the herd size has been cut in half (English et al., 1984). Efficiency improvements should continue to produce gains in productivity, along with associated reductions in CH_4 emissions.

Bovine growth hormone, a bioengineered imitation of a naturally occurring protein in cattle, is expected to increase productivity in dairy cattle by 10-15%. This drug, which has not yet been approved by the U.S. Food and Drug Administration, is likely to decrease CH_4 production per unit of milk (Tyrell, 1988). A net decrease in CH_4 production could be achieved through a reduction in the size of the dairy herd.

Improving reproductive efficiency in dairy cows and beef cattle would reduce the brood herd requirement, and thereby decrease CH_{4} emissions by decreasing the livestock The total size of the cattle population. population can be reduced by reducing losses from disease, increasing the birth rate and decreasing the inter-calving interval of cows used to produce calves, and increasing the success rate of replacement heifers. In developing countries nutritional management programs may be required to improve the reproductive success rate and calf survival (Gibbs et al., 1989).

The development of a methanogenesis inhibitor for dairy cattle is unlikely in the near future. Improving the ionophore delivery system for range cattle could increase use of that additive. There is also some potential for reducing CH_4 production by inhibiting fungus in the rumen of cattle. These fungal interactions need to be more thoroughly investigated before fungal inhibitors can be developed.

Through longer-term research in biotechnology, there exists the potential to develop microbial species capable of converting hydrogen to a useful hydrogen sink, rather than to CH_4 . Acetic acid is such a hydrogen sink, which is useful as an energy source in cattle.

Animal scientists have long been working on the problems of improving feeduse efficiency and livestock system productivity and, thereby, the problem of CH_4 generation. This research should continue to reduce CH_4 generation per unit of animal product within highly managed systems.

Research Needs and Economic Considerations

Further research is needed on livestock in developing countries in order to devise a strategy to reduce CH_4 generation. For example, estimates of CH_4 generation are needed for a range of livestock (including draft animals) on a variety of diets. Also, the potential for using antibiotics, such as ionophores, on cattle needs to be explored.

We also need to quantify CH_4 generation from manure under a range of management and disposal options. Incentives may need to be provided to initiate further use of manure as an energy source.

Commodity programs in the U.S. encourage a larger cattle population than there otherwise would be. Unnaturally low grain prices, which are a result of price supports, are, in effect, a subsidy to beef and dairy production. Beef producers are also protected by a tariff, which in recent years has been converted to a variable levy (Schuh, 1988). These policies result in a larger cattle herd and increased production of CH_4 .

NOTES

- 1. EJ = exajoule; 1 exajoule = 10^{18} joules.
- 2. kJ = kilojoule, 1 kilojoule = 10^3 joules.
- 3. GJ = gigajoule, 1 gigajoule = 10^9 joules.
- 4. $PJ = petajoule; 1 petajoule = 10^{15} joules.$
- 5. $1 \text{ MJ} = 1 \text{ megajoule} = 10^6 \text{ joules}.$

6. Natural gas is mostly methane, but the methane content can vary from less than 70% to nearly 100% depending on the source of the gas. We refer to the vented or flared gases as methane, although other trace gases may also be present.

7. This estimate assumes a carbon content of 22% (Bingemer and Crutzen, 1987), that 90% of municipal solid waste generated is landfilled, and a conservative methane production efficiency of 0.25 ton of methane per ton of carbon.

- 8. 1 hectare = 2.471 acres.
- 9. t C = tons of carbon.
- 10. Pg = petagram. 1 $Pg = 10^{15}$ grams.

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CHAPTER VI

THINKING ABOUT THE FUTURE

FINDINGS

Decisions made in the next few decades about how electricity is produced, homes are constructed, and cities are laid out, for example, will have an impact on the climate in 2100 and beyond. While it is not possible to precisely predict the level of greenhouse gas emissions over this time period, it is possible to construct scenarios of economic and technological development, and a reasonable range for resulting greenhouse gas emissions, concentrations, atmospheric and global Global temperature temperature changes. change estimates provide an indicator for the rate and magnitude of climate change.

If stabilizing policies are not adopted, carbon dioxide $(\overline{CO_2})$ emissions are likely to grow by a factor of 2 to 5 during the next century, primarily due to expansion of global coal consumption. Options are available, however, that could stabilize or reduce CO_2 emissions. Despite the Montreal Protocol to control CFCs, without the June 1990 London Amendments global emissions of these compounds would remain constant, or even increase significantly. The stabilizing policy scenarios presented here were produced prior to the negotiations of the London Amendments and are somewhat more stringent than the London Amendments. Methane emissions could increase by 60-100%, or even more during the next century unless measures to control these emissions are taken.

• Although per capita emissions of greenhouse gases are currently very low in developing countries, their share of global emissions will probably rise significantly in the future.

• The relative contribution of CO_2 to greenhouse warming is likely to increase significantly in the future. Carbon dioxide accounts for at least 60% of the increased commitment to global warming between 2000 and 2100 in all of the scenarios analyzed in this report. This represents a significantly higher estimate of the role of CO_2 compared to its roughly 50% contribution to greenhouse forcing in the last few decades, but is similar to the estimated contribution of CO_2 to increases in the greenhouse effect over the last century.

• If there is no policy response to the risk of climate change, CO_2 concentrations are likely to reach twice their pre-industrial levels sometime in the latter half of the 21st century, but total greenhouse gas concentrations equivalent to this level may occur by 2030 or before, and are likely to occur before 2050.

• Even with modest economic growth and optimistic assumptions regarding technical progress, the world could be committed to an equilibrium warming of 1-2°C by 2000, 2-5°C by 2050, and 3-6°C by 2100 (assuming the climate sensitivity to doubling CO_2 is 2.0-4.0°C). Realized warming would be about 2°C by 2050 and 3-4°C by 2100.

• With rapid, but not unprecedented rates of economic growth, the world could be committed to an equilibrium warming of 1-2°C by 2000, 3-6°C by 2050, and 5-10°C by 2100 (assuming that the climate sensitivity to doubling CO_2 is 2.0-4.0°C). Realized warming would be 2-3°C by 2050 and 4-6°C by 2100. Estimated warming commitments greater than 6°C may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

• The adoption of policies to limit emissions on a global basis, such as simultaneous pursuit of energy efficiency, nonfossil energy sources, reforestation, the elimination of CFCs and other measures, could reduce the rate of warming during the 21st century by 60% or more. Even under these assumptions, the Earth could ultimately warm by 1-4°C or more relative to preindustrial times. Extremely aggressive policies to reduce emissions would be necessary to ensure that total warming is less than 2°C.

INTRODUCTION

Although technological advances in industry and agriculture have provided extraordinary wealth to a portion of the global population of over 5 billion people, these technologies have the potential to dramatically alter the Earth's climate by causing changes in the composition of the atmosphere as discussed in Chapters II through IV. Global increases in the atmospheric concentrations of carbon dioxide (CO_2) , nitrous oxide (N_2O) , methane (CH_4) , and chlorofluorocarbons (CFCs) are now well documented (see CHAPTER II), perhaps already committing the Earth to significant climate change. Myriad human activities are contributing to this situation, and continued population and economic growth raise the prospect of accelerated greenhouse gas buildup in the future (see CHAPTER IV).

If current trends in trace-gas concentrations continue, the average surface temperature of the Earth could be warmer than at any time in recorded human history by the second decade of the 21st century. If the composition of the atmosphere were stabilized by 2000, on the other hand, detectable climatic change is still possible, but its magnitude would be limited, and the rate of change might be similar to natural fluctuations recorded in the geologic record (Hansen et al., 1988).

What will happen in the future cannot be predicted. The future evolution of the atmosphere will depend largely on the paths of economic development and technological change, as well as on the physical, chemical, and biological processes of the Earthatmosphere system. While we have no control over this system once gases enter the atmosphere, economic and technological change will be influenced by policy choices made at local, national, and international This chapter explores some of the levels. paths that the world might follow in the decades ahead and provides an indication of the relative climatic consequences under these After a discussion of the alternatives. economic and social factors that determine emissions, six scenarios of economic and technological development are presented. These scenarios are not intended to capture the full range of possibilities; rather, they have

been developed in order to explore the greenhouse consequences of significantly different, but plausible, economic and technological conditions. The warming implications of these scenarios are analyzed using an integrated atmospheric stabilization framework described briefly in this chapter and in greater detail in Appendix A and ICF (1989). The chapter concludes by discussing the results of this analysis, compares these results with other studies, and evaluates how changes in key parameters affect our portraval of the rate and magnitude of global climate change.

APPROACH TO ANALYZING FUTURE EMISSIONS

The scope of this analysis must be global, and because of the long lags built into both the economic and climatic systems, this study must consider a time horizon of more than a century -- we chose 2100 as the ending year for the analysis. While this is an eternity for most economists and planners, it is but a moment for geologists. And indeed, decisions made in the next few decades about how electricity is produced, homes are constructed, and cities are laid out, for example, will have an impact on the climate in 2100 and beyond. Decisions about what kinds of automobiles and other industrial products to produce and how to produce them will also have a profound impact. These choices, which will affect the amount and type of fuel we use to travel, to heat and light our homes and offices, and to run our factories, will influence the magnitude of greenhouse gas emissions for many years.

The vast difference between the energy demand projections of the early 1970s and what has actually occurred in the 1980s illustrates the danger inherent in simple trend extrapolations, and even in making predictions based on results obtained from more complex econometric models. Our approach, then, is not an attempt to predict the future, but a construction of what we believe are logically coherent scenarios of possible paths of economic and technological development. An analytical framework is used to keep track of the assumptions, data, and relationships needed to define the scenarios. Our intent is to define the climatic risks associated with various economic/social/technological alternatives and, in so doing, increase the likelihood that these risks will be taken into account when policy decisions are made. If we believe that under a wide variety of assumptions about long-term economic growth and technological change the world will face rapid warming in the absence of political or economic forces arising from concerns over the greenhouse problem, then it will be necessary to seriously examine the options available for reducing greenhouse gas emissions.

Projections of greenhouse gas emissions are very uncertain, however, because of uncertainties in world economic growth, future fuel prices (which demonstrably affect both the intensities of their use and the substitution amongst alternative energy sources), future rates of land clearing, and rates of technological change, among other factors. For example, both the vagaries of the world oil market in the medium term, as well as uncertainties regarding the long-term relationship between the cost of producing fossil fuels, and the cost of using those fuels in ways that are relatively benign to the local environment, mean that at best we can only guess at future fossil-fuel use.

Another avenue of analysis, however, yields information that can guide policymakers who will be faced with these uncertainties. If we can construct scenarios of future energy demand, land-clearing rates, CFC production, etc., that are driven by reasonable assumptions about population growth, economic growth, technologies, and energy prices, then we can develop a plausible range of future greenhouse gas emissions. To accomplish this task we must consider the structural factors that determine the quantities and patterns of emissions of chemically and radiatively important trace gases (i.e., those gases whose presence in the atmosphere contribute to greenhouse warming).

It is conceptually useful to distinguish between production activities and consumption activities. *Production*, that is, the processing of bulk materials -- steel from ore, plastics from petroleum, cement and glass from limestone and silicate rock -- requires large amounts of energy per unit of industrial value added (i.e.,

the difference in value between an industry's products and its inputs) and may also be associated with direct emissions of greenhouse gases. For example, during cement-making, limestone ($CaCO_3$) is reformed to lime (CaO) and CO_2 , and the CO_2 is released to the atmosphere; during the making of plastic foams, CFCs are released. Much lower emissions per unit of value added are generally associated with fabrication and finishing. Food production leads to emissions of CH₄ and N_2O as discussed in Chapter IV, as well as to emissions of CO_2 and other gases as a result of the energy used on and, even more, off the farm. The large amount of energy required to move freight is also attributable to production activities. Consumption leads to greenhouse gas emissions as people use energy, primarily in pursuit of comfort (space heating and air conditioning) and mobility (automobile and air travel). Other major end uses for energy include refrigeration, lighting, water heating, and cooking.

Production

As societies develop over time, both the quantity and the structure of activities that influence emissions change radically. For example, energy use per unit of Gross National Product (GNP) has declined steadily and dramatically over the past 70 years in the United States, even in periods of declining real energy prices (see Figure 6-1). This decline is due to a combination of two factors. First, improvements in production processes, which often save capital and labor as well as energy, reduce the energy intensity per ton of physical output. For example, in steel production modern energy recovery and process technology make it possible to produce a ton of steel using only 13x10⁹ joules (13 GJ) of final energy, less than half of the current U.S. average.¹ New processes under development in Sweden (Elred and Plasma-Smelt) that integrate several operations have even lower energy requirements and reduced overall costs (Goldemberg et al., 1988). Second, the bulk of value added by industry tends to shift from basic materials processing to fabrication and finishing as a country's infrastructure matures. Williams et al. (1987) suggest that consumption of steel, cement, and other raw materials begins to decline after income surpasses about \$5000 (1985\$) per capita (see



Figure 6-2). These shifts in technology and the mix of products generally increase the share of energy consumed as electricity but do not significantly increase absolute electricity intensity because efficiency in electric end uses improves as well (Kahane, 1986). Rapid economic growth over the long term can be expected to accelerate the reduction of industrial energy intensity in wealthier countries by promoting the replacement of old plants and equipment with more efficient technology, as well as by accelerating the shift toward a less energy-intensive product mix.

In industrialized societies, services such as public and private administration, health care, and education are likely to grow faster than GNP, both because much of industry is being redefined as services and because much of our new wealth is being created by the development and transfer of information. Heating, air conditioning, and lighting, which dominate energy and electricity use in buildings today, will become less energyintensive (even as indoor environmental quality continues to rise) as more efficient technologies are adopted. At the same time, information technology is exerting upward pressure on electricity use per square foot in office buildings and schools. The Business Services sector depends more on electricity than does any other sector in the economy, although it still uses less electricity per unit of output than industry. If there is to be a large increase in electricity use in industrialized countries, it will most likely come from a massive expansion of the services sector.

The greatest potential for large increases in production-related emissions lies in developing countries. As these countries expand their industrial infrastructure, the demand for basic materials could skyrocket. But developing countries have the opportunity to take advantage of new processes and materials that sharply reduce the energy required to produce a given level of amenity. As a result, it is unlikely that materials and energy intensity per capita in developing countries would reach the levels of industrialized countries today, even as similar levels of per capita income are achieved. The extent to which developing countries seize these opportunities will strongly influence future greenhouse gas emissions.

Consumption

The factors influencing emissions arising from consumption are quite different from those that affect production. In developing countries, energy use in consumer products can be expected to increase rapidly as the number of households that can afford to acquire fans, televisions, refrigerators, and automobiles grows. Part of the reason that developing country energy demand has historically increased faster than it did in member countries of the Organization for Economic Cooperation and Development (OECD) is that households in developing countries can afford to purchase these products at lower income levels than households in industrialized countries. The declining price-to-income ratios for many of the energy-intensive consumer goods make this possible, with the consequence that energy consumption in developing countries tends to grow more rapidly than the experience of the industrialized countries might indicate. At the same time, the efficiency of many of these products is increasing, so that per capita energy consumption in developing countries may not reach the levels of industrialized countries today.

As a society becomes wealthier, it becomes saturated with energy-intensive equipment (there are, e.g., 600 cars for every 1000 people in the U.S. compared to 6 cars per 1000 in Asian countries). In addition, changes in the efficiency of the stock and how the stock is used become more important than changes in the levels of ownership alone. For example, as automobile ownership shifts from corporate to private hands, the number of vehicles increases dramatically, but the miles driven per vehicle declines. Consumers rarely consider energy use in making major purchases, and many key decisions that determine energy requirements are made by developers rather than by the consumers who pay the energy bills (Ruderman et al., 1987). Amenity levels can often be increased at the same time that energy use and emissions are reduced (better insulated houses are more comfortable because they are less drafty, and more efficient air conditioners are usually quieter), but more affluent consumers are likely to choose powerful cars and spacious dwellings, paying less attention to the





associated operating costs. Furthermore, because a very wide range of efficiency can be achieved with a small impact on total costs over the life-cycle of the product (see CHAPTER V; von Hippel and Levi, 1983; Ruderman et al., 1987), consumers who are concerned primarily about initial cost are unlikely to choose a product with the maximum level of efficiency justified on economic and environmental grounds.

The level and pattern of mobility may be the most significant uncertainty in future energy use. Will we spend our free time in our air-conditioned homes watching rented movies on the VCR/TV, or are we more likely to drive to the countryside to go hiking? Not surprisingly, the pattern of automobile use at present (roughly 1/3 of all passengerkilometers driven in the U.S. are to and from work, 1/3 are for family business, and 1/3 are in pursuit of leisure activities; OTA, 1988) is a function both of distances between where we live, work, and relax, and of how often we choose to move about. Similarly, airline travel, already dominated in the U.S. by personal rather than business travel, is increasingly determined by how and where people want to spend their free time. Meanwhile, in cities like Hong Kong, Sao Paulo, New York, and Los Angeles, congestion is increasingly constraining automobile use. The level of fuel economy and emissions achieved by a particular automobile in practice is very sensitive to average speed, which is down to about 15-20 miles per hour in Los Angeles and under 10 miles per hour in New York City (M. Walsh, pers. communication, 1988). How and whether cities solve these congestion problems -- with roads, car and van pools, buses, light rail, or all of the above -will have a large impact on both urban and global environmental quality.

SCENARIOS FOR POLICY ANALYSIS

In order to explore some of the implications of the relationships discussed briefly above, we have constructed six scenarios of future patterns of economic and technological development starting with alternative assumptions about the rate of economic growth and the adoption of policies that influence climate change (see Table 6-1). These six scenarios cannot capture all the possibilities, of course; rather, they allow us to explore likely climatic outcomes and the impact of strategies for stabilizing the atmosphere as well as policies that may accelerate emissions. The sensitivity of the results to a wide range of specific assumptions has been tested and is discussed later in this chapter and in Appendix C.

Two scenarios explore alternative pictures of how the world may evolve in the future assuming that policy choices allow unimpeded growth in emissions of greenhouse gases (these are referred to as the "No Response" scenarios). One of these scenarios, called a Rapidly Changing World (RCW), assumes rapid economic growth and technical change; the other assumes more gradual change and is called the Slowly Changing World (SCW). That is, we have invented one future with relatively high and robust economic growth and another representing a more pessimistic view of the evolution of the world's economies. The first world would likely illustrate the upper half of the potential range of future greenhouse gas emissions, because in general, higher economic activity means higher total energy use and emissions. Conversely, the second world could serve as a useful guide to the lower half of the range. In either case, our scenarios are first constructed as if there were no interventions motivated by global climate problems.

In constructing these two worlds/ scenarios, we have borne two important ideas in mind. First, there is evidence that with more rapid economic growth, energy-efficiency improves more rapidly than with slower growth (Schurr, 1982). This occurs because innovation proceeds more rapidly and because older, less efficient systems are more rapidly replaced with new technology. History shows, for example, that for almost every country, energy efficiency in industry increases with increasing incomes, as sophistication and scale win over brute force. At the same time, higher incomes allow people to spend more money on two key energy-intensive uses, space conditioning (heating and air conditioning), and automobiles. Thus, not all of the technological benefits of rapid economic growth put the brakes on overall energy use. But more rapid economic growth allows society to put resources aside to improve the

TABLE 6-1

Overview of Major Scenario Assumptions

Slowly Changing World

Slow GNP Growth Continued Rapid Population Growth Minimal Energy Price Increases Slow Technological Change Carbon-Intensive Fuel Mix Increasing Deforestation Montreal Protocol/Low Participation

Slowly Changing World with Stabilizing Policies

Slow GNP Growth Continued Rapid Population Growth Minimal Energy Price Increases/Taxes Rapid Efficiency Improvements Moderate Solar/Biomass Penetration Rapid Reforestation CFC Phaseout

Rapidly Changing World with Accelerated Emissions

High CFC Emissions Cheap Coal Cheap Synfuels High Oil and Gas Prices Slow Efficiency Improvements High Deforestation High-Cost Solar High-Cost Nuclear

Rapidly Changing World

Rapid GNP Growth Moderated Population Growth Modest Energy Price Increases Rapid Technological Improvements Very Carbon-Intensive Fuel Mix Moderate Deforestation Montreal Protocol/High Participation

Rapidly Changing World with Stabilizing Policies

Rapid GNP Growth Moderated Population Growth Modest Energy Price Increases/Taxes Very Rapid Efficiency Improvements Rapid Solar/Biomass Penetration Rapid Reforestation CFC Phaseout

Rapidly Changing World with Rapid Emissions Reductions

Carbon Fee High MPG Cars High Efficiency Buildings High Efficiency Powerplants High Biomass Penetration Rapid Reforestation efficiency of both space comfort and personal transportation. Similar patterns can be expected in other economic sectors.

Conversely, slower economic growth retards innovation, in part because neither consumers nor producers see bright economic times that would make innovation and expansion into new technologies useful. Comfort and mobility still manage to increase as important drivers of personal energy demand, but at a slower rate. When these two paths are compared, the effect of more rapid efficiency increases in the higher growth world is a narrowing of the difference in greenhouse gas emissions; that is, the likely difference between levels of emissions in the Rapidly and Slowly Changing Worlds is less than the differences in GNP. This result makes our scenarios somewhat more robust than one might otherwise think.

The second idea concerns energy prices. In a world of high and robust economic growth, which we have assumed in the RCW scenario, energy demand will likely increase, and in the medium term, so will energy prices. Yet if energy efficiency increases, then energy prices can increase more rapidly than the rate of economic growth and still not consume an increasing share of national wealth and income. In other words, energy prices can rise without putting the brakes on economic growth, as long as the price increases are gradual (CONAES, 1980). But in a world of sluggish economic growth, energy demand rises more slowly, so that energy prices would rise very little. This relationship is an additional reason why we believe that energy efficiency increases more rapidly in the high growth scenario (RCW) than in the low growth scenario (SCW).

With these ideas in mind, we can build scenarios of world energy demand by end use and region, as well as levels of other activities that emit greenhouse gases. The scenarios are not exact predictions; rather, they serve as guides to the level of emissions associated with each important purpose or end use in the worlds we constructed.

This approach allows us to compare the utilization efficiencies that we assume for the No Response scenarios with those we believe achievable if more than just market forces Two additional scenarios were acting. (referred to as the "Stabilizing Policy" scenarios) incorporate the same economic and demographic assumptions but also assume that policies to contend with global climate change are adopted. These scenarios are called the Slowly Changing World with Stabilizing Policies (SCWP), and the Rapidly Changing World with Stabilizing Policies (RCWP). In addition, we add a variant of the RCWP case called the Rapidly Changing World with Rapid Emissions Reductions (RCWR); for this scenario we assume that policies are more aggressive than those under the RCWP A fourth additional scenario scenario. assumes emissions accelerate because of policy choices that directly conflict with concerns about global warming: this scenario, called the Rapidly Changing World with Accelerated Emissions (RCWA), is more pessimistic than the RCW scenario since policy choices increase the rate of greenhouse gas buildup.

Using our best information about technologies that could become available, or technologies that are already available but not taken up by the market because of market failures or other reasons, we can reconstruct activity patterns that are still consistent with our overriding economic assumptions, but produce much lower (or higher) levels of greenhouse gas emissions. Key changes are assumed in energy efficiency, the energy supply mix, land-clearing rates, and other factors that might be changed by government policies or other means.

In other words, we keep the basic scenarios but, for example, manipulate important energy-use patterns within these scenarios. These manipulations can only be carried out if greenhouse gas emissions in each scenario are constructed from the bottom up, i.e., by specifying the level of each major emitting activity, as well as the emissions per unit of activity (e.g., total harvested rice paddy area and methane emissions per square meter of paddy).

Thus, the scenarios we constructed illustrate a range of greenhouse gas emissions under two quite different assumptions about economic growth and under various assumptions about adoption of a variety of strategies to reduce emissions. In the final analysis, our work can be turned around, and we can ask what level of economic growth, agricultural activity, policy implementation, etc., is necessary in order to leave the world's climate tolerable.

Scenarios with Unimpeded Emissions Growth

In a Slowly Changing World (SCW) we consider the possibility that the recent experience of modest economic growth will continue indefinitely, with no concerted policy response to the risk of climate change. In this scenario we assume that the aggregate level of economic activity (as measured by GNP) increases relatively slowly on a global basis (see Table 6-2). Per capita income is stagnant for some time in Africa and the Middle East as rapid population growth continues. Modest increases in per capita income occur elsewhere, and per capita growth rates increase slightly over time in all developing countries as population growth rates slowly decline (see Figure 6-3). The share of global income going to the developing world increases with time, but not dramatically. The population engaged in traditional agriculture and shifting cultivation continues to increase, as do demand for fuelwood and speculative land clearing. These factors lead to accelerated deforestation until tropical forests are virtually eliminated toward the middle of the next century.

In industrialized countries economic growth is sluggish, although per capita income reaches about \$40,000 by 2100 in the OECD. Because of slack demand, real energy prices increase slowly. Correspondingly, existing capital stocks turn over slowly, and production efficiency in agriculture and industry improve at only a moderate rate. The energy efficiency of buildings, vehicles, and consumer products also improves at a slow rate.

In a Rapidly Changing World (RCW) we assume that rapid economic growth and structural change occur and that little attention is given to the global environment. Per capita income rises rapidly in most regions and consumer demand for energy increases, putting upward pressure on energy prices. On the other hand, there is a high rate of innovation in industry, and capital stocks turn over rapidly, which leads to an accelerated reduction in energy required per unit of industrial output. An increasing share of energy is consumed in the form of electricity, produced mostly from coal. The fraction of global economic output produced in the developing world increases dramatically as post-industrial structural change continues in the industrialized world. As educational and income levels rise, population growth declines more rapidly than in the SCW scenario (see Figure 6-3).² Deforestation continues at about current rates, spurred by land speculation and commercial logging, despite reduced rates of population growth. Energy efficiency is not much of a factor in consumer decisions, as incomes increase faster than real energy prices. Private vehicle ownership increases rapidly in developing countries while air travel increases rapidly in wealthier ones. Nonetheless, significant reductions in energy intensity occur with technological innovation and structural change.

Scenarios with Stabilizing Policies and Accelerated Emissions

Three variants of the above scenarios explore the impact of policy choices aimed at reducing the risk of global warming. These scenarios, labelled Slowly Changing World with Stabilizing Policies (SCWP), Rapidly Changing World with Stabilizing Policies (RCWP), and Rapidly Changing World with Rapid Emissions Reductions (RCWR), start with the same economic and demographic assumptions used in the SCW and RCW scenarios, respectively, but assume that government leadership is provided to ensure that limiting greenhouse gas emissions becomes a consideration in investment decisions beginning in the 1990s. We assume that policies to promote energy efficiency in all sectors succeed in substantially reducing energy demand relative to the No Response scenarios, and that because of efforts to expand the use of natural gas, its share of primary energy supply increases relative to other fossil fuels in the near term. Research and development into non-fossil energy supply options such as photovoltaics (solar cells) and biomass-derived fuels (fuels made from plant material) assure that these options are available and begin to become competitive after 2000. In addition, the RCWR case

TABLE 6-2

Economic Growth Assumptions

(percent per year)

	<u></u>		Slowly Changing World		Rapidly Cha	nging World
	1965-1975	1975-1985	1985-2025	2025-2100	1985-2025	2025-2100
<u> </u>	······································		· · · · · · · · · · · · · · · · · · ·			
US & OECD	3.9	2.8	1.7	1.0	2.7	1.5
USSR & Eastern Europe	6.2	NA	2.2	1.6	4.3	2.6
Centrally Planned Asia	7.0	7.8	3.2	2.5	5.1	4.0
Other Developing Countries	5.6	3.2	2.7	2.1	4.5	3.3
World	4.4	2.9*	2.0	1.5	3.4	2.6

^a Excludes USSR and Eastern Europe.

Source: Historical rates taken from IMF, 1988. Assumptions derived from World Bank, 1987.



POPULATION BY REGION



Sources: U.S. Bureau of the Census, 1987; Zachariah and Vu, 1988.

considers the imposition of even more aggressive policies (compared to the RCWP case) such as a substantial carbon emission fee and rapid reforestation. In all three scenarios, non-fossil energy sources meet a substantial fraction of total demand in later periods. The Montreal Protocol to reduce CFC emissions is assumed to be strengthened, leading to a phaseout of fully halogenated compounds and a freeze on methyl chloroform. A global effort to reverse deforestation transforms the biosphere from a source to a sink for carbon, and technological innovation and controls reduce agricultural, industrial, and transportation emissions of greenhouse gases.

While the general policy assumptions apply to the SCWP, RCWP, and RCWR cases, the degree and speed of improvement are higher in the Rapidly Changing variants because technological innovation and capital stock replacement are greater in these cases. In the long time frame of our analysis, lifestyles will certainly change, although the policies we consider do not restrict basic living patterns. For example, energy use in buildings is greatly reduced in the Stabilizing Policy scenarios relative to the No Response scenarios, but the floor space available per person and the amenity levels provided are assumed to be the same. The technological strategies available to achieve the Stabilizing Policy scenarios were discussed in detail in Chapter V; the policy options for implementing these strategies will be examined in Chapters VII and VIII.

The fourth policy case considers a Rapidly Changing World with Accelerated Emissions (RCWA). In this scenario, not only are concerns over climate change ignored, but other policies adopted actually exacerbate the buildup of greenhouse gas emissions. For example, current U.S. energy policy is to increase coal production and use, reduce dependence on imported oil, and boost employment; the U.S. Department of Energy (U.S. DOE) has made numerous suggestions concerning various policies to increase the role of coal in relative and absolute terms (U.S. DOE, 1988; National Coal Council, 1987; see Figure 6-4). Furthermore, recent initiatives in utility regulation and alternative fuels may also increase greenhouse gas emissions.

Improving the efficiency of coal combustion in so-called "clean coal" technologies may reduce greenhouse gas emissions relative to the current generation of coal-burning plants. Over the long run. however, more efficient coal-burning technologies may increase greenhouse gas emissions by making coal economically attractive relative to other fuels. (This proposition is tested in the modeling analysis presented below.) Numerous policy proposals have also been made to increase U.S. coal exports in order to improve the balance of trade. A recent proposal by the U.S. DOE coal advisory committee would link exports of clean-coal technology to an agreement to purchase U.S. coal, a policy that might slow the adoption of more efficient technology for burning less expensive domestic coal in some developing countries like China (National Coal Council, 1987).

The need to consider more carefully the potential impact of government decisions on greenhouse warming is evident from analyses of two recent policies with ambiguous impacts on greenhouse warming. The Alternative Motor Fuels Act of 1988 (Public Law 100-494) creates incentives for auto manufacturers to produce vehicles powered by methanol, ethanol, and substitutes for gasoline. This program was adopted to lessen dependence on imported oil and to improve urban air quality. During Congressional debates, however, concern was expressed that if methanol were produced in large quantities from coal, the result would be a significant increase in greenhouse gas emissions. Congress therefore included a provision for study of this (The potential effect of relationship. accelerated synthetic fuels development is presented below.)

Another example of a policy with ambiguous, but potentially significant, effects on greenhouse gas emissions is rule changes proposed by the Federal Energy Regulatory Commission (FERC) to facilitate non-utility power production. The draft environmental impact statement on these rules concluded that coal-fired technologies have, so far, played a limited role in the development of independent power projects relative to resource recovery, hydroelectric power, and natural gas. As a result of the FERC



proposals, coal could assume a much larger role in future non-utility power production because (1) cogeneration requirements that are typically incompatible with the most economic coal technologies would be eliminated, and (2) larger firms that have the resources necessary to undertake large-scale coal projects would find the electric power market more attractive. Alternative assumptions, however, imply natural gas use will grow much more than coal (FERC, 1988).

ANALYTICAL FRAMEWORK

To make it possible to assess the implications of the kinds of scenarios just described, we have developed an integrated analytical framework to organize the data and assumptions required to calculate emissions of radiatively and chemically active gases, concentrations of greenhouse gases, and the rate of temperature change. This framework is described very briefly here, and in more detail in Appendix A and ICF (1989).

The analytical framework consists of four emissions modules and two concentration modules as shown in Figure 6-5. The four emissions modules use input data, including scenario specifications for population growth, GNP, energy efficiency, etc., to estimate emissions of greenhouse gases for nine regions of the globe (see Figure 6-6). Emissions are calculated every 5 years from 1985 to 2025 and then every 25 years through 2100. Emissions of the greenhouse gases CO_2 , CH_4 , N_2O , and numerous CFCs are explicitly calculated within the framework. Emissions of carbon monoxide (CO) and nitrogen oxides (NO_{x}) , which are not themselves greenhouse gasés, are also explicitly calculated, since these gases can significantly alter the chemistry of the atmosphere and thus affect the concentrations of the greenhouse gases. The concentrations of other greenhouse gases, such as water vapor and ozone, are calculated implicitly, or explicitly, as a function of the other gases. The atmospheric composition and ocean modules together estimate global concentrations of the greenhouse gases resulting from the projected emissions and increases in global temperatures resulting from the calculated concentrations. The atmospheric trace-gas

concentrations and temperatures affect the emissions and concentration modules in the next time period.

Energy Module

The energy module consists of a Global Energy Supply Model (SUPPLY), which is based on the energy- CO_2 model of Edmonds and Reilly (1983a, 1984) and was developed by ICF Inc. for this study; a global energy end-use analysis (DEMAND), conducted by the World Resources Institute and Lawrence Berkeley Laboratory; and combustion emission coefficients developed by Radian Corporation (1987).

DEMAND estimates energy consumption based on specific assumptions about the level of energy-using activities and technical efficiency by region and sector (i.e., industry, transportation, buildings). Although this analysis provided more detail than most previous global studies, this level of aggregation obscures many important variations, particularly for developing countries. For example, per capita incomes vary from \$150 for Bangladesh to \$7000 for Singapore within the South and East Asia region. The share of energy used by the manufacturing sector, vehicle ownership levels, and types of fuels used (particularly the importance of biofuels), all vary from one economy to another. In conducting the analysis, we capture some of this diversity by examining energy use by region and by income group within regions. For the first four scenarios, detailed analysis was performed for 2025 to anchor the demand estimates calculated for other years using SUPPLY. The RCWR and RCWA scenarios were analyzed using more aggregated assumptions ίΠ SUPPLY, as variants of the RCWP and RCW scenarios, respectively.

SUPPLY includes estimates of energy resources and costs by region and can balance supply and demand using a highly aggregated estimate of demand as a function of price and income. Supply-demand equilibration takes place within SUPPLY, which projects fuel mix and final prices. Trace-gas emissions are calculated by allocating the final fuel

FIGURE 6-5

STRUCTURE OF THE ATMOSPHERIC STABILIZATION FRAMEWORK







technologies for which emission coefficients are available. Additional emissions associated with fuel production are also estimated.

Industry Module

The industry module consists of a CFC model and a model for other non-combustion, industrial trace-gas sources. The CFC model was developed by U.S. EPA for use in assessing stratospheric ozone depletion (U.S. EPA, 1987). It projects production and emissions of the following compounds: CFC-11, CFC-12, HCFC-22, CFC-113, CCl₄, CH₃CCl₃, CH₃Cl, CH₃Br, CF₄, halon 1211, and halon 1301. Other industrial sources of trace gases include landfilling and cement production. Emissions from these activities are estimated as a simple function of population and per capita income.

Agriculture Module

The agriculture module uses the IIASA/IOWA Basic Linked System, or BLS (Frohberg, 1988), to forecast fertilizer use, agricultural land use, and agricultural production. These estimates are used with emission coefficients derived from the literature to calculate emissions of N_2O from fertilizer use, CH_4 from rice production, CH_4 from enteric fermentation in domestic animals, and emissions of CH_4 , N_2O , NO_x , and CO from the burning of agricultural wastes.

Land-Use and Natural Source Module

This module consists of components dealing with several land surface processes and other natural sources of trace gases. The most important of these is carbon dioxide released from land-use change, particularly deforestation, which is projected with the Biological Laboratory/Terrestrial Marine Carbon Model, or MBL/TCM (Houghton et al., 1983), based on assumptions about future rates of land clearing. Other anthropogenic emissions related to land clearing, such as a portion of CO emissions from biomass burning and N_2O emissions from land disturbance, are scaled based on the CO_2 emissions calculated by the MBL/TCM. Natural emissions of CO, CH_4 , N_2O , and NO_x from sources such as forest fires, wetlands, soils, oceans, and fresh water are based on values from the literature

and generally are held constant throughout the projection period (biogeochemical feedbacks can be assumed to alter these emissions; see end of this chapter).

Ocean Module

Ocean uptake of heat and CO_2 are modeled using the Box-Diffusion approach introduced by Oeschger et al. (1975) as implemented for the Goddard Institute for Space Studies general circulation model (GISS GCM) (Hansen et al., 1984). The ocean mixing parameter for heat uptake is chosen to reproduce, as closely as possible, the time scales obtained in the time-dependent calculations with the GISS GCM (Hansen et al., 1988). Alternative values for this parameter can be used to approximate the time scales of other approaches to estimating ocean heat uptake (see end of this chapter). Alternative ocean model formulations for CO_2 , such as the Advective-Diffusive Model of Bjorkstrom (1979) and the Outcrop-Diffusion Model of Siegenthaler (1983), are included in the integrating framework and can be used for alternative estimates of CO₂ uptake. Total carbon uptake is calibrated using estimates of historical emissions of CO_2 from fossil fuels (Rotty, 1987a,b) and deforestation (Houghton, 1988). The atmospheric CO_2 concentration is assumed to be 285 parts per million by volume (ppm) in 1800 and is forced to be equal to the values obtained at Mauna Loa for the period of record (1960-1985). The excess flux required to meet these conditions is calculated and held constant in the future at the average value for 1975-1985. Alternative assumptions are considered in Appendix C.

Atmospheric Composition and Temperature Module

The atmospheric composition model was developed for this study (Prather, 1989). It estimates changes in the concentration of key atmospheric constituents and the global radiation balance based on the emissions/ uptake projected by the other modules. Perturbations to atmospheric chemistry are based on first-order (and incorporated occasionally second-order) relationships derived from more process-based chemical models and observations. The model is zero-dimensional, but it essentially

distinguishes between the northern hemisphere, southern hemisphere. troposphere, and stratosphere. Global surface temperature change is calculated based on the radiative forcing of the greenhouse gases derived from Lacis et al. (1981) and Ramanathan et al. (1985) coupled to heat uptake by the ocean model using a specified climate sensitivity parameter. This sensitivity parameter is set to yield a global equilibrium temperature increase of 2°C or 4°C when the CO_2 concentration is doubled, reflecting a central estimate of the range of uncertainty; a broader range of possibilities is examined later in this chapter (see CHAPTER III).

Assumptions

Population Growth Rates

The population estimates for the Rapidly Changing World scenario were developed from Zachariah and Vu (1988) of the World Bank; for the Slowly Changing World scenario, estimates were taken from the U.S. Bureau of the Census (1987). These two sources agree quite closely on the size of the world's population through 2000, then diverge thereafter due to different assumptions about the rate at which the global population will stabilize. Zachariah and Vu (1988) assume that population growth rates in developing countries will begin to decline markedly after 2000, achieving a net reproduction rate of unity in every country by 2040. (A net reproduction rate of unity indicates that people of child-bearing age have children at a replacement rate; it eventually leads to a stable population level.) U.S. Bureau of the Census (1987) assumes that global population stability will occur at a later date, with developing countries experiencing rapid population growth rates until the middle of the next century.

Economic Growth Rates

The primary source for the economic growth rate estimates was the World Bank (1987). In their report, Gross Domestic Product (GDP) forecasts were provided for the 1986-1995 period for several different types of country groups. Most countries could be classified into one of these three general categories: low income, middle income, or

industrialized. In addition, the World Bank defined several other more select groups for which separate growth rates were estimated, including oil exporters, exporters of manufactured products. highly indebted countries, and sub-Saharan Africa. The World Bank's low growth case was used as a starting point for this analysis because these estimates were more consistent with recent historical trends and other forecasts. For the RCW (SCW) scenario these initial values were generally increased (decreased) by one percentage point for developing and Eastern European countries and by one-half percentage point for OECD countries to reflect the greater uncertainty regarding future growth in developing and centrally-planned economies. The growth rates were applied for the period 1985-2000, and were generally reduced by one-half percentage point each 25year period, beginning in 2000, to reflect structural change and the decline in population growth rates over time. Nonetheless, GDP per capita continues to increase throughout the projection period, although the rate of growth is substantially lower in the SCW scenario.

Oil Prices

The oil prices used in this analysis were taken from EIA (1988), which supplied a range of oil price forecasts. The Middle Price forecast from U.S. DOE was used for the RCW scenario (by 2000 the world oil price is about \$31/barrel in 1987 dollars), while the Low Price forecast was used for the SCW scenario (oil prices by 2000 were about \$25/barrel in 1987 dollars). Since the U.S. DOE price forecasts did not extend beyond 2000, oil prices were derived from the SUPPLY model; in each scenario prices escalated about 0.8% annually from 2000 to 2100.

Limitations

This analytical framework attempts to incorporate some representation of the major processes that will influence the rate and magnitude of climate change during the next century within a structure that is reasonably transparent and easy to manipulate. In so doing we recognize a number of major limitations: • Economic growth rates are difficult to forecast. Our alternative assumptions may not adequately reflect the plausible range of possibilities. In particular, we have assumed that aggregate economic growth rates will generally decline over time from the levels assumed for 1985-2000; this may not be the case.

• Economic linkages are not fully captured. The economic analysis uses a partial-equilibrium framework, making it impossible to ensure that the activity levels assumed in each sector are completely consistent with the aggregate economic assumptions. In addition, capital markets are not explicitly considered. This is particularly significant in examining developing countries, as it is unclear if they will be able to obtain the capital investments needed to develop the energy supplies assumed in some of the scenarios.

Technological changes are difficult to Substantial improvements in the forecast. efficiency of energy-using and energyproducing technologies are assumed to occur even in the absence of substantial energy price increases or policy measures. If this assumption proves to be untrue, then greenhouse gas emissions may be substantially underestimated in the No Response and Accelerated Emissions scenarios. Similarly, aggressive research and development is assumed to substantially reduce the cost of renewable technologies in the Stabilizing Policy scenarios. The impact of policies may be overestimated if such improvements fail to materialize or if they would have materialized as rapidly even without increased government support.

• Detailed cost analyses have not been conducted. Technological strategies have been screened based on judgments about their potential cost-effectiveness, but no attempt has been made to rank the cost-effectiveness of each strategy or to estimate the government expenditures or total costs associated with the stabilizing strategies.

• The modules of the framework are not fully integrated. Existing models of individual processes that affect greenhouse gas emissions were assembled within the analytical framework and were used with consistent assumptions. However, it was not possible to ensure complete consistency of results. For example, while the biomass energy supplies arrived at in the Energy module do not appear to be inconsistent with the land-use patterns calculated in the Agriculture and Land-Use and Natural Source modules, there is no explicit coupling among these results.

• The ocean models employed are highly simplified. The ocean plays an important role in absorbing both CO_2 and heat. The one-dimensional models used to represent this process may not adequately reflect the underlying physical processes, particularly as climate changes.

Changes in atmospheric chemistry are calculated in a highly simplified fashion. Chemical interactions are analyzed based on parameters derived from detailed chemical models. These parameters may not adequately reflect the underlying chemistry, particularly as atmospheric composition changes the significantly from current conditions. Also, it is not possible to explicitly model the heterogeneous conditions that control, for example, tropospheric ozone concentrations. In our analysis we also assume that nonmethane hydrocarbon emissions remain constant, which may cause future methane and ozone changes to be underestimated.

SCENARIO RESULTS

Using the integrated analytical framework developed for this study, we have estimated the implications of the six scenarios described above for emissions of chemically and radiatively important trace gases arising from energy production and use, industrial processes, changes in land use, and agricultural activities. The resulting changes in atmospheric composition and global average temperature increases are also estimated for all six scenarios.

Energy Production and Use

The single most important determinant of greenhouse gas emissions is the level of energy demand and the combination of sources that is used to supply that energy. Given the dominance of fossil fuels as a source of greenhouse gas emissions, technologies to reduce use of fossil fuels must play a central role in any effort to stabilize concentrations. Fossil-fuel-based technologies supply over 70% of global primary energy needs in the No Response scenarios. A major focus for policies to reduce emissions, as discussed in Chapters VII and VIII, must accordingly be to promote demand-side measures that reduce total energy demand and supply-side measures that promote less carbon-intensive fuels.

The No Response scenarios assume that technological innovation and market forces will yield substantial efficiency gains. The range of demand-side measures discussed in Chapter V illustrates how this assumed efficiency improvement might occur, as well as improvements incorporated into the Stabilizing Policy scenarios.

End-Use Consumption

Government policies that affect demand for energy are likely to be the most important determinant of greenhouse gas emissions in the near term. Figure 6-7 illustrates global end-use energy consumption by region. Total end-use energy consumption increases from 227x10¹⁸ joules (227 EJ) in 1985 to 344 EJ in 2025 in the SCW versus 458 EJ in the RCW.³ Greater improvements in energy efficiency in the SCWP, RCWP, and RCWR cases reduce end-use demand in 2025 by 15%, 22%, and 27%, respectively, relative to the No Response scenarios; smaller improvements in energy efficiency in the RCWA case increase end-use demand in 2025 by 35%. Extrapolating these trends to 2100 yields 429 EJ in the SCW and 850 EJ in the RCW scenarios, while in the Stabilizing Policy cases there is 21%, 42%, and 45% lower demand, respectively; in the RCWA case, end-use demand is 67% higher compared to the RCW case.

In each scenario, the growth in end-use demand is driven almost entirely by countries outside the OECD (USSR, Eastern Europe, China, and other developing countries) as a result of higher rates of economic and population growth in these regions and of more rapid efficiency improvements and the saturation of energy-intensive technologies in the OECD (e.g., steel production, automobile transportation, and central heating). Fuel use, in particular, is not expected to grow significantly in the U.S. and other OECD countries as efficiency gains compensate for increases in floor space, mobility, and production. Electricity use is projected to grow much more rapidly than fuel use in all cases, and significant increases in OECD electricity demand are reflected in the RCW.

It is important to note that both the SCW and RCW scenarios assume substantial efficiency due gains to technological innovation and market forces. For example, fuel use per square meter of residential and commercial floor space is assumed to fall by 45-55% in the United States and Western Europe by 2025. Similarly, fleet average fuel efficiency of U.S. cars and light trucks reaches 7.8 and 6.9 liters per 100 kilometers (liters/100 km), or 30 and 34 miles per gallon (mpg), in the SCW and RCW scenarios, respectively. In the SCW, industrial energy use per unit of GNP falls by 1.5-2%/yr in the industrialized countries, in accordance with recent trends. This rate accelerates to 2-3.5%/yr in the RCW, the highest rate of improvement stemming from the USSR and Eastern European countries as they have the highest initial industrial energy intensities. Less optimistic assumptions about efficiency gains in the No Response scenarios would imply higher rates of associated temperature rise as shown by the RCWA scenario and greater relative improvement in the Stabilizing Policy scenarios.

In developing countries, the use of biofuels for cooking is strongly influenced by urbanization and the efficiency with which these fuels are used. Urban populations have better access to modern fuels, and thus, a smaller share of urban households will use traditional fuels. There is substantial scope for improvement in the efficiency of biomass Laboratory experiments in Asia with use. improved cookstoves suggest that it is possible to achieve efficiencies of up to 33% (compared with current averages of 8%). However, experience from the last decade of improved cookstove dissemination projects suggests that efficiencies are unlikely to exceed 20% in the We assume the dissemination of field. efficient cookstoves to almost all users of biomass only in the Stabilizing Policy cases. Thus, the average efficiency of biomass use is



END-USE ENERGY DEMAND BY REGION

FIGURE 6-7

Vear

assumed to improve to 15-17% in each region in these scenarios. As a result of these efficiency improvements and because an increasingly larger share of the population is assumed to move to urban areas where there is better access to modern fuels, the amount of biofuels consumption declines in the household sector for each scenario.

Important structural shifts underlie the aggregate trends in these scenarios. Electricity's share of end-use consumption more than doubles in the RCW, from 14% in 1985 to 19% in 2025 and 30% in 2100, while it grows less dramatically in the SCW, reaching 21% in 2100. These trends are accentuated in the policy scenarios, as there appears to be even greater room for reductions in fuel use than in electricity use, partly because electricity is substituted for fuel in some highly efficient applications. For example, electricity accounts for 33% of end-use consumption by 2100 in the RCWP scenario because of dramatic increases in electricity use in developing countries. The distribution of energy use among the industrial, transportation, and residential and commercial sectors also shifts. In the RCW, the share of end-use energy going to the residential and commercial sectors declines slightly, then increases as the share going to industry increases until the middle of the 21st century and then declines. This pattern reflects the increasing importance of developing countries, which currently have low heating demands and a greater percentage of modern energy devoted to the industrial sector, but whose share of residential and commercial energy demands increases as incomes rise and industrialization proceeds. As the most intense phase of industrialization is completed, the transportation sector begins to take off, its share rising steadily after 2050. In the SCW scenario, the share of end-use energy consumed in the industrial sector grows less dramatically and does not peak until 2050, since industrialization in developing countries is stretched out over a longer time-span and dramatic increases in mobility are delayed. In the Stabilizing Policy scenarios, the growth in transportation energy use is suppressed by much higher fuel efficiency, and the share of end-use energy going to the residential and commercial sectors increases slightly toward the end of the next century.

Primary Energy Supply

While policies affecting demand will have the largest impact on near-term greenhouse gas emissions, changes in the supply mix will also be very important over the long term. Global primary energy supply by source under the six scenarios is shown in Figures 6-8 (exajoules per year) and 6-9 (percent share). Growth in primary energy production is substantially higher than growth in end-use energy consumption because of increased requirements for electricity and synthetic fuel production. For example, in the RCW scenario primary energy production increases from 300 EJ in 1985 to 650 EJ in 2025 and 1485 EJ in 2100, a 115% and 395% increase, respectively, compared with 100% and 275% increases in end-use consumption. In the RCWA scenario these increases are even more dramatic, with primary energy production increasing to 970 EJ in 2025 and 2595 EJ in 2100, increases of 225% and 765%, respectively, compared with increases in enduse consumption of 170% and 525%.

The use of synthetic fuels to supplement conventional oil and gas production becomes particularly important after 2025, influencing both total requirements and the mix of sources (see Figure 6-10). In the RCW, conventional oil production and gas production increase through 2025 and 2050, respectively, then begin to decline due to resource depletion (the share of primary energy supplied by oil and gas declines throughout the projection period). As a result, synthetic fuels are increasingly relied on to supply liquid and gaseous fuel requirements. By 2050, 19% of primary energy is used in synthetic fuel production, and this value increases to 39% by 2100. In the SCW heavy dependence on synthetic fuels begins later because conventional oil and gas resources are depleted more gradually. Coal is the dominant feedstock for synfuel production in both of these scenarios.

The mix of primary energy resources used to generate electricity is also crucial in determining future greenhouse gas emissions. While non-fossil energy sources (nuclear, solar, and hydro) increase their absolute contribution to primary energy supply in all scenarios, in the absence of policies to limit greenhouse gas emissions, it is likely that future electricity



PRIMARY ENERGY SUPPLY BY TYPE

FIGURE 6-8

Note: Scale is different for the RCWA case.

FIGURE 6-9



SHARE OF PRIMARY ENERGY SUPPLY BY TYPE

VI-25



0

2025

2100

2050

Year

ENERGY DEMAND FOR SYNTHETIC FUEL PRODUCTION

FIGURE 6-10

VI-26

2100

2050

Note: Scale is different for the RCWA case.

Year

0

2025

production will be dominated by coal-based technologies over the long term (in the near term, current gas prices make gas-based combustion turbine technology very attractive in many regions). Thus, in the RCW, demand for electricity and synfuel production pushes global coal consumption up by more than a factor of ten between 1985 and 2100. In the RCWA coal consumption by 2100 is nearly 25 times higher than 1985 levels; correspondingly, the share of primary energy supplied by coal increases, for example, in the RCW from 29% in 1985 to 42% in 2025 and 63% in 2100 (see Figure 6-9). The same forces are at work in the SCW, but the results are less dramatic. Coal production increases by less than a factor of four, and its share of primary energy reaches just over 50% by 2100 in the SCW scenario.

In the Stabilizing Policy scenarios, natural gas is relied on more heavily in the near term while accelerated research and development and other incentives are assumed to make several non-fossil electricity supply technologies strongly competitive over the long term. In particular, photovoltaics, biomass-based combustion turbines, and advanced nuclear reactors appear to be strong candidates to make a large contribution to future electricity production (these and other options were discussed in some detail in Chapter V). In the policy scenarios, these technologies begin to supply energy after 2000 and become strongly competitive by 2025. By 2050 they supply 54%, 62%, and 64% of global electricity in the SCWP, RCWP, and RCWR scenarios, respectively.⁴

It is also assumed that research priorities and other policies will promote the use of biomass-derived fuels rather than coalbased synfuels. In fact, in 2025 and 2050 total synfuel production is higher in the policy scenarios because biomass production and conversion is assumed to become competitive with imported oil and gas in many developing regions starting around 2010 (Walter, 1988). The particular mix among the non-fossil supply technologies shown in Figure 6-9 is rather arbitrary, but the type of non-fossil technologies is of little consequence to total greenhouse gas emissions. Greenhouse Gas Emissions From Energy Production and Use

The heavy reliance on coal in the SCW. RCW, and RCWA scenarios leads to large increases in both CO_2 and CH_4 emissions (see Figures 6-13 and 6-15 later in the chapter). In the SCW scenario energy-related emissions of CO_2 increase from 5.1 petagrams of carbon (Pg C) in 1985 to 7.6 Pg C in 2025 and 10.4 Pg C in 2100.⁵ Emissions ultimately reach more than twice this level in the RCW scenario: 11.2 and 25.0 Pg C in 2025 and 2100, respectively. In the RCWA, emissions are even higher: 19.8 Pg C in 2025 and 54.4 Pg in 2100 (see Table 6-3). This growth in emissions of 0.6 Pg C per decade in the SCW, 1.5 Pg C per decade in the RCW, and 3.8 Pg C per decade in the RCWA between 1985 and 2025 compares with the average growth of 1.1 Pg C per decade between 1950 and 1980.

Emissions of CH_4 from fuel production, predominantly coal mining, grow even more dramatically. The estimated emissions from fuel production in 1985 are 60 teragrams of CH_4 (Tg CH_4), or just over 10% of the total.⁶ In the SCW estimated emissions from this source increase to 98 Tg CH_4 in 2025 and 154 Tg CH_4 in 2100. The corresponding values for the RCW are 152 Tg CH_4 in 2025 and 389 Tg CH_4 in 2100, about 21% and 35% of the CH_4 total, respectively. In the RCWA, emissions from fuel production are 307 Tg CH_4 in 2025 and 855 Tg CH_4 in 2100, about 34% and 54% of the CH_4 total, respectively.

The combination of higher efficiency and greater reliance on non-fossil fuels assumed in the Stabilizing Policy scenarios serves to substantially curtail CO_2 and CH_4 emissions. In the SCWP and RCWP cases, CO_2 emissions from energy use reach only 5.6 and 5.9 Pg C in 2000, after which time they decrease, reaching 2.6 and 5.2 Pg C by 2100 in the two cases, respectively. In the RCWR case, CO_2 emissions from energy use are reduced even further, to 2.9 Pg C in 2025 and 1.5 Pg C in 2100. Similarly, CH_4 emissions from fuel production increase slightly in the RCWP, from 60 Tg CH₄ in 1985 to 81 Tg CH₄ in 2100, while they decline substantially in the SCWP and RCWR scenarios, to 39 Tg CH_4 in

TABLE 6-3

Key Global Indicators

		Year			
Parameter	Scenario ^a	1985	2025	2100	
GNP/capita	SCW, SCWP	3.0	3.7	7.1	
(1000 1988 \$)	RCW, RCWA RCWP, RCWR		6.7 6.7	35.9 35.9	
Primary Energy	SCW	300	460	650	
(EJ) [®]	RCW		650	1480	
	RCWA		970	2590	
	SCWP DCWD		390 520	510	
	RCWR		520	800 800	
Fossil Fuel CO2	SCW	5.1	7.6	10.4	
$(Pg C)^{c}$	RCW		11.2	25.0	
	RCWA		19.8	54.4	
	SCWP		5.5	2.6	
	RCWP		5.7	5.2	
	KUWK		2.9	1.5	
		1985-	2025	2025-2100	
GNP/capita	SCW, SCWP	0	.5	0.9	
(%/yr)	RCW, RCWA,	2	.0	2.3	
	RCWP, RCWR	2	.0	2.3	
Energy/GNP	SCW	-1	.0	-0.9	
(%/yt)	RCW	-1	.4	-1.5	
	RCWA	-0	4	-1.3	
	SCWP DCWP	-1	.4	-1.2	
	RCWR	-1	.1	-2.1	
Fossil Fuel	SCW	0	0.0	-0.1	
CO ₂ /Energy	RCW	0	.0	0.0	
	RCWA	0	.4	0.1	
(%/yr)	NC WA				
(%/yr)	SCWP	-0	.5	-1.4	
(%/yr)	SCWP RCWP	-0 -1	.5	-1.4 -0.8	

^a SCW = Slowly Changing World; SCWP = Slowly Changing World with Stabilizing Policies; RCW = Rapidly Changing World; RCWA = Rapidly Changing World with Accelerated Emissions; RCWP = Rapidly Changing World with Stabilizing Policies; RCWR = Rapidly Changing World with Rapid Emissions Reductions.

^b EJ = exajoule; 1 EJ = 0.948 quadrillion Btus.

^c Pg C = petagrams of carbon; 1 Pg = 10^{15} grams.

the SCWP and 19 Tg CH_4 in the RCWR by 2100.

Energy-related emissions, other than CO_2 and CH_4 emissions, are strongly affected by the type of control technology employed in addition to the total amount and type of energy used. Emissions of CO and NO_x associated with energy use can be expected to increase almost as rapidly as primary energy consumption in the absence of new policies. On the other hand, in the Stabilizing Policy scenarios NO, emissions are roughly constant, and CO emissions are cut by more than half. This assumes that the rest of the world gradually adopts control technology similar to that required of new mobile and stationary sources in the United States today, and that industrialized countries adopt standards consistent with the use of Selective Catalytic Reduction technology in utility and industrial applications after 2000, with developing countries following after 2025.

Comparison to Previous Studies

Despite the large range of outcomes illustrated by the six scenarios developed here, none of the global rates of change are unprecedented (see Table 6-3). Global reductions in aggregate energy intensity generally fall within the range of 1-2% per year; the lower value is consistent with longterm trends, and the higher value is consistent with recent experience. Changes in the amount of carbon emitted per unit of energy consumed (carbon intensity) between 1985 and 2025 vary from an increase of 0.4% per year in the RCWA to a decrease of 2.6% per year in the RCWR with significant declines apparent only in the Stabilizing Policy cases. The larger reductions in the Stabilizing Policy cases (up to 1.4% per year) may be difficult to achieve, but they are not unprecedented: carbon intensity declined by an average of 1.5% per year between 1925 and 1985 because of increased reliance on oil and gas over coal. The reduction in carbon intensity of 2.6% per year implied by the RCWR scenario is the most ambitious scenario.

While we know of no previous attempts to develop long-term scenarios for emissions of the full set of gases discussed above based on explicit economic and technological assumptions, there have been a number of previous studies that relate to many of the components examined here. Over the last decade there have been many studies of U.S. energy futures that can be compared to our U.S. results. In addition, there have been several recent studies of long-term global energy use and CO₂ emissions (see CHAPTER I). One recent study developed "conventional wisdom reference scenarios" for CH₄, CO, NO_x, and N₂O emissions related to major energy sources (Darmstadter et al., 1987). This section compares the scenarios presented here to those developed in previous work.

Since the OPEC oil embargo focused the world's attention on energy in 1973, numerous studies have examined the future of energy supply and demand in the United States. Those analyses contain much more detail, particularly in the short term, than is possible in this study, as our focus is necessarily global and long term. Nonetheless, it is useful to compare the results of this study for the U.S. with selected previous work. The National Energy Policy Plan (NEPP) prepared by the U.S. Department of Energy (U.S. DOE, 1988) and Energy for a Sustainable World (ESW), an international study supported by the World Resources Institute (Goldemberg et al., 1985, 1987, 1988) are examples of two important recent studies.

The results of these studies for the United States are summarized and compared with our scenarios in Tables 6-4 and 6-5. A key point is that both the SCW and RCW No Response scenarios developed here incorporate lower growth in energy use and CO_2 emissions than is projected in the NEPP reference and NEPP High-Efficiency cases. The largest discrepancies are in demand for electricity and consumption of coal, although all energy sources, other than gas, and all sectors show higher consumption in the NEPP The NEPP Reference Case projections. projects an increase of over 45% in U.S. CO_2 emissions between 1985 and 2010, while the High Efficiency case produces about a 20% By contrast, the RCW scenario, increase. which has GNP assumptions similar to those used in NEPP, estimates about a 20% increase in CO_2 emissions, while the SCW scenario predicts essentially flat emissions. In fact, the RCWA scenario is most similar to the NEPP

TABLE 6-4

Comparison of No Response Scenarios and NEPP: Year 2010

		U.S. End-Use Energy Demand (exajoules)							
		Estin				mates for 2010			
Sector		1985	SCW ^a	RC₩ ^b	RCWA ^c	NEPP-RC ^d	NEPP-HE		
Residential/Commercial	Fuel Electricity	11 5	12 7	12 8	14 9	13 9	19 ^r		
Transport	Fuel Electricity	21 0	22 0	21 0	22 0	23 0	22 0		
Industry	Fuel Electrícity	16 3	18 4	21 4	24 5	26 7	28 ^f		
Total	Fuel Electricity	48 8	52 11	53 12	60 15	62 15	55 13		
		U.S. Primary Energy Consumption (exajoules)							
		Estimates for 2010							
Primary Energy		1985	SCW	RCW	RCWA	NEPP-RC	NEPP-HE		
Coal		18	21	26	41	38	31		
Oil		30	31	30	30	35	33		
Gas		19	22	23	26	19	17		
Other ^s		8	9	11	8	22	20		
Total		75	84	91	106	114	101		
	<u></u>	U.S. Carbon Dioxide Emissions (petagrams of carbon)							
Estimates for 2010						s for 2010			
		1985	SCW	RCW	RCWA	NEPP-RC	NEPP-HE		
CO ₂		1.3	1.4	1.6	2.0	1.9	1.6		

^a Slowly Changing World scenario.
^b Rapidly Changing World scenario.
^c Rapidly Changing World with Accelerated Emissions scenario.
^d National Energy Policy Plan (NEPP) Reference Case (U.S. DOE, 1988)
^e National Energy Policy Plan (NEPP) High Efficiency Case (U.S. DOE, 1988)

' Fuel + Electricity. Separate values not given.

⁸ Excludes dispersed wood.

TABLE 6-5

	U.S. End-Use Energy Demand (exaioules)								
		Estimates for 2020							
Sector		1985	SCWP ^a	RCWP ⁵	RCWR ^c	ESW-S ^a	ESW-R ^e		
Residential/Commercial	Fuel	11	10	8	6	5	5		
	Electricity	5	6	6	5	4	4		
Transport	Fuel	21	17	13	10	12	14		
-	Electricity	0	0	0	0	0	0		
Industry	Fuel	16	14	16	16	14	15		
·	Electricity	3	3	4	4	5	5		
Total	Fuel	48	40	37	33	31	34		
	Electricity	8	10	10	9	9	9		
	U.S. Primary Energy Consumption								
		Estimates for 2020							
Primary Energy		1985	SCWP	RCWP	RCWR	ESW-S	ESW-R		
Coal		18	12	10	4	11	3		
Oil		30	25	19	14	13 ^f	14 ⁽		
Gas		19	19	20	19	13 [¢]	14 ^f		
Other ⁸		8	13	17	24	14	14		
Total		75	68	67	62	52	56		
	U.S. Carbon Dioxide Emissions								
	(petagrams of carbon)								
		1985	SCWP	RCWP	DCW/D	<u>FSW-S</u>	ESW.P		

Comparison of Stabilizing Policy Scenarios and ESW: Year 2020

^a Slowly Changing World with Stabilizing Policies.

^b Rapidly Changing World with Stabilizing Policies.

^e Rapidly Changing World with Rapid Emissions Reductions.

^d Energy for a Sustainable World, Goldemberg et al., 1987, 1988. Assumes a 50% increase in per capita GNP from 1980 to 2020. Note that the SCWP case assumes a 50% increase from 1985 to 2020.

1.0

1.3

0.9

0.6

0.7

0.8

^e Energy for a Sustainable World, Goldemberg et al., 1987, 1988. Assumes a 100% increase in per capita GNP from 1980 to 2020. Note that the RCWP and RCWR cases assume a 120% increase from 1985 to 2020.

^f Given as Oil + Gas. A 50% split is assumed following the global supply scenario given by Goldemberg et al., 1987, 1988.

⁸ Excludes dispersed wood.

 CO_2

Reference case, with energy use and CO₂ emissions virtually equal between the two cases. This similarity illustrates that if the NEPP reference case had been adopted as one of our No Response scenarios, the U.S. contribution to global emissions would have been substantially higher than what we have estimated in the SCW and RCW cases, and the difference between the No Response and Stabilizing Policy cases would have been significantly greater.

Comparing low emissions scenarios, U.S. energy use is considerably higher in our Stabilizing Policy cases than in those given in Energy for a Sustainable World (ESW), except in the RCWR case, where primary energy consumption is higher but end-use energy demand is about equal to the ESW-R case. The largest differences in consumption are in the residential and commercial sectors, with significant differences also in the transportation sector in the slow-growth cases. We assume that slower turnover of the housing stock leads to higher residential and commercial demand, particularly in the slowgrowth variant, whereas Goldemberg et al. (1985, 1987, 1988) assume that income does not affect demand in this sector. Despite higher energy consumption in our scenarios, our rapid-growth cases have similar or lower CO_2 emissions due to lower consumption of coal and heavier reliance on gas and non-fossil energy sources in the RCWP and RCWR scenarios compared to the ESW cases.

The global energy use and CO_2 emissions calculated for 2050 in the six scenarios developed here are compared to the bounding extrapolations discussed in Chapter IV and the results of selected previous studies in Table 6-6. With the exception of the RCWA case, the total energy use derived in our scenarios falls within the lower end of the range given by trend extrapolation and previous analyses. In those studies that included a "Base Case" that assumed no implementation of policies to reduce CO_2 emissions, the estimated primary energy demand for the year 2050 ranges from 21 to 52 terawatts (TW). This level of energy demand is approximately 2.2 to 5.5 times the 1985 consumption level of 9.4 TW. The RCW scenario has total energy demand (29.4 TW) that is quite similar to the Base Case

given by several previous studies, including Edmonds and Reilly (1984), Seidel and Keyes (1983), and World Energy Conference (1983). The Slowly Changing World scenario, with almost 50% less total energy use in 2050, lies between the median and 25th percentile nonzero correlation scenario of Edmonds et al. (1986) and Reilly et al. (1987). The estimated uncertainty bounds in the systematic uncertainty analysis conducted by Edmonds et al. (1986) are not symmetric; their median scenario has significantly lower energy use and CO_2 emissions than both the mean of their results and the result of using the median values for all model parameters. The implication is that very high energy-use scenarios may be much less probable than is suggested by simply considering the range given by many studies.

Compared to the energy use estimates, there is substantially less, though still considerable, variation in the CO₂ emissions estimates for 2050. None of the studies cited in Table 6-6 approach, within a factor of four, the result of exponentially extrapolating the pre-1973 rates of energy demand growth, assuming no change in the mix of sources. This reflects the constraint due to the finite size of the fossil-fuel resource base (see CHAPTER IV), which implies that very high growth in energy consumption would need to be accompanied by a significant shift away from fossil fuels (but not before atmospheric CO₂ concentrations reached extraordinarily high levels). Considering the full range of values for both energy use and CO_2 emissions represented in Tables 6-4 and 6-5, it does appear that, as intended, the SCW and RCW scenarios represent very different but not extreme possibilities.

While the general agreement found between this study and previous studies at the aggregate level may be comforting, substantial disagreements are possible when the results are examined more closely. For example, the global increase in energy demand obtained in the RCW scenario is the result of little growth in OECD countries coupled with very vigorous growth in energy demand in developing countries. Other scenarios with nearly identical global demand in 2050 may not distinguish among regions (e.g., Nordhaus and Yohe, 1983) or may have a more even pattern

TABLE 6-6

Summary of Various Global Primary Energy Forecasts for the Year 2050

Report	"Base Case"	Range	"Base Case"	Range
	(TW)	(TŴ)	(Pg C/yr)	(Pg C/yr)
This Study. No Response and RCWA cases		16.0-51.0	-	7.9-34.6
This Study, Stabilizing Policy and RCWR cases	a _	15.2-21.6	-	1.0-5.3
Trend Extrapolation (see CHAPTER IV)		10-130	-	19-240
Darmstadter et al. (1987)	35.1		22.2	
Edmonds and Reilly (1983b) ^a	52.2		26.3	15.7-26.3
Edmonds et al. (1984)	28.4	17-63	14.5	6.8-47.4
Edmonds et al. (1986); Reilly et al. (1987) ^b	21.3	12.7-38.8	7.7	4.3-18.7
Goldemberg et al. (1985) ^a	11.2 (2020)	11.2-14.8 (2020)	4.6 (2020)	4.6-5.9 (2020)
IIASA (1981)	-	22.4-35.7 (2030)	-	10-17 (2030)
IIASA (1983)	26.3	` ´	9.4	
Keepin et al. (1986)	-	10-35	-	2-20
Legasov et al. (1984)	42		13	
Lovins et al. $(1981)^{a}$	4.6		<1.0 (2030)	
Nordhaus and Yohe (1983) ^c	30.6	18.1-43.1	13.9	7.2-20.6
Reister (1984)	29.9	24.0-41.3	10.7	9.7-27.1
Rose et al. $(1983)^a$	-	16.3-32.3	-	2.7-15
Seidel and Keyes (1983) ^a	30.0		15	10-18
World Energy Conference (1983)	29.8	18.9-29.8	14.4	10.0-14.4

^a Policies to limit CO₂ emissions are explicitly considered in some or all of these cases.
^b Median, 25th, and 75th percentile, non-zero correlation between parameters.
^c Probability weighted mean ± one standard deviation.

Source: Adapted from Keepin et al. (1986). See text, Chapter I, and original sources for further discussion and notes.
of energy demand growth (e.g., Edmonds et al., 1984). Similarly, the GNP growth rate assumed in the RCW scenario is higher than what was assumed by Seidel and Keyes (1983), but because higher rates of technical efficiency improvements were assumed in the RCW case, energy demand and CO_2 emissions are almost identical in 2050.

The results obtained in the policy developed scenarios here are most appropriately compared with the results of Lovins et al. (1981), Rose et al. (1983), and Goldemberg et al. (1985, 1987, 1988). These studies all emphasize the possibility that increased efficiency of energy use could limit energy demand and CO₂ emissions while allowing for sustainable economic growth. They conclude that energy demand in 2050 could be held to between 5 and 16 TW by supplying energy services with advanced costeffective technology that is either available or nearly commercial today. In these scenarios, efficiency improvements combined with shifts in energy supply allow CO_2 emissions to be held at or below today's level, and Lovins et al. (1981) argue that it is technically feasible to reduce fossil-fuel CO₂ emissions by about 80% The SCWP, RCWR, and over 50 years. RCWP scenarios have global energy consumption of 15, 20, and 22 TW respectively in 2050 -- similar to, but somewhat higher than, what previous studies suggested was feasible. Part of this difference may be explained by the high rate of economic growth assumed in the RCWP case, and our assumption that efficiency measures are not adopted up to their technical potential, particularly in comparison to Lovins et al. (1981). The CO_2 emissions in the RCWP and SCWP scenarios are 10-20% below current levels, again consistent with some previous analyses. This result, however, is obtained in different ways. For example, like the RCWA case, the lowest CO_2 scenario given by Rose et (1983) assumes substantially al. more contribution from non-fossil energy sources than do the other policy scenarios developed here, while the Goldemberg et al. (1985, 1987, 1988) high-demand scenario has somewhat more oil and gas and less coal than does the RCWP case in 2020.

The estimates of energy-related (fossil fuel and wood use) emissions of CH₄, N₂O, NO, and CO developed in the RCW and RCWP scenarios are compared in Table 6-7 with results of a study by Darmstadter et al. (1987). While the main purpose of their study was to develop an historical database, reference values for future emissions are presented assuming either constant emission coefficients or coefficients declining by 1% per year. The emissions calculated with constant coefficients by Darmstadter et al. (1987) increase much more rapidly than those obtained in any of our scenarios. These differences are not too surprising given our explicit assumptions regarding technological change, including increasing penetration of emission control technologies. The largest discrepancy is for N_2O , reflecting not only our assumptions regarding technical change, but also the much higher initial emission coefficient adopted by Darmstadter et al. (1987) based on Hao et al. (1987) (see CHAPTER II). The initial estimate of CO emissions given by Darmstadter et al. (1987) is a factor of two lower than ours, probably due primarily to their extrapolation of the U.S. emission coefficient for gasoline to the rest of the world. We have attempted to account for variations in automobile emission control technology by region, with most regions having higher average CO emissions than the U.S. The closest agreement lies in CH_4 , probably because these emissions are directly proportional to the total quantity of coal and gas produced and are not assumed to depend on production technology in our No Response scenarios.

When Darmstadter et al. (1987) assume that all emission coefficients decline by 1% per year, they obtain estimates of NO_x emissions that are similar to those occurring in the RCW case and CH₄ emissions estimates closer to those obtained in the RCWP case. Their CO emissions estimate falls between these two Overall, the RCWP case has cases. significantly lower emissions than are obtained by Darmstadter et al. (1987) even when they decrease their emission coefficients by 1%/yr for a full century. This is a result not only because of the assumptions regarding emission

TABLE 6-7

Trace Gas	Scenario	Emissions of Trace Gases (teragrams)					
		1985/1980	2025/2030	2075/2080			
CH ₄	RCW	70	164 78	325 82			
(19 0114)	Darmstadter et al. (1987) ^a Darmstadter et al. (1987) ^b	63	192 117	432 131			
N ₂ O (Tg N)	RCW RCWP	1.2	2.4 1.6	3.8 1.4			
	Darmstadter et al. (1987) ^a Darmstadter et al. (1987) ^b	4.3	16 9.5	57 21			
NO _x (Tg N)	RCW RCWP	26	49 32	79 24			
(151)	Darmstadter et al. (1987) ^a Darmstadter et al. (1987) ^b	20	62 37	184 68			
CO (Tp C)	RCW RCWP	206	354 125	653 73			
	Darmstadter et al. (1987) ^a Darmstadter et al. (1987) ^b	108	292 177	614 226			

Comparison of Energy-Related Trace-Gas Emissions Scenarios

^a Constant emission coefficients.

^b Emission coefficients decline 1% per year.

control technology, but also because our policy scenarios have substantially lower total energy demand and a very different fuel mix.

Industrial Processes

Halocarbon Emissions

The most important industrial source of greenhouse gases not directly associated with energy use is the production and release of CFCs and halons. In both the SCW and RCW scenarios. the Montreal Protocol, as formulated without the June 1990 London Amendments, is assumed to come into force and apply throughout the projection period. This agreement (described in CHAPTERS IV, VII, and VIII) calls on developed countries to reduce their emissions of certain CFCs 50% from 1986 levels by 1998, and to freeze their use of halons at 1986 levels in approximately 1992. Developing countries with low per capita consumption, however, are allowed to increase the use of these compounds for up to ten years -- as a result, emissions of the controlled compounds could actually increase substantially, depending on the number of countries that participate in the Protocol and the rate at which use increases in developing and non-participating nations (Hoffman and Gibbs, 1988). The London Amendments were not included because this analysis was conducted prior to their adoption. The London Amendments were not included because this analysis was conducted prior to their adoption.

For the SCW scenario, we adopt the assumptions of the Protocol scenario developed for the Regulatory Impact Analysis of rules to implement the Montreal Protocol in the United States (U.S. EPA, 1988). Namely that, in addition to the U.S., 94% (in terms of current CFC consumption) of developed countries and 65% of developing countries participate in the agreement. In this scenario the global average annual growth rate in demand for products and services that would use CFCs, if they were available, is approximately 4.0% from 1986 to 2000 and 2.5% from 2000 to 2050 (constant production is assumed after 2050). Growth in demand is much higher in certain developing countries, particularly India and China. These growth rates are not applied directly to CFC use in

non-participating and developing countries, however, because it is assumed that shifts in technology development away from CFCs in the United States and other participating countries "rechannel" demand in other countries as well.⁸ In the RCW scenario, the rate of growth in demand was increased 75% to reflect the higher economic growth rates. Also, 100% of the developed countries and 75% of the developing countries participate in the Montreal Protocol. In the RCWA scenario, we have assumed a low rate of participation in and compliance with the Protocol, assumptions similar to those used in the "low case" analysis in the Regulatory Impact Analysis (U.S. EPA, 1988). The SCWP, RCWP, and RCWR scenarios assume that the Montreal Protocol is strengthened to produce a complete phaseout of CFCs in participating countries by 2003.9 This phaseout assumption is somewhat more stringent than the phaseout actions required by the June 1990 London Amendments to the Montreal Protocol.

A considerable amount of recent analysis evaluates the potential for further reducing emissions of CFCs and related compounds beyond what is required by the Montreal Protocol (see Hoffman and Gibbs, 1988, or Makhijani et al., 1988). A phaseout by 2000 appears to be feasible given that substitutes and alternative technologies now being developed and tested are expected to become available over the next decade as a result of the considerable research currently underway in response to the Montreal Protocol.

Figure 6-11 shows the estimates for emissions of CFC-11, -12, and -113, and HCFC-22 under the six scenarios. Emissions change more slowly than production because a significant portion of each year's production is "banked" in air conditioners, refrigeration systems, and closed-cell foams. The model keeps track of the size of this bank and estimates the gradual release of these CFCs. In the SCW scenario, emissions are relatively constant despite the Protocol's requirement of a 50% reduction in participating industrialized countries. After declining to 12% below 1985 levels between 1990 and 2020, emissions of CFC-11 begin to rise again, reaching 1985 levels by the end of the projection period.





EMISSIONS OF MAJOR CFCs

CFC-113 emissions also fall significantly for a few decades but rise again toward 1985 levels. CFC-12 emissions never decline to 1985 levels: they decline by 11% between 1990 and 2015, reaching a few percent above 1985 values, then they rise slowly, almost reaching the 1990 peak levels towards the end of the 21st century. Emissions of HCFC-22 grow rapidly as the compound is issued as a substitute for the fully halogenated species that have the highest ozone-depletion potential. Although HCFC-22 has a shorter lifetime and weaker radiative forcing than the fully halogenated compounds, it could make a significant contribution to global warming during the next century because it is not controlled by the Montreal Protocol (the London Amendments passed in June 1990 include a non-binding resolution to phaseout HCFCs).

In the RCW scenario, higher consumption growth rates in developing countries more than compensate for higher participation and rechanneling rates. CFC-11 emissions decline by no more than 6% below 1985 levels, while CFC-12 and -113 each increase by more than 25% by 2100. Emissions of HCFC-22 grow dramatically in this scenario. In the RCWA case emissions of all the CFCs increase rapidly until about 2050, and then flatten out. In the SCWP case emissions of the fully halogenated compounds fall by more than 80% from 1985 levels by 2025, which is sufficient to reverse the trend in concentrations (see Figure 6-16 later in the chapter). Emission reductions in the RCWP and RCWR cases are not quite as large, but the rate of growth in concentrations slows considerably after 2000. HCFC-22 emissions are assumed to be the same in the No Response and Stabilizing Policy cases; however, these emissions could rise as a result of a CFC phaseout if chemical substitution is the primary approach to eliminating CFCs, or fall, if product substitution and process redesign are the major approaches (see CHAPTER V).

Emissions From Landfills and Cement

Other important activities included in the industrial category are CO_2 emissions from cement production and CH_4 emissions from landfills. The growth of these activities in developing countries is assumed to be related to per capita income in a simple fashion, although growth is curtailed as current per capita levels in industrialized countries are approached. The result is a three to fourfold increase in CO₂ emissions from cement in the SCW and RCW scenarios, respectively, though emissions remain less than 0.5 Pg C/yr in all cases. Landfill CH_4 emissions increase by more than fivefold in the RCW, reaching 15% of the total by 2100. In the policy scenarios, advanced materials are assumed to reduce the demand for cement (relative to the No Response scenarios), while gas recovery systems and waste reduction policies are assumed to limit emissions from landfills. The result is that emissions from cement making still increase by a factor of two to three, but CH_{4} emissions from landfills are held essentially constant.

Changes in Land Use

Deforestation has been a significant source of CO_2 in the atmosphere over the last centuries, as indicated by two the measurements of CO₂ concentrations in Greenland and Antarctic ice, which show that concentrations began to rise before fossil-fuel use became significant (see CHAPTER II). If current trends continue, tropical forests could be completely eliminated during the next century, adding significantly to the CO_2 emissions from fossil fuels. On the other hand, efforts are underway to reverse deforestation; if these afforestation and reforestation efforts succeed, forests could become a net sink for atmospheric CO_2 . The total amount of carbon that can move in either direction between the atmosphere and terrestrial ecosystems is ultimately constrained by the area of forests available for deforestation or by the area of land available to support new forests. The timing and magnitudes of these carbon fluxes are determined by the timing and extent of changes in land use as influenced by local, national, and international policies.

The causes of deforestation are complex and vary from country to country. This makes it difficult to directly tie assumptions about deforestation rates to the economic and demographic assumptions of the general scenarios. Qualitatively, we assume that in a Slowly Changing World poverty, unsustainable

agricultural practices, and rapid population growth lead to continuously increasing pressure on remaining forests. The rate of deforestation is assumed to increase from current levels at the rate of population growth, and tropical deforestation increases from 11 million hectares per year (Mha/yr) in 1980 to 34 Mha/yr in 2047, when all the unprotected forests in Asia are exhausted. By 2078, all available tropical forests have been cleared. In а Rapidly Changing World, improved agricultural practices and the substitution of modern fuels for traditional uses of wood ease the pressure on forests. could Nonetheless, clearing of forest lands for agriculture, pasture, logging, and speculation could continue apace, even if small areas are set aside as biological preserves. In this scenario tropical deforestation is assumed to increase very gradually, reaching 15 Mha/yr in 2097, when the unprotected forest areas of Latin America are exhausted.

In the Stabilizing Policy scenarios, it is assumed that a combination of policies succeed in stopping deforestation by 2025, while about 850 Mha is reforested by 2100. Only land that once supported forests and is not intensively cultivated is assumed to be available for reforestation. These lands include 85% of the area currently involved in shifting cultivation (370 Mha) under the assumption that this practice is replaced by sustainable low input agriculture (Sanchez and Benites, 1987) and by planted pasture in Latin America (100 Mha), which is abandoned and allowed to support forests again. Of the reforested land, about 380 Mha of plantations are established in the tropics (sufficient to produce the biomass energy requirements of the RCWP or RCWR case depending on the productivity increases assumed; see Walter, 1988); the rest of the land absorbs carbon at a much lower rate but reaches a higher level of average biomass per hectare since the land is not routinely harvested.10

The carbon fluxes associated with these deforestation/reforestation scenarios based on Houghton's (1988) low estimates of average biomass are shown in Figure 6-12. In the SCW, CO_2 emissions from deforestation increase rapidly from 0.4 Pg C/yr to 2.4 Pg C/yr in 2046 before the Asian forests are exhausted. All available Latin American and

African forests are exhausted by 2075, reducing emissions drastically. Total deforestation emissions are almost the same in the RCW, but they are spread out over a longer period. Annual emissions are close to 1 Pg C/yr from 2000 to 2100. In the Stabilizing Policy scenarios the biosphere becomes a sink for carbon by 2000 and reaches its peak absorption of 0.5 Pg C/yr in 2015. The size of this sink declines gradually after 2025 as forests reach their maximum size and extent.

Agricultural Activities

The demand for agricultural products is a direct function of population but is not strongly dependent on income levels. Thus, there are only small differences in demand between the scenarios as the much higher incomes largely offset the somewhat lower populations in the RCW compared with the SCW. The land area used for rice production, and thus the methane emissions from this source, increases by only about 50% by 2100 in both the SCW and RCW scenarios (production per hectare increases by 80-Meat production increases more, 100%). about 125%, as demand rises with income to some extent. Satisfying the demands of increasing populations with a finite amount of land requires more intensive cultivation, and fertilizer use increases by 160% as a result.

In the Stabilizing Policy scenarios, we assume that changes in technology and production methods, not in the demand for agricultural commodities, could reduce greenhouse gas emissions per unit of product. Although the impact of specific technologies cannot be estimated at present, several techniques have been identified for reducing methane emissions associated with rice and meat production and nitrous oxide emissions related to the use of fertilizer (see CHAPTER V). For simplicity, we have assumed that CH_{d} emissions per unit of rice, meat, and dairy production decrease by 0.5% per year' (emissions from animals not used in commercial meat or dairy production are assumed to be constant). Emissions of N₂O per unit of nitrogenous fertilizer applied are also assumed to decrease by 0.5% per year for each fertilizer type. In addition, fertilizer use is assumed to shift away from those types with the highest emissions after 2000. Based on



CO2 EMISSIONS FROM TROPICAL DEFORESTATION

FIGURE 6-12



Year

these assumptions, CH_4 emissions from rice production remain roughly constant until 2075, after which time they fall by about 20% as the global population stabilizes. Methane emissions from domestic animals increase by 40-50% by the middle of the 21st century, before falling to within about 30% of 1985 levels. Similarly, N₂O emissions from fertilizer use increase from 1.6 to about 3.0 Tg N/yr between 1985 and 2025 and then decline slightly.

Total Emissions

Total emissions of the key radiatively important trace gases, the aggregate of estimates of the emissions from each activity discussed above and of natural emissions, are shown in Table 6-8. Overall, emissions increase gradually in the SCW scenario and more dramatically in the RCW, while in the policy scenarios emissions are reasonably stable or declining.

In the No Response scenarios, CO_2 emissions are projected to increase by a much greater percentage than emissions of the other gases. This is because all net CO₂ emissions are assumed to be anthropogenic in origin and because CO_2 is a fundamental product of all fossil-fuel combustion. In the SCW, increased deforestation contributes significantly to nearterm growth in CO₂ emissions, and total emissions are relatively constant between 2025 and 2075 as forests are exhausted (see Figure 6-13). In the RCW, CO_2 emissions are dominated by the growth in fossil-fuel combustion, and total emissions increase by a factor of three by 2050. In the Stabilizing Policy scenarios, increased end-use efficiency and reforestation significantly contribute to decreased emissions in the near term, while decreased reliance on fossil fuels in conjunction with continued improvements in efficiency allows for further decreases later.

The regional allocation of CO_2 emissions shows a rapid increase in the amount attributed to developing countries in all scenarios except in the RCWR case (see Figure 6-14). This share increases from about 35% currently to 55% by 2025, and levels off at about 60% after 2050 in the RCW. The developing countries account for a little over 50% of CO₂ emissions in the SCW after 2025, with the share from developing countries, other than China, decreasing after 2050 as deforestation emissions decline. China's share of emissions grows most dramatically in the Stabilizing Policy scenarios, as deforestation is eliminated in other developing countries and China becomes, by far, the world's largest coal About 67% of global CO₂ consumer. emissions are from China and other developing countries by 2100 in the RCWP scenario, but only 32% in the SCWP. In the RCWR scenario, developing countries contribute virtually no net CO₂ emissions as reforestation and biomass energy production offset emissions from fossil-fuel use (China's reliance on fossil fuels makes it the largest CO₂ contributor globally).

The projected increases in CH₄ emissions in the No Response and Accelerated Emissions scenarios are attributable to a variety of sources (see Figure 6-15). In the SCW over 50% of the increase between 1985 and 2050 is because of enteric fermentation and rice cultivation, whereas in the RCW these sources account for about 40% of the increase, and the growth in emissions from fuel production accounts for another 40%. In the RCWA fuel production accounts for nearly 75% of the growth. In these scenarios, emissions from landfills increase steadily, becoming quite significant by the end of the period. Reduced growth in each component is responsible for relatively stable CH₄ emissions in the Stabilizing Policy scenarios. The total increases gradually until 2050 in the RCWP and declines to near 1985 levels by the end of the period. In the SCWP, CH₄ emissions peak in 2025, then fall below 1985 levels by 2100. In the RCWR, emissions peak in 2000, falling constantly to 90% of 1985 levels by 2100.

Total N₂O emissions do not increase dramatically in the scenarios except in the RCWA, although we note again that current, and therefore future, emissions of N₂O are highly uncertain. These uncertainties, however, do not appear to have a large impact on the overall rate or magnitude of climate change in these scenarios (see APPENDIX C). In the SCW, emissions related to deforestation and land clearing, as well as fertilizer-induced emissions, increase significantly through 2025, and total emissions growth is driven mainly by a

TABLE 6-8

Trace Gas Emissions

	1985	2000	2025	2050	2075	2100
CO_{λ} (Pg C)	<u> </u>		<u></u> _			
SCW	6.0	7.6	9.6	9.9	9.6	10.7
RCW	6.0	8.1	12.4	16.9	22.0	26.1
RCWA	6.0	9.1	21.9	36.6	50.3	54.8
SCWP	6.0	5.6	5.2	4.0	3.3	2.6
RCWP	6.0	5.9	5.4	5.3	5.2	5.3
RCWR	6.0	5.2	2.1	0.3	0.5	0.8
N ₂ O (Tg N)						
ŠĊŴ	12.5	14.3	16.5	17.1	15.8	15.6
RCW	12.5	14.2	16.1	17.2	18.1	18.1
RCWA	12.5	14.7	18.5	20.7	21.3	22.0
SCWP	12.5	12.9	13.1	13.1	13.0	12.8
RCWP	12.5	12.9	13.3	12.9	12.7	12.6
RCWR	12.5	12.8	13.1	12.7	12.6	12.5
CH ₄ (Tg CH ₄)						
SCW	510.7	581.0	687.9	748.4	783.9	829.7
RCW	510.7	590.1	731.9	901.1	1,044.5	1,126.1
RCWA	510.7	614.4	911.9	1,237.6	1,504.0	1,576.9
SCWP	510.7	528.1	544.8	527.9	518.0	483.0
RCWP	510.7	536.7	561.2	567.3	548.9	524.6
RCWR	510.7	529.6	520.8	500.2	484.1	462.7
NO _x (Tg N)						
SČW ,	54.2	61.2	71.1	72.2	66.7	69.0
RCW	54.2	62.4	79.2	95.4	110.4	121.6
RCWA	54.2	67.1	104.9	145.3	174.2	186.8
SCWP	54.2	51.8	47.8	44.0	43.9	44.7
RCWP	54.2	52.9	56.1	47.8	47.4	48.8
RCWR	54.2	51.3	53.2	45.5	46.0	48.1
CO (Tg C)						
SCW	505.8	610.8	825.4	842.2	614.1	625.0
RCW	505.8	561.7	724.6	885.3	1,052.3	1,192.2
RCWA	505.8	619.6	976.2	1,197.1	1,050.1	1,122.3
SCWP	505.8	366.3	289.4	251.5	257.9	254.5
RCWP	505.8	364.5	294.2	237.5	232.9	230.3
RCWR	505.8	363.2	272.6	225.0	232.7	236.1
CFC-11 (Gg)					••• • ••	607 (
SCW	278.3	310.9	260.7	291.6	297.4	297.4
RCW	278.3	337.6	281.2	319.8	327.1	327.1
RCWA	278.3	438.9	611.1	995.4	1,056.4	1,056.4
SCWP	278.3	295.0	42.0	50.4	53.5	53.5
RCWP	278.3	331.4	56.0	55.8	57.9	57.9
RCWR	278.3	331.4	56.0	55.8	57.9	57.9

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.

TABLE 6-8 (Continued)

Trace Gas Emissions

	1985	2000	2025	2050	2075	2100
CFC-12 (Gg)			<u></u>	<u>,</u>		
SCW	363.8	419.5	393.5	420.0	426.5	426.5
RCW	363.8	500.2	450.3	508.7	519.1	519.1
RCWA	363.8	614.6	857.2	1,400.0	1,483.1	1,483.1
SCWP	363.8	402.9	50.6	64.5	68.5	68.5
RCWP	363.8	491.4	83.5	87.9	91.2	91.2
RCWR	363.8	491.4	83.5	87.9	91.2	91.2
HCFC-22 (Gg)						
SCW	73.8	206.1	407.0	754.5	879.1	879.1
RCW	73.8	263.0	830.7	2,425.8	3,124.5	3,124.5
RCWA	73.8	263.0	830.7	2,425.8	3,124.5	3,124.5
SCWP	73.8	206.1	407.0	754.5	879.1	879.1
RCWP	73.8	263.0	830.7	2,425.8	3,124.5	3,124.5
RCWR	73.8	263.0	830.7	2,425.8	3,124.5	3,124.5
CFC-113 (Gg)						
SCW	150.5	121.3	124.2	142.2	142.2	142.2
RCW	150.5	178.4	170.5	195.3	195.3	195.3
RCWA	150.5	248.6	371.7	618.7	618.7	618.7
SCWP	150.5	112.7	8.8	14.0	14.0	14.0
RCWP	150.5	174.7	19.9	26.1	26.1	26.1
RCWR	150.5	174.7	19.9	26.1	26.1	26.1





CO2 EMISSIONS BY REGION

FIGURE 6-14



FIGURE 6-15

Note: Scale is different for the RCWA case.

fourfold increase in fossil-fuel combustion emissions between 1985 and 2100. Similarly, in the RCWA fossil-fuel-related emissions increase ninefold. In the Stabilizing Policy and RCWR cases, total emissions remain constant because decreases in emissions per unit of fertilizer use and fossil-fuel combustion are assumed and because deforestation is halted.

In the No Response scenarios, emissions of both NO_x and CO increase significantly through 2050. After 2050 declining emissions related to deforestation in the SCW compensate for continued increases in energyemissions. related The deforestation assumptions have a particularly large impact on CO emissions as deforestation accounts for 40-50% of the total between 2000 and 2050 in In the RCW, deforestation this case. emissions are relatively uniform, and both CO and NO_x emissions continue to increase through 2100. In the RCWA, large increases in fossil-fuel use increase NO_x and CO emissions significantly through 2100. In the Stabilizing Policy cases, emission controls produce relatively stable NO_x emissions and declining CO emissions from fossil-fuel combustion sources, while deforestation emissions are eliminated. The result is a moderate decline in NO_x emissions and more than a 50% cut in CO emissions by 2050.

Atmospheric Concentrations

Figure 6-16 shows concentrations of greenhouse gases that result from the pattern of emissions discussed above. Because CO_2 , N_2O , and CFCs are long-lived in the atmosphere, their concentrations respond gradually to changes in emissions. CH_4 has an intermediate lifetime (about 10 years), which is itself affected by changes in emissions of CO, NO_x , CH_4 , and other trace gases, so its atmospheric concentration may respond rapidly to changes in emission rates of these gases.

 CO_2 concentrations reach twice their pre-industrial levels (570 ppm) in about 2080 in the SCW scenario. This level is reached by 2055 in the RCW, and concentrations more than three times pre-industrial values are reached by 2100 (see Figure 6-16). In the RCWA case, CO_2 concentrations reach twice their pre-industrial levels by 2035 and are nearly six times higher by 2100. Despite declining CO₂ emissions in the Stabilizing Policy scenarios, CO₂ concentrations continue to increase throughout the projection period, reaching about 430 ppm in the SCWP case and about 475 ppm in the RCWP case by 2100. In the RCWR case, concentrations peak around 2025 at about 380 ppm, then decline to about 350 ppm by 2100. It is interesting to note that the fraction of total CO₂ emissions during the 21st century that remains in the atmosphere in 2100 is 46% in the RCW case and 39% in the RCWP case, so that emission reductions have a more than linear impact on concentrations.

CH₄ concentrations increase by about a factor of 2 in the SCW and a factor of nearly 2.8 in the RCW, relative to 1985 levels, with the most rapid growth occurring between 1985 and 2050 (see Figure 6-16). In the RCWA case, concentrations increase nearly fourfold between 1985 and 2100. Interestingly, the 2050 concentration obtained in the SCW is similar to the result of linearly extrapolating the currently observed growth rate of 1% per year, whereas the RCW value is close to an exponential extrapolation of current growth; the 2100 values lie substantially below a continuation of such extrapolations for another 50 years. In the Stabilizing Policy cases, CH_{A} concentrations increase by 10-20% between 1985 and 2025, after which they level off and decline to roughly 1985 levels by 2100. In the RCWR case, concentrations decrease 1985 by 2100. below levels CH_{4} concentrations are affected by temperature on atmospheric feedbacks chemistry: increasing the climate sensitivity of the model from 2.0°C to 4.0°C reduces concentrations by 65 ppb in the RCWR (the smallest change) and about 450 ppb in the RCWA (the greatest change), assuming that emissions are not affected (see end of chapter).

In contrast to methane, N_2O concentrations increase gradually in all the scenarios (see Figure 6-16). The concentration increase between 1985 and 2100 is about 115 parts per billion by volume (ppb) in the SCW, 130 ppb in the RCW, and 185 ppb in the RCWA. This compares to 70 ppb in the SCWP and about 65 ppb in the RCWP and RCWR. Thus, the policy assumptions reduce the concentration growth by 40-65%.



 $\mathsf{CH}_{\mathbf{4}} \text{ EMISSIONS BY TYPE}$

FIGURE 6-15

Note: Scale is different for the RCWA case.

fourfold increase in fossil-fuel combustion emissions between 1985 and 2100. Similarly, in the RCWA fossil-fuel-related emissions increase ninefold. In the Stabilizing Policy and RCWR cases, total emissions remain constant because decreases in emissions per unit of fertilizer use and fossil-fuel combustion are assumed and because deforestation is halted.

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ATMOSPHERIC CONCENTRATIONS

(3.0 Degree Celsius Climate Sensitivity)

CFC concentrations increase dramatically in the No Response and Accelerated Emissions scenarios despite the assumption that at least 65% of developing countries and 95% of industrialized countries participate in the Montreal Protocol (see Figure 6-16). The total concentration of CFCs, weighted by their relative contribution to the greenhouse effect, increases by a factor of 4.8, 7.5, and 14.6 in the SCW, RCW, and RCWA scenarios, respectively. On the other hand, the phaseout assumed in the Stabilizing Policy cases stabilizes CFC concentrations (other than HCFC-22) by 2025, but their total radiative forcing still increases to 1.7-3.1 times the current levels.

It is worthwhile to compare the concentration changes calculated here, on the basis of explicit assumptions linking emissions with activities, to recent studies that have made less formal estimates based primarily on current trends in concentrations and/or emissions (see Table 6-9). Our No Response estimates of future concentrations are in close agreement with those of Ramanathan et al. (1985) for 2030 and Dickinson and Cicerone (1986) for 2050. A notable exception is the estimation of future concentrations of CFCs; we expect significantly lower concentrations as a result of the recent Montreal Protocol to control production of these compounds. In addition, our 2030 estimates of N₂O concentrations are at the lower end of the range given by Ramanathan et al. (1985), although they are closer to the center of Dickinson and Cicerone's (1986) range for 2050.

The differences between the SCW and RCW scenarios are significantly less than the ranges suggested by these authors for all the compounds listed in Table 6-9 -- at least in part because the only differences between the SCW and RCW scenarios are assumptions about activity levels and technology. In contrast, the estimated concentration ranges from the literature also consider uncertainties in current sources, atmospheric chemistry, and ocean carbon uptake (uncertainties in these factors are considered later in this chapter and in Appendix C). Also, the Slowly Changing World and Rapidly Changing World scenarios are not intended to completely bound future possibilities; significant reductions in emissions per unit of GNP are built into the No Response scenarios. If this fails to materialize, and/or if economic growth is more rapid than assumed here, concentrations of several greenhouse gases could be dramatically higher than is estimated in these scenarios. For example, in the RCWA scenario CO_2 concentrations are about 750 ppm in 2050, CH_4 concentrations about 4.5 ppm, and N₂O concentrations about 390 ppb.

Global Temperature Increases

Evaluating the consequences of alternative climate change scenarios is beyond the scope of this report (a variety of potential domestic effects are examined in the companion report, The Potential Effects of Global Climate Change on the United States, Smith and Tirpak, 1989), but an indicator of the relative magnitude of change is needed as a basis for comparing the scenarios considered here. Analysts of trace gas emissions have often emphasized the year by which carbon dioxide concentrations (or the equivalent combination of trace gases) can be expected to reach twice their pre-industrial level (referred to as $2xCO_2$), which is about 285 ppm. In the absence of policies to reduce emissions, however, climate change is potentially unbounded. Atmospheric composition and climate would continue to change after the $2xCO_2$ level was reached, and the ecological and social consequences may depend as much on what happens after CO_2 doubles (if it does) as on when this benchmark occurs. More relevant to ecological and social systems are the average and maximum rate of climate change. Therefore, we focus on the average rate at which global temperature may increase during the next century as well as the maximum rate of change. We emphasize that these parameters are only indicators of global change; changes at the regional level will vary in both magnitude and timing, and changes in precipitation may be as important as changes Nonetheless, the global in temperature. quantities calculated here can be used to compare the scenarios presented here among themselves and with results of more detailed climate models.

TABLE 6-9

	Concentrations in 2030									
Trace Gas	Ramanathan et al. (1985)	Ā	GISS B	-c	SCW	RCW	RCWA	SCWP	RCWP	RCWR
CO ₂ (ppm)	450	443	427	368	440	460	530	400	400	380
CH₄ (ppm)	2.3(1.8-3.3)	3.5	2.5	1.9	2.6	2.6	3.3	1.9	1.9	1.7
Tropospheric-O ₃ (%)	12.5	*	0	0	20	20	38	-0.3	1	-2.4
N ₂ O (ppb)	375(350-450)	381	352	314	350	350	360	335	335	330
CFC-11 (ppb)	1.1(0.5-2.0)	2.3	0.8	0.2	0.5	0.6	0.8	0.4	0.4	0.4
CFC-12 (ppb)	1.8(0.9-3.5)	3.9	1.4	0.5	1.0	1.1	1.6	0.7	0.8	0.8
HCFC-22 (ppb)	0.9(0.4-1.9)				0.4	0.7	0.7	0.4	0.7	0.7
					Conce	ntrations	n 2050			
Trace Gas	Dickinson & Cicerone (1986)	Ā	<u>GISS</u> B	Ċ	SCW	RCW	RCWA	SCWP	RCWP	RCWR
CO ₂ (ppm)	400-600	513	465	368	495	560	750	410	425	370
CH₄ (ppm)	2.1-4.0	4.7	2.7	1.9	2.9	3. 2	4.5	1.8	1.9	1.6
Tropospheric-O ₃ (%)	15-50	*	0	0	24	26	60	-2.3	-1.1	-7
N ₂ O (ppb)	350-450	480	376	314	375	370	390	345	345	345
CFC-11 (ppb)	0.7-3.0	4.2	1.0	0.2	0.6	0.6	1.2	0.3	0.3	0.3
CFC-12 (ppb)	2.0-4.8	7.3	1.8	0.4	1.3	1.4	2.4	0.7	0.8	0.8
HCFC-22 (ppb)					0.7	1.8	1.9	0.6	1.7	1.6

Comparison of Estimates of Trace-Gas Concentrations in 2030 and 2050

* In this scenario the effect of O_3 and other trace-gas changes is approximated by doubling the radiative forcing contributed by CFC-11 and CFC-12.

The changes in concentrations shown in Figure 6-16 produce the estimated global temperature changes shown in Figure 6-17 and Table 6-10 for a range of climate sensitivity (2.0-4.0°C equilibrium increase in global temperature from doubling the atmospheric concentration of CO₂; see CHAPTER III). Both the "equilibrium warming commitment" and the "realized warming" are presented as a function of time. The equilibrium warming commitment for any given year is the temperature increase that would occur in equilibrium if the atmospheric composition was fixed in that year. Because the oceans have a large heat capacity, the temperature change realized in the atmosphere lags considerably behind the equilibrium level. Realized warming has been estimated with a simple model of ocean heat uptake as discussed in Chapter III.

Because the response of the climate system to changes in greenhouse gas concentrations is quite uncertain, we also consider a range of "climate sensitivities." Climate sensitivity is defined as the equilibrium warming commitment due to doubling the concentration of carbon dioxide from pre-industrial levels. Given a particular emissions scenario and climate sensitivity, the realized warming is much more uncertain than the equilibrium warming commitment because the effective heat storage capacity of the ocean is not known. On the other hand, because the amount of unrealized warming increases with increasing climate sensitivity, for a given scenario, realized warming depends less on climate sensitivity than does warming commitment.

The SCW, RCW, and RCWA scenarios lead to substantial global warming. In the SCW, estimated realized warming increases 1.0-1.6°C between 2000 and 2050, and 1.9-3.2°C between 2000 and 2100 (see Table 6-10). The maximum decadal (per decade) rate of change associated with this scenario is 0.2-0.3°C sometime in the middle of the next The total equilibrium warming century. commitment is substantially higher, reaching 3.3-6.6°C by 2100 relative to pre-industrial levels. The equilibrium warming commitment equivalent to doubling the concentration of CO₂ from pre-industrial levels is reached by about 2040 in the SCW scenario.

The rate of change during the next century would be more than 50% greater in the RCW scenario, which shows a global temperature increase from 2000 of 1.3-2.0°C by 2050 and 3.1-5.0°C by 2100 (see Table 6-10). In this case the maximum rate of change is 0.4-0.6°C per decade, which occurs sometime between 2070 and 2100. The equilibrium warming commitment is 5-10°C by 2100 in this scenario, and the $2xCO_2$ equivalent level is reached by about 2030.¹¹

The rate of change is substantially higher in the RCWA case compared to the SCW and RCW scenarios. The global temperature increase from 2000 to 2050 is 2.1- 3.1° C; by 2100, it is 5.4-8.3°C. The maximum rate of change is about 0.7-1.0°C per decade, which occurs toward the end of the next century. The equilibrium warming commitment in this scenario is 8.2-16.3°C by 2100, and the 2xCO₂ equivalent level is reached by about 2015.

By contrast, the rate of climate change in the Stabilizing Policy scenarios would be less than 1.6°C per century. Global temperatures in the SCWP case increase by 0.4-0.7°C from 2000 to 2050, and 0.5-1.1°C from 2000 to 2100. Corresponding values are 0.5-0.9°C and 0.8-1.5°C in the RCWP case, and 0.2-0.5°C and 0.1-0.4°C in the RCWR case. The maximum rate of change in these scenarios is less than 0.2°C per decade and occurs before 2010, largely as a result of warming to which the world may already be committed. In these three cases the additional commitment to warming is greater between 2000 and 2050 than it is between 2050 and 0.1-1.1°C versus (-0.5)-0.5°C. The 2100: lowest values occur in the RCWR, where aggressive policies reduce the equilibrium warming commitment throughout most of the Total equilibrium warming next century. commitment reaches 1.4-2.8°C in the SCWP, 1.9-3.6°C in the RCWP, and 0.8-1.6°C in the RCWR. While not without some risk, the rate of change represented by the Stabilizing Policy scenarios would give societies and ecosystems much more time to adapt to climate change than would be the case in the No Response scenarios.

Carbon dioxide accounts for at least 60% of increased commitments to global



FIGURE 6-17 REALIZED AND EQUILIBRIUM WARMING

TABLE 6-10

Realized Warming - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
SCW	0.5	0.7	1.2	1.7	2.2	2.6
RCW	0.5	0.7	1.3	2.0	2.9	3.8
RCWA	0.5	0.7	1.5	2.8	4.5	>6.0*
SCWP	0.5	0.7	0.9	1.1	1.2	1.2
RCWP	0.5	0.7	1.0	1.2	1.4	1.5
RCWR	0.5	0.7	0.9	0.9	0. 9	0.8
Realized Warming - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
SCW	0.7	1.0	1.8	2.6	3.4	4.2
RCW	0.7	1.0	1.9	3.0	4.4	6.0
RCWA	0.7	1.1	2.1	4.2	>6.0*	>6.0*
SCWP	0.7	1.0	1.4	1.7	1.9	2.1
RCWP	0.7	1.0	1.5	1.9	2.2	2.5
RCWR	0.7	1.0	1.4	1.5	1.5	1.4
Equilibrium Warming Commitment - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
SCW	0.7	1.1	1.7	2.3	2.8	3.3
RCW	0.7	1.1	1.9	2.9	4.0	5.1
RCWA	0.7	1.1	2.4	4.4	>6.0*	>6.0*
SCWP	0.7	1.0	1.2	1.4	1.4	1.4
RCWP	0.7	1.0	1.3	1.5	1.7	1.9
RCWR	0.7	1.0	1.2	1.1	1.0	0.8
Equilibrium Warming Commitment - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
SCW	1.5	2.2	3.5	4.7	5.7	>6.0*
RCW	1.5	2.2	3.8	5.8	>6.0*	>6.0*
RCWA	1.5	2.3	4.7	>6.0*	>6.0*	>6.0*
SCWP	1.5	2.0	2.5	2.7	2.8	2.8
RCWP	1.5	2.0	2.6	3.1	3.4	3.6
RCWR	1.5	2.0	2.3	2.1	1.9	1.6

Scenario Results For Realized And Equilibrium Warming

* Estimates of equilibrium warming commitments greater than 6°C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms. These estimates are represented by >6°C. warming between 2000 and 2100 in all of the scenarios analyzed in this report (see Figure 6-18). This represents a significantly higher estimate of the role of CO₂ compared with estimates for the last few decades (roughly 50%) and in Ramanathan et al.'s (1985) scenario for 2030. Much of this difference is because of smaller increases in CFCs in our scenarios due to our assumption that the Montreal Protocol comes into force. In addition, growth in emissions of CH_4 and N_2O is projected to be slower than that of CO_2 , particularly after 2030. The role of CO_2 is greatest in the Stabilizing Policy scenarios because our assumptions lead to relatively stable concentrations of CH₄ and tropospheric ozone, while CO₂ concentrations continue to increase gradually.

Comparison with General Circulation Model Results

Hansen et al. (1988) analyzed three transient trace gas scenarios using the GISS GCM (see Table 6-9). The GISS A scenario, based on exponential extrapolation of current greenhouse gas trends, most closely resembles our RCW with 4.0°C climate sensitivity (the climate sensitivity of the GISS GCM is 4.2°C). Indeed, both the equilibrium and realized global warming in these cases are within 0.1°C in 2025.¹² By 2050, the continuation of exponential growth in trace gas concentrations in the GISS A scenario leads to an equilibrium warming commitment that is about 30% higher than in the RCW, with a corresponding realized warming of 3.4° versus 3.0°C (all references to realized warming in the GISS scenarios are based on five-year running means; see Figure 3b in Hansen et al., 1988). By 2060, the end of the GISS simulation, the realized warming in the GISS A scenario is 4.2°C compared with 3.6°C in the RCW. The GISS B scenario, which is based on linearly increasing trace gas concentrations at current rates, is most similar to the RCWP case (with 4.0°C climate sensitivity). These two cases have very similar equilibrium warming commitments and realized warmings in 2030 (the end of the GISS simulation for this The final scenario examined by scenario). GISS, case C, assumes that atmospheric composition is stable after 2000, which leads to realized warming of about 0.9°C by 2040. The Stabilizing Policy cases examined here do not achieve this result; realized warming reaches 1.4-1.5°C by 2025 if the climate sensitivity is 4.0°C. Thus, the GISS scenarios bracket the range of the scenarios developed here and may provide some indication of the regional differences in the rates and magnitudes of temperature change that might be associated with our cases (possible regional variations are discussed in Hansen et al., 1988).

Relative Effectiveness of Selected Strategies

The major assumptions that distinguish the RCW and RCWP scenarios from each other have been grouped into eleven categories in order that we may examine the relative importance of different policy Similarly, the rapid emissions strategies. reduction policies and the accelerated emissions policies have been grouped into six and eight such categories, respectively. Each set of options was applied individually to the RCW case; the combination of all the strategies represents the RCWP, RCWR, and RCWA cases, respectively. Figures 6-19 through 6-21 present the results in terms of the effect of each policy strategy in reducing or equilibrium increasing the warming commitment in 2050 and 2100. This analysis suggests that accelerated energy-efficiency improvements, reforestation, modernization of biomass use, carbon emissions fees, and a CFC phaseout could have the largest near-term impact on the rate of climate change. In the long run, advances in solar technology and biomass plantations also play an essential role.

Comparing the results in Figures 6-20 and 6-21 suggests, however, that the effects of policy choices that increase the rate of growth in greenhouse gas emissions could be much larger than the effects of policies that accelerate reductions in future emissions rates. In other words, it may be easier for government policy to worsen the problem than to ameliorate it. If the policies evaluated here are representative of the range of relevant choices, policies that increase emissions may make the situation much worse than current trends suggest, and they may produce large effects very quickly. FIGURE 6-18



FIGURE 6-19

STABILIZING POLICY STRATEGIES: DECREASE IN EQUILIBRIUM WARMING COMMITMENT





Figure 6-19 -- NOTES

Impact Of Stabilizing Policies On Global Warming

^a The average efficiency of cars and light trucks in the U.S. reaches 30 mpg (7.8 liters/100 km) by 2000, new cars achieve 40 mpg (5.9 liters/100 km). Global fleet-average automobile efficiency reaches 43 mpg by 2025 (5.5 liters/100 km). In the RCW case global vehicle efficiencies for cars and light trucks achieve 30 mpg by 2025.

^b The rates of energy efficiency improvements in the residential, commercial, and industrial sectors are increased about 0.3-0.8 percentage points annually from 1985 to 2025 compared to the RCW, and about 0.2-0.3 percentage points annually from 2025 to 2100.

^c Carbon fees are placed on fossil fuels in proportion to their carbon content. Fees are placed only on production; maximum production fees (1988\$) are \$1.00/gigajoule (GJ: 1 GJ = 10^9 joules) for coal (about \$25/ton), \$0.80/GJ for oil, and \$0.54/GJ for natural gas. These fees increase linearly from zero, with the maximum production fee charged by 2025. In the RCW case no carbon fees were assumed.

^d Assumes that technological improvements in the design of nuclear powerplants reduce costs by about 0.6 cents/kWh (1988\$) by 2050. In the RCW we assumed that nuclear costs in 1985 were 6.1 cents/kWh (1988\$).

^e Assumes that low-cost solar technology is available by 2025 at costs as low as 6.0 cents/kWh. In the RCW case these costs approached 8.5 cents/kWh, but these levels were not achieved until after 2050.

^f Assumes the cost of producing and converting biomass to modern fuels reaches \$4.35/GJ (1988\$) for gas and \$6.00/GJ (1988\$) for liquids. The maximum amount of liquid or gaseous fuel available from biomass (i.e., after conversion losses) is 205 EJ.

⁸ Assumes that economic incentives to use gas for electricity generation increases gas share by 5% in 2000 and 10% in 2025.

^h Assumes more stringent NO_x and CO controls on mobile and stationary sources, including all gasoline vehicles using three-way catalysts, in OECD countries by 2000 and in the rest of the world by 2025 (new light-duty vehicles in the rest of the world use oxidation catalysts from 2000 to 2025). In the RCW case only the U.S. adopts three-way catalysts (by 1985), the OECD countries adopt oxidation catalysts by 2000, and the rest of the world does not add any controls. From 2000 to 2025 conventional coal boilers used for electricity generation are retrofit with low NO_x burners with 85% retrofit in the developed countries and 40% 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. In the RCW case no additional controls are assumed.

i A 100% phaseout of CFCs by 2003 and a freeze on methyl chloroform is imposed. There is 100% participation by industrialized countries and 94% participation by developing countries. In the RCW scenario we assumed compliance with the Montreal Protocol, which called for a 50% reduction in the use of the major CFCs. The London Amendments to the Protocol were not included in this analysis because they were adopted in June 1990, after this analysis was completed. The 100% phaseout assumed here is more stringent that the phaseout reflected in the London Amendments.

^j The terrestrial biosphere becomes a net sink for carbon by 2000 through a rapid reduction in deforestation and a linear increase in the area of reforested land and biomass plantations. Net CO_2 uptake by 2025 is 0.7 Pg C. In the RCW case, the rate of deforestation continues to increase very gradually, reaching 15 Mha/yr in 2097 and no reforestation occurs.

^k Assumes that research and improved agricultural practices result in an annual decline of 0.5% in the emissions from rice production, enteric fermentation, and fertilizer use. CH_4 emissions from landfills are assumed to decline at an annual rate of 2% in developed countries because of policies aimed at reducing solid waste and increasing landfill gas recovery, while emissions in developing countries continue to grow until 2025 and then remain flat due to incorporation of the source policies. Technological improvements reduce demand for cement by 25%.

¹ Impact on global warming when all the above measures are implemented simultaneously. The sum of each individual reduction in warming is not precisely equal to the difference between the RCW and RCWP cases because not all the strategies are strictly additive. FIGURE 6-20

RAPID REDUCTION STRATEGIES: ADDITIONAL DECREASE IN EQUILIBRIUM WARMING COMMITMENT





FIGURE 6-20 -- NOTES

Impact Of Rapid Reduction Policies On Global Warming

^a High carbon emissions fees are imposed on the production of fossil fuels in proportion to the CO₂ emissions potential. In this case, fees of about S4.00/GJ were imposed on coal (S100/ton), S3.20/GJ on oil (S19/barrel), and S2.15/GJ on natural gas (S2.00/mcf). These fee levels are specified in 1988\$ and are phased in over the period between 1985 and 2025. No fees were assumed in the RCW case.

^b Assumes that the average efficiency of new cars in the U.S. reaches 50 mpg (4.7 liters/100 km) in 2000 and that global fleetaverage auto efficiencies reach 65 mpg in 2025 (3.6 liters/100 km) and 100 mpg (2.4 liters/100 km) in 2050.

^c Assumes that the rate of technical efficiency improvement in the residential and commercial sectors improves substantially beyond that assumed in the RCWP case. In this case, the rate of efficiency improvement in the residential and commercial sectors is increased so that a net gain in efficiency of 50% relative to the RCWP case is achieved in all regions.

^d Assumes that, by 2050, average powerplant conversion efficiency improves by 50% relative to 1985. In this case the design efficiencies of all types of generating plants improve significantly. For example, by 2025, new oil-fired generating stations achieve an average conversion efficiency roughly equivalent to 5% greater than that achieved by combined-cycle units today.

^e The availability of commercial biomass is doubled relative to the assumptions in the RCWP case. In this case the rate of increase in biomass productivity is assumed to be at the high end of the range suggested by the U.S. DOE Biofuels Program. Conversion costs were assumed to fall by one-third relative to the assumptions in the RCWP case.

^f A rapid rate of global reforestation is assumed. In this case deforestation is halted by 2000 and the biota become a net sink for CO₃ at a rate of about 1 Pg C per year by 2025, about twice the level of carbon storage assumed in the RCWP case.

⁵ Impact on warming when all of the above measures are implemented simultaneously. The impact is much less than the sum of the individual components because many of the measures are not additive.

FIGURE 6-21

ACCELERATED EMISSIONS CASES: INCREASE IN EQUILIBRIUM WARMING COMMITMENT



FIGURE 6-21 -- NOTES

Impact Of Accelerated Emissions Policies On Global Warming

^a Assumes a low level of participation in and compliance with the Montreal Protocol. The assumptions used in this case are similar to those used in the "Low Case" analysis described in the U.S. EPA's Regulatory Impact Analysis report (U.S. EPA, 1988), i.e., about 75% participation among developed countries and 40% among developing countries. This analysis does not include the London Amendments to the Protocol, which were adopted in June 1990 after this analysis was completed.

^b Assumes that advances in the technology of coal extraction and transport rapidly reduce the market price of coal at the burner tip. In the RCW scenario, the economic efficiency of coal supply is assumed to improve at a rate of approximately 0.5% per year. In this case, it is assumed to improve at a rate of 1% per year.

^c Assumes that the non-fuel cost of converting coal to synthetic oil and gas is reduced by 50% relative to the RCW case.

^d Assumes that OPEC (or some other political entity) can control production levels and thus raise the border price of oil and gas. To simulate this effect, oil and gas resources were shifted to higher points on the regional supply curves. In addition, extraction costs for oil in each resource grade were increased relative to the assumptions in the RCW case.

^e Assumes that technical gains in the engineering efficiency of energy use occurs only half as rapidly as assumed in the RCW case. In the RCW case it is assumed that energy intensity per dollar of GNP improves at rates of approximately 1-2% per year. In the Slow Improvement case the assumed rates were reduced to only 0.5-1.0% per year. The lower rate of improvement is similar to the assumptions in recent projections for the U.S. Department of Energy's National Energy Policy Plan.

^f Assumes annual tropical deforestation increases at a rate equal to the rate of growth in population.

⁸ Assumes that solar energy remains so expensive that its price precludes the possibility of its making any significant contribution to global energy supply.

^h Assumes that the cost of electricity from fission electric systems becomes so high that their contribution to global energy supply is permanently limited. In this case, an environmental tax of about 6 cents/kWh (1988\$) on the price of electricity supplied by nuclear powerplants was phased in by 2050.

¹ All of the above assumptions were combined in one scenario. The result is not equal to the sum of the warming in the RCW and the eight individual cases because of interactions among the assumptions.

SENSITIVITY ANALYSES

The RCW and SCW scenarios presented earlier in this chapter describe two significantly different futures for the global community. Although these two potential paths capture a wide range of uncertainty, they do not represent all possible outcomes. Alternative assumptions are clearly possible for many of the parameters specified in these scenarios; these alternative specifications could alter the timing and magnitude of global climate change described in the RCW and SCW scenarios. To understand the importance of these alternative assumptions, this section examines how changes in key parameters affect our portrayal of the rate and magnitude of global climate change. These sensitivity analyses include alternative assumptions about the magnitude and timing of global policies to combat climate change, rates of technological change, the carbon cycle, sensitivity of the climate system, and feedbacks.

The sensitivity analyses discussed in this section are generally run relative to the RCW scenario, unless specified otherwise. Only a few of the major sensitivity analyses are discussed here for the reader; more detailed discussion of all of the sensitivity analyses that were evaluated are provided in Appendix C.

Assumptions About the Magnitude and Timing of Global Climate Stabilization Strategies

The analyses of the Stabilizing Policy scenarios presented in this Report are based on the assumption that the global community takes immediate, concerted action to contend with the consequences of climate change. Potential actions, which are discussed in Chapters V, VII, and VIII, include reducing the amount of energy required to meet the increasing needs, developing world's alternative technologies that do not require the consumption of fossil fuels, halting deforestation, and making changes in agricultural practices, among others. For many reasons, however, the world may not respond to the threat of climate change in a timely fashion. This section explores the consequences of other possibilities, particularly the unwillingness or inability of some countries to participate in climate stabilization

programs and the implications of delaying global action until a later date.

No Participation by the Developing Countries

Most of the greenhouse gas emissions currently committing the world to climate change can be traced to activities by the industrialized countries. Although the quantity of emissions generated by developing countries has been increasing, some argue that since the greenhouse problem has been largely caused by the industrialized countries, those countries should be responsible for solving the problem. Also, despite the potential environmental consequences of global climate change, other problems facing the developing countries, such as poverty, inadequate health care, and more immediate environmental problems may make it difficult for developing countries to commit any resources to climate stabilization policies.

Regardless of the merits of these arguments, for this sensitivity analysis we have assumed that developing countries do not participate in any climate stabilization activities; that is, only developed, industrialized countries adopt policies to limit global climate For this analysis the developing change. countries include China and other centrallyplanned Asian economies, the Middle East, Africa, Latin America, and South and Southeast Asia. We have assumed that industrialized countries (i.e., the U.S., the rest of the OECD countries, and the USSR and Eastern Europe) follow the path assumed in RCWP scenario, while developing the countries follow the path assumed in the RCW case, in which the entire global community does not respond to climate change.

Even if developing countries do not participate in global stabilization policies, policies adopted by the industrialized countries likely lead to technological are to advancements, altered market conditions, etc., that indirectly reduce emissions in the developing countries as well. For example, advancements by the developed countries in automobile fuel efficiency or fuel supply technologies may be partly adopted by the developing countries, tangentially allowing for some climate stabilization benefits. If the developing countries do not participate, however, they may tend to adopt technological advances more slowly and at a higher cost than if they had participated from the start. This slower rate of technological diffusion could occur for many reasons -- for example, if the industrialized countries take actions that prevent easy access to improved technologies or they are unwilling or unable to make the necessary capital available for investment, or if developing countries decide to invest their limited resources in other areas.

Since we cannot be certain of the direction that non-participation by the developing countries might take, we analyzed two cases to capture the potential range of likely possibilities. In the first case, little technological diffusion was assumed, resulting in a future path of energy consumption and investment trends for developing countries similar to those assumed in the RCW scenario. In the second case, developing countries were assumed to have greater access to the efficiency improvements and technological advances assumed for the RCWP case as a result of policies by the industrialized countries to make these improvements available and to extend the credit necessary for investment by the developing countries in these improvements.

In this analysis key assumptions for the developing countries included the following: (1) rates of energy-efficiency improvements for all sectors are the same as in the RCW case or midway between the RCW and RCWP case; for example, automobile efficiency levels, which by 2050 in developing countries were 5.9 liters/100 km (40 mpg) in the RCW case, and 3.1 liters/100 km (75 mpg) in the RCWP case, were varied from 5.9-4.1 liters/100 km (40-58 mpg); (2) CFCs are not phased out (although compliance with the Montreal Protocol would still occur); (3) agricultural practices that cause methane emissions from rice and enteric fermentation and nitrous oxide emissions from fertilizers do not change or show modest improvements; (4) deforestation continues as in the RCW case with an exponential decline in forest area; (5) non-fossil energy supply technologies developed by the industrialized countries are available to developing countries at a later date and higher cost than assumed in the RCWP case; for example, technological diffusion of biomass gasification technology would occur ten years later than it would in the RCWP case, but feedstock costs would remain high due to a lack of investment by the developing countries in highly productive energy plantations; and (6) no additional incentives are provided for increased use of natural gas.

Without the participation of the developing countries to stabilize the atmosphere, the amount of greenhouse gas emissions will increase substantially. In the two analyses considered here, CO₂ emissions are 3.9-5.3 Pg C higher than in the RCWP case by 2050 and 4.6-8.5 Pg C higher by 2100 (emissions by 2100 are 12.3 to 16.2 Pg C lower than in the RCW case since industrialized countries adopt climate stabilization policies), and other greenhouse gas emissions are also higher (based on 3°C climate sensitivity). These emission increases are sufficient to increase realized warming by 0.4-0.6°C in 2050 compared with the RCWP case and 1.2-1.6°C by 2100 (see Figure 6-22), with equilibrium warming by 2100 up to 1.9-2.6°C higher (based on 3°C climate sensitivity). Figure 6-22 also shows the results for the SCW scenarios. These emission increases are sufficient to increase realized warming by 0.4-0.5°C in 2050 compared with the SCWP case and 0.8-1.0°C by 2100, with equilibrium warming by 2100 up to 1.2-1.6°C higher.

The implications of these results are clear: even if the industrialized countries adopt very stringent policies to counteract the effects of climate change, the atmosphere will continue to warm at a rapid rate. Unilateral action by the industrialized countries can significantly slow the rate and magnitude of climate change, but because of the growing impact that developing countries have on the global climate, without the participation of the developing countries, substantial global warming is unavoidable. Because most of the world's population resides in these countries. their role in climate stabilization becomes increasingly important as the demand for resources to feed and clothe their growing populations and to improve their standard of living expands.

Delay in Adoption of Policies

For the Stabilizing Policy cases it is assumed that the global community takes

FIGURE 6-22



immediate action to respond to the dangers posed by climate change. For this sensitivity analysis we have assumed that the global community delays any response to the threat of climate change, with developed countries (i.e., the United States, the rest of the OECD countries, the USSR and centrally-planned European economies) delaying action until 2010, and the developing countries delaying action until 2025. Additionally, once regions do initiate action to combat global warming, they do so at a slower rate than that assumed in the RCWP case. This slower approach assumes a minimum 25-year delay in attaining the policy goals of the RCWP case; that is, levels technological of improvement, availability of alternative energy supply technologies, etc., will be achieved at least 25 years later. For example, in the RCWP case, automobile efficiency reaches 3.1 liters/100 km (75 mpg) by 2050, whereas in the Delay case industrialized countries reach 3.9 liters/100 km (60 mpg) by 2050, while developing countries reach 4.7 liters/100 km (50 mpg). The rate of efficiency improvement for energy the residential, commercial, and industrial sectors is unchanged from the rates assumed in the RCW case, through 2010 for industrialized countries and through 2025 for developing countries. After these years, energy efficiency improvements occur at the same rate as was assumed in the RCWP case, and the implementation of production and consumption taxes on fossil fuels from the RCWP case is delayed until 2010 for developed countries and until 2025 for developing countries.

Delaying the adoption of policies to stabilize the atmosphere significantly increases the Earth's commitment to global warming. With delay by the industrialized countries until 2010 and by the developing countries until 2025, the increase in realized warming compared to that assumed in the RCWP case is 0.5-0.7°C by 2050 and 0.6-0.9°C by 2100, and equilibrium warming is 0.7-1.4°C higher by 2050 and 0.7-1.4°C higher by 2100, respectively (based on climate sensitivities of 2.0-4.0°C; see Figure 6-23). Figure 6-23 also shows the results for the Slowly Changing World If global delays do occur, the scenarios. increase in realized warming compared to that assumed in the SCWP case is 0.4-0.6°C by 2050 and 0.4-0.6°C by 2100, and equilibrium warming is $0.5-1.1^{\circ}$ C higher by 2050 and $0.4-0.8^{\circ}$ C higher by 2100, respectively (based on climate sensitivities of 2.0-4.0°C).

Assumptions Affecting Rates of Technological Change

The extent of global warming will depend on the availability of energy supplies and technologies that minimize dependence on carbon-based fuels, nitrogen-based fertilizers, and other sources of greenhouse gas emissions. The availability of non-fossil-fuel technologies could have an impact on the rate of change in greenhouse gas emissions. Alternative assumptions regarding this issue are presented below.

Availability of Non-Fossil Technologies

Most technologies in use currently rely on fossil fuels to supply their energy needs. In the Rapidly Changing World, fossil-fuel-based technologies continue to dominate throughout the next century: by 2100 fossil fuels still supply over 70% of primary energy needs. However, if non-fossil technologies can be commercialized earlier, the magnitude of global climate change can be reduced because these technologies do not emit the greenhouse gases that cause global warming. To evaluate the implications of the availability of non-fossil technologies, two different scenarios were analyzed: (1) an Early Non-Fossil case, in which non-fossil technologies, specifically solar photovoltaics, advanced nuclear power designs, and production of synthetic fuels from biomass, are commercially available by 2000 at a rate faster than that assumed in the RCWP case; and (2) an Intermediate Non-Fossil case, in which non-fossil technologies are widely available by the middle of the next century (i.e., greater use of non-fossil technologies than in the RCW case, but less than in the RCWP case). The intent of these two cases is to capture a range of possible roles for nonfossil technologies, with the first case reflecting very optimistic assumptions on non-fossil availability and the second case reflecting more modest assumptions.

In the Early Non-Fossil case, non-fossil energy sources increase their share of total primary energy supply from 12% in 1985 to about 40% by 2025 and 55% by 2100, while in FIGURE 6-23



the Intermediate Non-Fossil case the share for non-fossil technologies increases to 20% by 2025 and about 50% by 2100 (see Figure 6-24a). In the near term, the non-fossil share of total energy could be greater than that reflected in the RCWP case if commercial availability is achieved at an earlier date. In this sensitivity analysis, however, the non-fossil share is lower in the long run compared with the share in the RCWP case because other policies that were included in the RCWP case to discourage the use of fossil fuels were not included in this case. In both cases, however, an increased role for non-fossil technologies can affect the amount of global warming. As shown in Figure 6-24b, for the Early Non-Fossil case the amount of realized warming compared with the RCW case is reduced about 0.1-0.2°C by 2050 and 0.6-0.9°C by 2100; equilibrium warming is reduced about 0.3-0.6°C by 2050 and 0.9-1.7°C by 2100 (based on 2.0-4.0°C climate sensitivities). For the Intermediate Non-Fossil case, the amount of realized warming compared with the RCW case is reduced about 0.1°C by 2050 and 0.4-0.6°C by 2100; equilibrium warming is reduced about 0.2-0.3°C by 2050 and 0.6-1.2°C by 2100.

Assumptions About Climate Sensitivity and Timing

Sensitivity of the Climate System

A general benchmark for comparing atmospheric models is their response to a doubling of CO₂ concentrations (see CHAPTER III). Simply put, this benchmark describes how much warming would be expected once the atmosphere stabilizes following a twofold increase in CO₂ concentrations (relative to pre-industrial levels). In our analyses we have used the range of 2.0-4.0°C. As discussed in Chapter III, there is a great deal of uncertainty about the strength of internal climate feedbacks and, in some cases, whether a feedback will be positive or negative. If cloud and surface albedo changes produce large positive feedbacks, as suggested by some analyses, the climate sensitivity could be 5.5°C or greater. On the other hand, these feedbacks could be weak, and cloud feedbacks could be negative, resulting in a climate sensitivity as low as 1.5°C. For this sensitivity analysis, therefore,

we have evaluated the extent of global warming using 1.5 and 5.5°C as lower and upper bounds, respectively. The impact of these assumptions on realized warming is illustrated in Figure 6-25 for the RCW and SCW cases. In the RCW case the range of realized warming for a 1.5-5.5°C climate sensitivity would be 1.6-3.5°C by 2050 and 3.0-7.0°C by 2100, compared to a range of 2.0-3.0°C by 2050 and 3.8-6.0°C by 2100, when the climate sensitivity is bounded by 2.0-4.0°C. The corresponding values for equilibrium warming for a 1.5-5.5°C climate sensitivity are 2.2-7.9°C by 2050 and 3.8-13.9°C by 2100, compared to 2.9-5.8°C by 2050 and 5.1-10.1°C by 2100 for a 2.0-4.0°C climate sensitivity. In the SCW case the range of realized warming for a 1.5-5.5°C climate sensitivity would be 1.4-3.0°C by 2050 and 2.0-5.0°C by 2100, compared to a range of 1.7-2.6°C by 2050 and 2.6-4.2°C by 2100, when the range of climate sensitivity is 2.0-4.0°C. The corresponding values for equilibrium warming for a 1.5-5.5°C climate sensitivity are 1.8-6.5°C by 2050 and 2.5-9.0°C by 2100, compared to 2.3-4.7°C by 2050 and 3.3-6.6°C by 2100 for a 2.0-4.0°C climate sensitivity.

Rate of Heat Diffusion

CO₂ and heat are currently transferred from the atmosphere to the oceans and within the ocean itself as a result of many complex chemical and physical interactions. One of these interactions is the transfer of heat from the mixed layer to the thermocline, thereby delaying global warming. In addition, changes in ocean mixing and circulation patterns as a result of climate change, could alter the capacity of the oceans to absorb heat (see **Biogeochemical Feedbacks** for further discussion). The rate at which heat is absorbed affects only the rate of realized warming, not the rate of equilibrium warming, because the oceans cannot absorb heat indefinitely.

In our model the rate at which mixing occurs between the mixed layer and the thermocline is parameterized with an eddydiffusion coefficient (see CHAPTER III). The value of the eddy-diffusion coefficient in the base cases was assumed to be 0.55×10^{-4} square meters per second (m²/sec). For




FIGURE 6-25



purposes of this sensitivity analysis, alternative values of 2 x 10^{-5} and 2 x 10^{-4} m²/sec have been evaluated.

As shown in Figure 6-26, the rate at which the oceans absorb heat can noticeably affect the amount of realized warming by 2100. If the rate of heat absorption is greater than that assumed in the base cases (i.e., if the eddy-diffusion coefficient is $2 \times 10^{-4} \text{ m}^2/\text{sec}$), realized warming by 2100 would be 0.5-1.2°C less than in the RCW case (assuming 2.0-4.0°C climate sensitivities). For the smaller eddy-diffusion coefficient of $2 \times 10^{-5} \text{ m}^2/\text{sec}$, realized warming by 2100 would be 0.3-0.9°C higher.

Biogeochemical Feedbacks

The sensitivity of the climate system to anthropogenic perturbations is determined by a combination of feedbacks that amplify or dampen the direct radiative effects of increasing concentrations of greenhouse gases. Several important internal climate feedbacks, such as those resulting from changes in water vapor, clouds, and sea ice albedo, are included in the estimates of climate sensitivity discussed throughout this report. There are a number of feedbacks of a biogeochemical origin, however, that may also play an important role in climate change that were not included in the analyses on which this range is based. Biogeochemical feedbacks include releases of methane from hydrates; changes in ocean chemistry, biology, and circulation; and changes in the albedo of the global vegetation.

Any attempt to quantify the impact of biogeochemical feedbacks is necessarily quite speculative at this time. However, it does appear that feedbacks could have an important impact on global climate. For example, Lashof (1989) has estimated that the gain from biogeochemical feedbacks ranges from 0.05-0.29 compared with a 0.17-0.77 gain from internal climate feedbacks. (The gain is defined as the portion of global equilibrium temperature change attributable to the divided by the total global feedback equilibrium temperature when the feedback is included). Some of these key feedbacks were incorporated into the atmospheric composition model for these sensitivity cases to determine the magnitude of their impact on global warming.

Ocean Circulation

As mentioned above, the oceans are currently a major sink for heat and CO_2 . Concerns have been raised, however, that the basic circulation patterns that allow these processes to continue could be significantly altered as the global climate changes. This possibility is suggested by the rapid rate of atmospheric CO_2 change during past periods of climate change (e.g., see **CHAPTER III**). If circulation patterns did change, it is plausible that the oceans would no longer be a net sink for heat and CO_2 .

It is not known at what point ocean circulation would be altered. For this analysis we assumed that a 2°C increase in realized warming would alter ocean circulation patterns sufficiently to shut off net uptake of CO_2 and heat by the oceans. This would increase atmospheric CO₂ concentrations from 10-13% by 2100, and would reduce the difference between realized and equilibrium warming as the atmosphere warmed more quickly due to the oceans' inability to continue to act as a heat sink. As shown in Figure 6-27, this feedback is sufficient to increase realized warming up to 1.6°C by 2050 and 1.3-3.6°C by 2100 compared with the warming estimated for the RCW case (assuming 2.0-4.0°C climate sensitivities).

Methane Feedbacks

Increases in global temperature could increase the amount of CH_4 emissions due to several feedback processes: (1) release of methane from hydrates, which are methane compounds contained in continental slope increasing temperatures sediments. as destabilize the formations; (2) additional methane from high-latitude bogs due to longer growing seasons and higher temperatures; and (3) increased rate of methanogenesis from rice cultivation. The amount of CH_4 that could be released from each of these feedback processes, and the rate at which any releases might occur, are highly speculative. For each process we have assumed that the rate of CH₄ release is linearly related to the increase in temperature, with each 1°C increase leading to an additional 110 Tg from methane hydrates, 12 Tg from bogs, and 7 Tg from rice culti-(Lashof, 1989). vation These methane

FIGURE 6-26

INCREASE IN REALIZED WARMING DUE TO RATE OF OCEAN HEAT UPTAKE

(Based on 3.0 Degree Sensitivity)



FIGURE 6-27

INCREASE IN REALIZED WARMING DUE TO CHANGE IN OCEAN CIRCULATION (Based on 3.0 Degree Sensitivity)



feedbacks could have a major impact on atmospheric CH_4 concentrations -- by 2100 concentrations would increase to about 6900-8050 ppb, compared with 4310-4550 ppb in the RCW case. As shown in Figure 6-28, this increase in CH_4 would be sufficient to increase realized warming relative to the RCW case about 0.1-0.2°C by 2050 and 0.4-0.8°C by 2100 (assuming 2.0-4.0°C climate sensitivities).

Combined Feedbacks

In addition to the two separate feedbacks discussed above, we analyzed the combined impact of several types of biogeochemical feedbacks. The following specific feedbacks were included: (1) methane from hydrates, bogs, and rice cultivation, as previously discussed; (2) increased stability of the thermocline, thereby slowing the rate of heat and CO_2 uptake by the deep ocean by 30% due to less mixing; (3) vegetation albedo, which is a decrease in global albedo by 0.06%per 1°C warming as a result of changes in the distribution of terrestrial ecosystems; (4) disruption of existing ecosystems, resulting in transient reductions in biomass and soil carbon at the rate of 0.5 Pg C per year per 1°C warming; and (5) CO_2 fertilization, resulting in an increase in the amount of carbon stored in the biosphere in response to higher atmospheric CO₂ concentrations at the rate of 0.3 Pg C per ppm increase (see Lashof [1989] for further discussion).

The combined impact of these feedbacks on realized warming is an increase of 0.2-0.7°C by 2050 and 0.7-2.2°C by 2100 relative to the RCW case (assuming 2.0-4.0°C climate sensitivities; see Figure 6-29); the increase in equilibrium warming is 0.2-1.3°C by 2050 and 0.6-2.6°C by 2100. These preliminary analyses strongly suggest that biogeochemical feedbacks could have a major impact on the rate of climate change during the next century.

CONCLUSIONS

While the future will never be anticipated with certainty, it is useful to explore the consequences of alternative The results of this plausible scenarios. exercise suggest that even with sluggish rates economic growth and of optimistic assumptions regarding technical innovation, the world could experience significant rates of climate change during the next century. Temperature increases reach 3-4°C by 2100 under our assumptions, and the world would be committed to an additional warming of up to 2.4°C at this date. With higher rates of economic growth, which is certainly the goal of most governments, significantly greater rates of climate change are possible. With our assumptions, which involve lower global energy use than considered in many previous studies, an average warming of 4-6°C could be expected by 2100, with an additional commitment of 1-4°C by that date. On the other hand, by vigorously pursuing a variety of technical and policy options simultaneously, it would be possible to reduce the average rate of warming during the next century by more than 60%. Chapters VII and VIII of this report explore options for implementing these policies in more detail.

FIGURE 6-28

INCREASE IN REALIZED WARMING DUE TO METHANE FEEDBACKS (Based on 3.0 Degree Sensitivity)



VI-74

FIGURE 6-29

INCREASE IN REALIZED WARMING DUE TO CHANGE IN COMBINED FEEDBACKS

(Based on 3.0 Degree Sensitivity)



NOTES

1. 1 GJ = 1 gigajoule = 0.948 million BritishThermal Units (Btu).

2. The sole exception is China, where aggressive policies are assumed in both cases. Slightly higher population growth is shown in the Rapidly Changing World scenario based on the sources of the alternative estimates (see **APPENDIX B**). This could be attributed to a relaxation of the one-child-per-family policy in response to greater economic growth.

3. 1 EJ = 1 exajoule = 0.948 quadrillion Btu(Quad).

4. This value includes all of the electricity generated from gas, reflecting the assumption that most of the synthetic gas used to produce electricity by 2050 is generated from biomass and is both produced and consumed in integrated gasifier-combustion turbine units.

5. 1 Pg = 1 petagram = 10^{15} grams.

6. 1 Tg = 1 teragram = 10^{12} grams.

7. 1 TW = 1 terawatt = 10^{12} watts = 31.54 EJ.

8. In the Slowly Changing World scenario this rechanneling effect is assumed to decrease growth in CFC demand by 63% in developed countries and by 50% in developing countries. In the Rapidly Changing World scenario the baseline growth rates are increased by a factor of 1.7 to reflect the higher rate of economic growth, but participation is assumed to be 100% in developed countries and 75% in developing countries. Rechanneling reduces the baseline growth rates (rechanneling does not affect developed countries in this scenario as 100% participation in the Protocol is assumed).

9. Participation is assumed to be 100% in industrialized countries and 85% in developing countries; rechanneling reduces the baseline growth rates of non-participants by 75%.

10. Plantation products decay at various rates at the end of each rotation; no attempt to protect this carbon from oxidation is assumed. 11. Estimates of equilibrium warming commitments greater than 6°C represent extrapolations beyond the range tested in most climate models, and this warming may not be fully realized because the strength of some positive feedback mechanisms may decline as the Earth warms.

12. The path to 2025, however, is not identical. The GISS scenarios are referenced to the atmospheric composition of 1960, whereas our scenarios are referenced to the estimated pre-industrial atmospheric composition. Thus, the warming commitment in 2000 is already 2.2°C in the RCW, whereas it is only 1.9°C in the GISS A scenario.

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CHAPTER VII

POLICY OPTIONS

FINDINGS

Many alternative policies are available that could be used to promote reductions in greenhouse gas emissions, including market incentives, research and development regulations. programs, and information programs. Choosing among these options will require a detailed evaluation of numerous criteria, including effectiveness in reducing emissions, economic impacts, administrative feasibility, enforceability, and compatibility with other environmental and social goals.

• Defining goals is an important issue in formulating policy responses to global warming. In the short run, the goal proposed by Congress for study in this report -stabilizing greenhouse gas concentrations -- is a costly, perhaps impossible, goal given current economic expectations and expected technological developments. Several states are now assessing the feasibility of reducing greenhouse gas emissions up to 20% over the next 10-20 years.

• If we assume that energy-related greenhouse gas emissions in the U.S. and elsewhere will continue increasing in the absence of government action, policies to achieve significant reductions may require major economic changes. However, further study is necessary to assess the likely cost of such measures, and many initial steps -particularly those to improve energy efficiency -- may have negative or very low costs, because they would produce large savings. Policies adopted today may substantially lower the cost of future actions by redirecting research and development priorities to technologies that lower greenhouse gas emissions.

• Near-term actions to reduce greenhouse gas emissions will be necessary if it is decided to limit the concentrations of greenhouse gases and facilitate future reductions. Atmospheric concentrations of most greenhouse gases will decline much more slowly than emissions. Putting off actions to reduce emissions would give us time to increase our knowledge of the risks and to refine policy options, but delay also could substantially increase the cost and reduce the effectiveness of policy responses. We will need time to agree on and implement policy responses since rapid changes in patterns of energy use and the industrial infrastructure responsible for emissions are likely to be disruptive and expensive.

• There is an important distinction between short-term and long-term policy options. In the short term, the most effective means of reducing emissions is through strategies that rely on pricing and regulation. In the long term, policies to increase research and development of new technologies and to enhance markets through information programs, government purchases, and other means could also make a major contribution.

• If limiting U.S. and global emissions of greenhouse gases is desired, government action will be necessary. Market prices of energy from fossil fuels, products made with CFCs, forest and agricultural products, and other commodities responsible for greenhouse gas emissions do not reflect the costs associated with the risk of climate change. As a result, increases in population and economic activity will cause emissions to grow in the absence of countervailing government policies to modify and/or supplement market signals.

• Policy preferences will vary among nations. However, nations can choose among many complementary policy options to reduce emissions consistent with governmental systems and other societal needs.

• The most direct means of allowing markets to incorporate the risk of climatic change is to assure that the prices of fossil fuels and other sources of greenhouse gases reflect their full social costs. It may be desirable to impose emission fees on these sources according to their relative contribution to global warming in order to accomplish this goal. Imposing fees would also raise revenues that could finance other programs. The acceptability of such fees will vary among countries, but would be enhanced if they are equitably structured.

• Regulatory programs would be a necessary complement when pricing strategies are not effective or produce undesirable impacts. In the U.S., greenhouse gas emissions are influenced by existing federal regulatory programs to control air pollution, increase energy efficiency, and recycle solid waste. Reducing greenhouse gas emissions could be incorporated into the goals of these programs. New programs could focus directly on reducing greenhouse gas emissions through such requirements as emissions offsets (e.g., tree planting), performance standards, or marketable permits.

Over the long term, other policies to . reduce emissions may be needed, and these can complement pricing and regulatory Other policy options include strategies. redirecting research and development priorities in favor of technologies that could reduce greenhouse gas emissions, developing and operating information programs to build understanding of the problems and solutions, and the selective use of government procurement to promote markets for technological alternatives.

• State and local government policies in such areas as utility regulation, building codes, waste management, transportation planning, and urban reforestation could make an important contribution to reducing greenhouse gas emissions.

• Voluntary private efforts to reduce greenhouse gas emissions have already provided valuable precedents for wider action and could play a larger role in the future.

• Government policy is already exerting considerable influence on the rate of growth in greenhouse gases. Clean Air Act provisions to attain and maintain National Ambient Air Quality Standards by regulating emissions of volatile organic compounds, nitrogen oxides, and carbon monoxide will not only produce cleaner air but also significantly affect greenhouse gases or their precursors. Major reductions of sulfur dioxide to 10 million tons below 1980 levels and of nitrogen oxides to 2 million tons below projected year 2000 levels will reduce greenhouse gas emissions by greatly encouraging energy efficiency. Phasing out CFCs, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs) in accordance with the Montreal Protocol and the Clean Air Act will substantially reduce emissions of greenhouse gases as well as protect the stratospheric ozone layer.

• Policies to create further incentives to improve energy efficiency, promote renewable energy technologies, encourage tree planting, and similar strategies may have the potential to achieve substantial further emissions reductions.

The President's proposed program for planting a billion trees a year will produce substantial benefits for wildlife, soil conservation, urban amenity, and energy saving, as well as directly take up CO₂ from the atmosphere. The increase in the federal tax enacted in gasoline the Budget Reconciliation Act of 1990 will reduce emissions by encouraging energy efficiency in Increased funding road transportation. requested in the 1991 budget for research and development in solar and renewable energy and energy conservation will be important in identifying and developing technologies that will allow us to meet our energy needs in environmentally efficient ways. New energy saving appliance standards promulgated by the U.S. Department of Energy will increase energy conservation and reduce demand.

• Many of the policies necessary to limit the buildup of greenhouse gases, such as improving energy efficiency and reversing deforestation, would produce other substantial short-term benefits. Therefore, it is very likely that additional policies can be found that, when analyzed, have sufficient benefits in areas not subject to the scientific and other uncertainties of climate change to justify their costs. Such policies can therefore be implemented in a manner that is consistent with other important economic, social, and environmental goals.

INTRODUCTION

If the government desires to stabilize the concentration of greenhouse gases at or near current levels, short-term actions must be considered. Market forces do not reflect the risks of climate change and therefore, barring government intervention, emissions -- and the risks of climate change -- can be expected to grow. The costs of taking action may increase with time; it takes many years to develop new technologies, implement policies, and replace the existing capital stock. There is also a long lag time between changes in emissions and consequent changes in the chemistry of the atmosphere, so that even with large reductions in emissions, atmospheric concentrations of some greenhouse gases may decline very slowly or even increase. The earth would continue to warm, and the climate may change for decades after atmospheric concentrations of greenhouse gases were stabilized.

Near-term government action to reduce emissions may consist entirely of policies that will contribute other substantial short-term benefits. The justification for policies that reduce greenhouse gas emissions may, therefore, be much greater than it would appear from a traditional comparison of costs and benefits. Decisions not to take action to reduce emissions could also facilitate the adoption of policies that result in increased emissions; such policies presumably would be less likely to be adopted if they were to contravene the purpose of other programs. This is a significant risk as we discuss later in this chapter; several recently proposed policies have the potential to significantly increase greenhouse gas emissions.

The government may pursue many policy alternatives to reduce greenhouse gas concentrations. In the short term, economic incentives and regulatory strategies will be most effective, but in the long run other policies will complement and support these approaches. Strategies to reduce greenhouse gas emissions can contribute to other goals, including economic growth, enhanced energy security, and a cleaner environment. Chapter V shows the wide range of measures available to limit greenhouse gas emissions. Many of these measures are nearly cost-competitive or are expected to be so soon. Is government intervention to reduce emissions therefore necessary? The analysis done for this report strongly suggests that without such action emissions will increase significantly. Without government intervention, there may be insufficient market incentive to develop and adopt the measures identified in Chapter V.

In the absence of government intervention, market prices will not reflect the cost to society of activities that are detrimental to the environment. Accordingly, we will not see a reduction in consumer demand for goods and services that increase environmental risk.

The obstacles to bringing about consumer response to environmental dangers particularly challenging for global аге problems like ozone depletion and the greenhouse effect. In this situation, there is the danger of what is commonly termed the "tragedy of the commons," the ecological destruction that can occur from uncontrolled use of shared resources like the atmosphere. There is probably no country for which reductions in global warming provide an adequate economic incentive to reduce greenhouse gas emissions unilaterally, even though such action could yield substantial global benefits. From any one country's viewpoint, the costs of controlling emissions may exceed the benefits since, without international agreement, reductions achieved by one nation may be offset by another. Therefore, even though the entire world may be better off as a result of efforts to lower emissions, new economic incentives are necessary to lead the market to a socially efficient outcome.

possible policy There are many responses for reducing greenhouse gas emissions; no one policy is likely to be totally effective without other supporting programs. However, as previously mentioned, consumers are not likely to reduce their demand for products and services that produce emissions of greenhouse gases unless the cost begins to exceed the benefits derived. In addition, other policies will be much less effective in the absence of economic incentives. In the short term, economic incentives and regulatory programs are likely to be the most effective policies. In the long term, research and development (R&D), information and

educational activities, government procurement, and other policies can make a substantial contribution.

The policies discussed here are most applicable to the United States. However, many of the ideas reviewed are likely to be potentially relevant to other countries. Policies most suitable for developing countries are discussed in Chapter VIII. Some programs developed in the U.S., such as energy conservation programs financed by electric utilities, may have even greater relevance for developing countries, which have higher interest costs and a greater need for new generating capacity.

GOALS

The choice of goals is a critical issue in thinking about the global warming problem. This study began with a request to identify policies that could stabilize greenhouse gas concentrations; for reasons discussed in Chapter VI, this goal may be extremely difficult to achieve, although some other studies have suggested otherwise (Mintzer, 1989). It is less obvious what goals ought to guide policymakers in responding to potential global warming.

Several legislative proposals have been framed to meet the goal proposed by the Toronto Conference discussed in Chapter VIII: to reduce emissions of carbon dioxide (CO_2) 20% by the year 2005. The government of Sweden has already agreed to limit its emissions of carbon dioxide to current levels. Proposals have also been made to limit greenhouse gas emissions on the basis of impacts. For example, a 1988 meeting of experts at Bellagio, Italy, proposed that the rate of global warming should not exceed 0.1°C per decade, a rate based on evidence of past adaptation by flora and fauna to changes in temperature.

These alternative goals reflect very different policy approaches, with substantially different potential environmental and economic consequences. Approaches based on *emissions* are most easily measured and enforced, at least insofar as they are applied to the commercial use of fossil fuels. Approaches based on limiting greenhouse gas concentrations come closer to addressing the underlying problem, but without precise means of attributing emissions to concentrations there are difficulties in devising programs to assure compliance. These problems are still greater with approaches based on rates of change or impacts, both of which require even more scientific precision and understanding.

Ultimately, a workable international agreement to address the problem will require goals that are readily understood and translated into enforceable requirements by implementing authorities. This problem is likely to be addressed in the ongoing intergovernmental process discussed in Chapter VIII.

CRITERIA FOR SELECTING POLICY OPTIONS

This chapter, and the chapter that follows, offer a wide variety of policy alternatives with differing advantages and disadvantages. The U.S. Environmental Protection Agency (U.S. EPA) tested the effectiveness of some of these options, as discussed in Chapter VI. Much more detailed analysis would be necessary prior to any effort to design a program for reducing greenhouse gas emissions, and numerous additional factors would have to be considered (McGarrity, 1983).

An initial consideration is effectiveness in reducing greenhouse gas emissions. Regulations, such as efficiency standards for automobiles and appliances, may appear to be the most predictable and reliable means of reducing greenhouse gas emissions. This is not necessarily so, however, as regulations may have unintended offsetting effects; for example, consumers have retained older, less efficient cars longer since such regulations went into effect, slowing the improvement in the overall efficiency of the vehicle fleet. Similarly troubling is the knowledge that automobiles usually travel fewer miles per gallon on the road than is indicated by the mileage ratings. Economic incentives may be more effective, although their results are also not always predictable. In the long run, R&D efforts may produce much greater results -- particularly if complemented by policies that create market incentives, such as energy taxes. (Many

strategies are complementary and not at all inconsistent, as discussed below.)

Cost is one key issue. Some evidence of the costs of policies to reduce emissions is presented in this chapter, and U.S. EPA has begun a separate cost study. Some of the difficulties in evaluating costs are discussed further below. *Economic efficiency* is a closely related consideration. Policies should encourage the most productive use of available resources, thereby minimizing the cost of achieving a given objective.

Public acceptability is also important. Taxes and economic incentives are often recommended by economists as the most efficient means of inducing behavioral changes, but such policies may be unrealistic because of popular resistance.

Regional and income equities are often an issue with energy policy proposals. Raising energy prices may disproportionately affect lower-income groups; restrictions on coal production may damage the economies of coal-producing regions. These considerations assume even greater importance in the international arena as any international accord to limit emissions must allow for enormous differences in national resources and needs.

The effect of policies on other societal goals, both positive and negative, may also be important. Energy conservation incentives that reduce oil imports may contribute to energy policy objectives and improve the balance of trade. Tree-planting programs may improve other measures of environmental quality by removing air or water pollutants. On the other hand, programs that impose large costs on the economy, or that require imported technology, may hamper economic goals.

Administrative burdens may be a factor with some policies. For example, some forms of regulatory programs require substantial data collection and paperwork and impose substantial time and monetary demands on both industry and government. In contrast, taxes and some economic incentive programs are relatively free of paperwork and easier to administer. Legal and institutional constraints complicate some policy choices. For example, the use of environmental fees or taxes may require new laws. Shared savings programs, a strategy for promoting investments in energy conservation, have not been widely utilized by federal agencies, in part because of restrictions on government procurement practices.

Enforceability is a concern with respect to some strategies. For example, some environmental regulations in the U.S. have arguably suffered from lack of specificity, making it difficult to detect and take action against violators.

No single policy can simultaneously satisfy all the criteria implied by the factors listed above; some trade-offs are inevitable, and the choices among different policy proposals must reflect judgments about the relative importance of these factors. Two examples, based on two of the largest sources of global energy consumption, automobiles and space conditioning, illustrate some of the issues. In the U.S., several approaches have been considered to promote improved automobile efficiency, including corporate average fuel economy (CAFE) standards, mandatory efficiency labeling, and government supported R&D. (Details concerning these policies are provided below.)

The standards approach has been the most controversial. On the one hand, it appears to offer the most certain promise of efficiency improvements; new car efficiency did improve substantially since standards went into effect, and Greene (1989) concluded that CAFE standards were perhaps twice as influential as gasoline price. However, the interest in further efficiency improvements has declined substantially since oil prices began to decline several years ago. There is also concern that the standards resulted in some unnecessary inefficiencies, benefitted foreign manufacturers, and encouraged an car undesirable market shift toward unregulated light trucks. Many economists have argued that gasoline taxes would be a much more effective and easily administered policy alternative; however, public support for a tax approach has been lacking.

Policies to promote improved building efficiency encounter a still more complex set of constraints because of the much larger number of builders, the lack of simple standards to measure efficiency, and the fragmentation of political authority among federal, state, and local jurisdictions. Regulations currently exist for only certain types of buildings (e.g., new homes) and jurisdictions; the federal government has not always applied accepted standards for minimizing energy costs in its own buildings. Proposed uniform national standards for new homes were adopted in the 1970s but later were rescinded because of technical difficulties and political opposition. Market incentives are also not easily implemented, because retail electricity and gas prices are controlled at the state level and usually reflect average costs rather than the marginal cost of new supply. Innovative approaches have been developed to create incentives for consumers and investors to take advantage of low-cost opportunities for cost reductions. Many utilities offer low-cost energy audits, energy labels, and rebates for the installation of efficient equipment. A few utilities have begun to offer direct payments for the incremental cost of efficiency investments that exceed minimum standards. The federal government has also achieved some notable successes through its R&D efforts, including the development of more efficient lights and heat pumps.

A recent report to Congress by the U.S. Department of Energy (U.S. DOE), "A Compendium of Options for Government Policy to Encourage Private Sector Responses to Potential Climate Change," provides a much more detailed catalog of policy instruments and their attributes. The report reviews four categories policies broad of roughly corresponding to those considered in this fiscal regulation, incentives. report: information, and research development and demonstration. The general attributes of each terms of efficiency, are described in requirements, distributional information effects, political sustainability, and applicability to greenhouse gas issues. The application of alternative policy instruments to different sectors of the economy is then assessed in terms of seven screening criteria: applicability, efficacy, time frame necessary to be effective, focus, decisionmaker sensitivity required,

current level of knowledge, and linkage to other goals. Some particularly promising options are emphasized, but U.S. DOE's report is similar to this one insofar as it avoids recommending specific policies: "We have sought to offer a menu of the options that are evaluated based on an initial systematic screening" (U.S. DOE, 1989).

COMPLEMENTARY STRATEGIES TO REDUCE GREENHOUSE GAS EMISSIONS

The policies described in this chapter are likely to be most effective when used in combination and, wherever possible, linked to the attainment of other national goals. Pricing and regulatory strategies are the most effective policies in the short term; however, the other policies reviewed in this section can complement and enhance pricing and regulatory approaches. In the long run, government-supported R&D, information programs, and other market-enhancing activities can make a significant contribution. Because government action to reduce greenhouse gas emissions will often be closely related to other national policies, programs must also be carefully crafted to meet several goals simultaneously (IEA, 1987).

Improving the efficiency of the U.S. economy is closely related to concerns about the country's economic competitiveness. While the U.S. has reduced its energy intensity principal economic substantially. our competitors have done even better and can offer more efficient technologies in many areas. Per capita energy consumption in the U.S. remains more than double that of Europe or Japan. Japanese industry uses half as much energy per dollar of value added as does industry in the U.S., although they spend about as much because energy prices are higher (Zimmerman and Reid, 1988; Flavin and Durning, 1988). Efficiency investments would make billions of dollars in capital available for other investments (Rosenfeld and Hafemeister, 1988). Oil imports are also a growing negative influence on the U.S. balance of trade, accounting for roughly a fourth of the merchandise trade deficit -- more than any other single item (Chandler et al., 1988).

Policies for reducing greenhouse gas emissions may also complement efforts to address concerns raised by recent growth in oil imports and potential risks to U.S. energy security (U.S. DOE, 1987c). Net oil and petroleum imports have increased from 27% of U.S. supply in 1985 to about 42% in 1989, and current forecasts indicate imports could exceed 50% by the mid-1990s (U.S. DOE, 1987c). By comparison, imports accounted for 35% of supply before the 1973 embargo and 43% before the 1979 embargo.

As discussed in Chapter IV, oil consumption for transportation is one of the largest sources of U.S. greenhouse gas emissions, as well as a major contributor to projected increases in global emissions. Transportation also accounts for almost twothirds of U.S. oil consumption. Further improvements in auto efficiency could therefore contribute to both decreases in greenhouse gas emissions and energy security objectives (MacKenzie, 1988).

Complementary strategies are very important in the buildings sector, where the effectiveness of pricing strategies is limited by extreme first-cost sensitivity, and the stringency of regulation is likely to reflect considerable Studies show that selective compromise. financial incentives in combination with information and training programs can be highly effective in promoting innovation not covered by standards, creating incentives for early adoption of standards, and enhancing compliance with standards. The result can be performance that is substantially better than mere compliance with minimum standards (Vine and Harris, 1988).

Complementary strategies can also work well to achieve the goal of reducing carbon emissions from automobiles. To achieve this goal, which is clearly consistent with efforts to promote higher average fuel economy, consumers must be able to evaluate the relative fuel efficiency of automobiles; federal fuel efficiency tests, gas mileage guides, and other information programs promote this goal.¹ Manufacturers have rightfully noted that consumer interest in fuel efficiency has declined with lower gasoline prices. Higher gasoline taxes, gas guzzler fees, or some other form of economic incentive is necessary to stimulate demand for efficiency.

Better management of solid wastes can reduce methane emissions. States with the most effective programs often combine some or all of the following policies: regulations on landfills, deposits on recyclable materials, tax incentives for recycling companies, and government procurement policies that promote purchase of recycled materials (Shea, 1988).

Research and development programs can assist on the supply side by accelerating the development and testing of new technologies. Procurement programs can provide an initial market and extensive testing for concepts prior to wider marketing. Minimum fuel economy standards fill a different role by providing clear targets and reducing market uncertainty, but regulations must be carefully structured to allow adequate time for adjustment, to avoid conflicts with other social goals and to preserve fair competition.

There is some concern that other national policies for reducing automobile oil consumption and improving urban air quality may lead to increased carbon emissions -- for example, legislation promoting large-quantity production of methanol from coal (see CHAPTER V), particularly if vehicles using such fuels are permitted to be less efficient as provided for in recent federal legislation.

Federal and state governments have also been considering air pollution regulations that unintentionally exacerbate global could warming. The problem is illustrated by the ongoing debate over acid rain legislation. Acid rain is caused in part by sulfur dioxide and nitrogen oxides emissions from electric utility powerplants. Some of the methods to limit these emissions could result in greater CO_2 emissions. For example, the use of scrubbers to control sulfur dioxide emissions from coal-fired or oil-fired powerplants would increase CO₂ emissions slightly because of the additional fuel required to operate the scrubbers. However, strategies that rely on natural gas or demand-side reductions would reduce carbon emissions (Centolella et al., 1988). Thus, an important priority for acid rain mitigation strategies should be to consider the global warming impacts of alternative acid rain programs.

Just as strategies to reduce greenhouse emissions must be applied in combination in order to be maximally effective, so too must we work together at all levels of government, as well as in the private sector.

Many short-term actions to reduce greenhouse gas concentrations could be implemented today on the basis of existing legislative authority. Indeed, some policies directed toward this objective are already under consideration. For example, agencies could make greater use of the environmental impact statement process to consider the extent to which their major projects will contribute to or be affected by climate change. The President's Council on Environmental Quality has done an analysis of projects that might warrant discussion of climate change issues and may issue guidelines for other agencies. U.S. EPA, which is legally required to review draft impact statements, has used its authority in at least one instance to comment on the additional greenhouse gas emissions that might result from actions proposed by the Federal Energy Regulatory Commission (FERC).

Much more could be done to improve the federal government's energy management within existing legislative authority, beginning with much more disaggregated reporting of energy use by agencies. The laws creating the Federal Energy Management Program require an examination of opportunities for energysaving alternatives in federal buildings. Such analysis is to be done on the basis of life-cycle costs, reflecting marginal fuel costs, and a 7%real discount rate -- terms intended to favor conservation, as compared with using average costs and a higher discount rate (Energy Security Act, PL 96-294, Section 405). The Department of Energy proposed U.S. implementing regulations in 1980, but final regulations were never completed. An Executive Order was initiated in 1990, however, that could reduce energy consumption in federal buildings by 10% in 1995.

Other short-term possibilities follow from some of the recent and pending agency decisions discussed above, such as ongoing consideration of rules to promote demand-side bidding by FERC and reconsideration of CAFE standards by the U.S. Department of Transportation (for further discussion see ADDENDUM TO CHAPTER VII).

The Cost Issue

Cost is obviously an important basis for comparing policy alternatives. As discussed in Chapter I, U.S. EPA recognizes the need for detailed analysis of the costs of alternative means of reducing greenhouse gas emissions and has initiated a separate cost study. This report reviews only policy options; costs are only one of many factors that will have to be examined in detail before recommendations can be made.

While no effort has been made to compare the costs of alternative policies, this chapter identifies numerous examples of policies that appear to offer opportunities for low-cost reductions in greenhouse gas emissions. Recent studies have identified substantial remaining opportunities for cost savings through investments in energy conservation. For example, a recent detailed study of electricity use in Michigan concluded that currently projected residential electricity demand in the year 2005 could be reduced by close to one-third for a total cost substantially less than the marginal cost of existing powerplants (see Figure 7-8). The cost of storing carbon by tree planting is also very modest, although costs can be expected to rise as programs increase in scale and land availability becomes a constraint.

The policy examples cited in this chapter also serve to make another important point about the cost issue. Since the policies available to reduce greenhouse gas emissions also produce other benefits -- energy conservation, enhanced air or water quality, economic development, etc. -- the costs attributable to reducing greenhouse gas emissions are often difficult to isolate. For example, a tree-planting program may reduce the risks of flooding, improve water quality, enhance local air quality, and provide fruit as well as store carbon dioxide. An energy conservation program may reduce energy imports, improve air quality, and save consumers money. In these circumstances, the

total cost of the measure may significantly overstate the cost of reducing greenhouse gas emissions.

Cost estimates may also be misleading insofar as they necessarily reflect existing opportunities and short-term projections. The analysis in this report highlights the importance of emphasizing long-term. cumulative emissions; for this reason, research and development to improve technologies and lower costs may be the highest priority, and the fact that the current cost of a technology is high makes it even more important.

Recent experience developing alternatives to chlorofluorocarbons (CFCs) in response to concerns about ozone depletion illustrates the importance of this point. In 1984, use of CFCs was growing rapidly, and studies of the feasibility and costs of alternatives prepared by industry and U.S. EPA contractors were extremely pessimistic. For some applications, particularly solvents, substitutes for CFCs could not be identified. However, the signing of the Montreal Protocol in September 1987 created a significant market incentive to explore alternatives, and as a consequence, promising new substitutes have been announced with increasing frequency at much lower cost than was previously assumed. At least with respect to CFCs, pre-regulatory experience was not an adequate indication of cost since alternatives were only seriously explored after regulations were implemented.

The ozone depletion problem and international regulation of CFCs resulted in a worldwide race to identify, test, and engineer acceptable substitutes. There may be additional costs associated with this kind of crash effort, as discussed with respect to the issue of timing (see next section). Costs may therefore be difficult to distinguish from government policy choices.

IMPLICATIONS OF POLICY CHOICES AND TIMING

The potential cost of government action to reduce greenhouse gas emissions may be much less than it would appear if such action serves other important economic or environmental objectives. Most of the measures proposed to reduce emissions are already of substantial public interest -- for example, policies that promote energy efficiency, reductions in use of CFCs, efforts to halt deforestation, and other desirable social policies -- so that the threat of a global warming is often simply another reason to implement such policies. The incremental cost of taking actions to limit global warming today may therefore be modest.

The technical feasibility of implementing various measures that have been proposed for limiting global warming has already been addressed in Chapter V. However, since the threat of global warming has so far not been an important consideration in government policymaking, it is important to note the other benefits of these measures. For example, serious consideration is being given to eliminating emissions of CFCs because of their impact on the ozone layer. In addition, a substantial number of states are promoting investments in energy-efficient technology in order to reduce energy costs and to meet the need for new electric generating capacity. Also, federal and state authorities are promoting waste reduction and recycling as alternatives to land disposal because of the high cost and environmental risks associated with traditional disposal methods. Finally, a large and growing international effort has been organized to slow tropical deforestation because of its impact on economic development and the quality of life in many developing countries.

For several reasons, near-term action may be necessary to stabilize greenhouse gas concentrations. For political and economic reasons, actions cannot be immediately implemented once it is agreed they are needed, and for reasons having to do with atmospheric chemistry, concentrations of greenhouse gases and the attendant risks will decline only gradually even after actions are implemented.

Policy development and implementation can be a lengthy process, particularly at the international level. Roughly a decade was required for the process that led to international agreement to reduce emissions of CFCs embodied in the Montreal Protocol, and it will take another decade to implement the agreed-upon reductions. An agreement to reduce emissions of greenhouse gases associated with the use of fossil fuels and with deforestation could take even longer to achieve: the activities responsible for CO_2 emissions are more economically valuable, the distribution of emissions is greater, the responsible countries have diverse economies and less shared interests, and the difficulty of implementing alternatives may be greater.

Implementing new technologies can also often be time-consuming. Most emissions result from activities that are fundamental to supporting the global economy (transportation, space conditioning, industrial production, land clearing, etc.); therefore, rapid introduction of new technologies for some uses could be very disruptive. Once a technology is cost-effective, it may take years before it achieves a large market share, and decades more for the existing capital stock to be replaced. The historical pattern of gradual displacement of old energy sources by new sources is shown in Figure 7-1. Government policy may be able to significantly accelerate this transition, although it is debatable whether such efforts have been very successful in the past.

New end-use technology with greater efficiency can replace existing technologies more quickly: it takes 5-10 years to develop new automobile models, and the existing fleet is largely replaced over 8-12 years; major home appliances and space heating and conditioning systems are in use for 10-20 years, and 20-40 years. industrial equipment, for Buildings may be used for 40-100 years or more, however, and the reduction in energy requirements that can be achieved (per unit) as a result of remodeling is more limited than what can be achieved in newly constructed buildings. Thus, depending on the sector, it traditionally takes roughly 20-50 years to substantially alter the technological base of industrial societies, and the cost of reducing emissions could rise dramatically as the time allowed for achieving these reductions is decreased. While the rate of change can be higher in rapidly developing countries, once the industrial infrastructure is built, it will normally be many years before it is replaced. This process will be naturally accelerated if new technologies become sufficiently attractive and government policies can encourage more rapid retirement of existing buildings and

equipment. Nevertheless, such efforts are likely to be more expensive and technically difficult.

Once greenhouse gases have entered the atmosphere, they continue to affect climate for decades. Even if all anthropogenic emissions of carbon dioxide could be suddenly eliminated, it may take more than a century for the oceans to absorb enough carbon to reduce the atmospheric concentration of CO_{2} even halfway toward its pre-industrial value CHAPTER II). With continued (see emissions, the time required to reduce excess concentrations by the same percentage increases further. For CFCs and N_2O_1 , it would be more than 50 years before their excess concentrations declined by half even if all anthropogenic emissions were eliminated. Only methane responds relatively quickly -the excess concentration would fall by 50% in less than a decade after anthropogenic emissions were eliminated (see Figure 7-2).

The climate response also lags behind the radiative forcing imposed by changes in atmospheric composition (see CHAPTER III). Due to the heat capacity of the ocean, the global average temperature will rise more slowly than if climate were continuously in equilibrium with the changing composition of the atmosphere. The climate will also cool more slowly if trace-gas trends are reversed. Consequently, any strategy that involves responding to climate impacts is very risky: once climate change occurs even draconian measures would not reverse the process for decades.

The effect of delaying policy responses is illustrated by Figure 6-23 (see CHAPTER VI), which shows the potential increase in realized warming that results from simply waiting before implementing a defined set of policies.

IMPORTANCE AND IMPLICATIONS OF A LONG-TERM PERSPECTIVE

In thinking about policies to address global warming, it is critical not to lose sight of the long-term nature of the problem. Short-term policy choices may be very important, for the reasons noted above. However, the choices outlined below are FIGURE 7-1



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designed to address very long-term needs as indicated by the scenarios tested in Chapter VI, which extend to the year 2100. In this time frame, it must be expected that substantial changes will occur in technologies and lifestyles that will have a significant effect on the global warming problem. Research and development strategies are of the utmost importance in providing long-term solutions. Improvements in nuclear energy systems, renewable energy technology, and other nonfossil sources of energy could make an difference in the scenarios enormous considered here, and research begun today could help provide these technologies.

A long-term focus also helps to identify constraints and opportunities associated with alternative technologies. For example, natural gas technologies are a promising interim means of reducing CO₂ emissions, but the analysis presented in Appendix C suggests the supply of natural gas is too limited to offer a long-term, worldwide substitute for coal. Similarly, a long-term global shift to nuclear energy would create concerns about both the supply of uranium and the proliferation problems associated with worldwide shipments of materials suitable for weapons production (Williams, 1988). Large-scale reliance on biomass and solar energy leads to concerns about land availability and conflicts with resources needed for food production.

INTERNALIZING THE COST OF CLIMATE CHANGE RISKS

One of the most potentially effective ways to promote energy efficiency and other strategies to reduce greenhouse gas emissions is to increase the cost of activities responsible for emissions to reflect the risks of climate change. The government could increase the price of fossil fuels and other sources of greenhouse gases by imposing taxes or fees, while reducing the price of desirable alternatives by providing direct or indirect subsidies. Prices of some relevant commodities, particularly electricity, are already regulated and could be adjusted to promote reduced emissions. Such policies have already been adopted to varying degrees in some states to promote other economic and environmental goals. However, the limitations of economic approaches should also be recognized; other types of policies may be more effective in redressing some market failures, and these can complement policies based on adjusting prices.

Evidence of Market Response to Economic Incentives: Energy Pricing

Proper pricing of energy to reflect the reality of the global warming threat could substantially reduce emissions. It was long assumed (based on historical data) that there was a constant relationship between the rate of growth in energy use and the rate of growth of GNP (Weinberg, 1988). The historical constancy of the relationship was often explained as a consequence of technology and stable or declining fuel prices. The chief flaw in this argument was its failure to anticipate the effects of rising real energy prices. During the century preceding 1973, the relative price of energy had fallen, while energy efficiency improved slowly as the capital stock turned over (Edmonds and Reilly, 1985). However, between 1973 and 1985 the price of energy rose, relative to other goods and services, and in accordance with basic economic theory, growth in energy demand slowed, and by some measures, declined significantly.

Prior to 1973, U.S. energy demand grew at a rate only slightly less than the rate of growth in real GNP. Had pre-1972 energy-use trends continued, by 1984 the United States would have been consuming almost 40% more energy than it actually did (U.S. DOE, 1987c). But efficiency improvements induced by significant oil price increases enabled the U.S. to hold energy use to 1973 levels while expanding the economy by 40%. By one estimate, energy efficiency improvements now save the U.S. economy \$160 billion annually.²

U.S. energy efficiency improved markedly between 1973 and 1985 while energy prices rose markedly (see Figure 7-3). However, efficiency improvements in the U.S. and many other industrialized countries have leveled off in recent years. Whereas energy intensity in the nations of the European Economic Community (EEC) declined 20% from 1973 to 1982, the corresponding figure for 1982 to 1986 is 2.4% (EEC, 1988). One





important factor is that oil prices have fallen continuously since 1981. Oil prices dropped precipitously in 1986: world oil prices fell from about \$25 per barrel in January 1986 to about \$10 per barrel in July 1986. Prices have since fluctuated in the \$15 per barrel range. Adjusted for inflation, gasoline prices in the first half of 1988 were 27% less than in 1985 and 48% less than in 1980 (Geller, 1989). The rapid decline in world energy prices has slowed the rate of improvement in energy efficiency. This trend is a predictable response to pricing and may continue for some time given U.S. Department of Energy forecasts of relatively constant or even declining energy prices in the short term (EIA, 1989).

The performance of other countries suggests that higher energy prices are conducive to greater efficiency. Japan, France, and West Germany, much more dependent on imported oil than the U.S., currently use much less energy per unit of output than does the United States (see Table 7-1). Many developing countries are much less energy efficient than the U.S., in part because they subsidize energy prices.

In recent years, the U.S. has debated and rejected higher oil import fees and gasoline taxes as an instrument of energy policy. The increase in the federal gasoline tax recently enacted in the 1990 Budget Reconciliation Act will produce increased revenues to reduce the deficit and will also assist in reducing greenhouse gas emissions by encouraging greater efficiency in highway transport.

Consumer concern about the "cost" of some products may in fact focus on first (initial) costs, or more simply, capital costs (as opposed to operating costs, including energy).³ Thus, the high-efficiency, long-life light bulb may pay for itself in savings over its useful life, but because the price is \$12 most

TABLE 7-1

Energy Intensity of Selected National Economies, 1973-85

Country	1973	1979	1983	1985	Percent Change 1973-85
Australia	21.6	23.0	22.1	20.3	-6
Canada	38.3	38.8	36.5	36.0	-6
Greece*	17.1	18.5	18.9	19.8	+16
Italy	18.5	17.1	15.3	14.9	-19
Japan	18.9	16.7	13.5	13.1	-31
Netherlands	19.8	18.9	15.8	16.2	-18
Turkey	28.4	24.2	25.7	25.2	-11
United Kingdom	19.8	18.0	15.8	15.8	-20
United States	35.6	32.9	28.8	27.5	-23
West Germany	17.1	16.2	14.0	14.0	-18

(megajoules per 1980 dollar of GNP)

* Energy intensity increased as a result of a move toward energy-intensive industries such as metal processing.

Source: IEA, 1987.

people are reluctant to buy it. There are some good reasons for this sensitivity to first costs, such as limited access to capital, doubts about performance claims, etc. These problems may be addressed through the provision to the consumer of accurate and useful information about costs and performance, utility programs to promote energy efficiency as an alternative to expensive investment in new capacity, or other incentive programs.

Another way of looking at costs is to focus on the necessary increase in current expenditures as a measure of the disruption associated with certain policy proposals. Thus, policies that require dramatic changes (or rates of change) in current investment practices may be characterized as "costly." For example, a compared the relative recent study effectiveness of energy conservation and nuclear generation as strategies for reducing CO_2 emissions (Koomanoff, 1989). The author found that to achieve a comparable reduction in greenhouse gas emissions, nuclear generation would have to increase at a rate more than 40 times the rate at which plants were completed during the peak decade 1975-1985. In contrast, end-use efficiency would have to increase 4.6% per year, a rate 60% greater than the 2.9% annual rate at which U.S. efficiency improved during 1978-1986 -- a challenging, but much less ambitious goal measured as a change from historical practice.

Existing federal law gives an additional economic incentive for efficiency through the so-called "gas-guzzler" tax. For 1986 and later models, the law imposes a \$500 tax on any car with a fuel economy rating less than 22.5 miles per gallon (mpg) and a \$3,850 tax on models with ratings less than 12.5 mpg. It was originally proposed that the revenues collected be given to purchasers of highly efficient cars in the form of a rebate; however, this proposal was rejected because at the time the beneficiaries would have been almost exclusively buyers of imported cars (see Bleviss, 1988).

Gas-guzzler fees could be used as a potentially more effective and acceptable substitute for gasoline taxes if set equal to the amount that would be collected from a gas tax over the expected lifetime of the automobile. For example, a 50 cents per gallon tax would become a \$1,000 excise tax on a 25 mpg car but only \$333 on a 75 mpg car (assuming the tax is calculated on the basis of driving 50,000 miles). An advantage of this strategy is that it is less regressive than gasoline taxes because it only applies to new vehicles and because it gives consumers greater freedom to reduce or avoid the tax by buying a more efficient model. The structure of the charge could vary with vehicle class so as not to unduly favor small cars over larger models. The effectiveness of such a system could be enhanced by rebating some of the revenue to buyers of the most efficient models, a concept that now may be more acceptable since several American models rate among the most efficient.

The market for electricity also demonstrates the influence of prices and competition on growth in demand. Until about 1970, the efficiency of new powerplants was improving and electricity prices were therefore declining, contributing to steady growth in the demand for electricity. From about 1970 through 1982, electricity prices rose mainly as a result of higher fuel costs and interest rates, construction delays, the cost of environmental controls, and the end to in generating significant improvements efficiency. In the last five years prices have been stable or declining as fuel costs stabilized, and the amount of new capacity being added slowed in response to the decline in demand (see Figure 7-4). The U.S. Department of Energy projects continued stable prices until the mid-1990s, followed by modest price increases (EIA, 1989).

Financial Mechanisms to Promote Energy Efficiency

Since the mid-1970s, the U.S. has experimented with a variety of financial incentives for energy efficiency. Most of these programs have been carried out by state and local governments and utility companies, usually without much publicity but often quite successfully.⁴ These efforts suggest that there are possibilities for more widespread programs in the future.

One of the most popular forms of financial incentives offered by utilities is rebates for high-efficiency appliances. A recent survey revealed 59 such programs FIGURE 7-4



among U.S. utilities in all parts of the country (Berman et al., 1987; ACEEE, 1988). The majority of these programs are only for residential customers, but more than 20 programs also provide incentives to commercial and industrial customers. Rebates are structured in many different ways; most go only to the purchaser, but some are also offered to retailers. Program coverage varies with differences in demand across the country; some summer-peaking utilities promote both high-efficiency air conditioners to reduce summer demand and heat pumps to increase demand in winter. Rebate amounts frequently vary with the size and efficiency of the appliance, sometimes according to a sliding scale to encourage maximum efficiency. In general, rebate programs appear to be highly cost-effective relative to the costs of new generating capacity. For 33 utilities reporting such data, the median cost of peak demand reduction was \$200 per kilowatt (kW) saved. (For an example of one unique utility conservation program, see Box 7-1.)

Some programs demonstrate the potential for giving economic incentives for energy efficiency to builders. For example, the Bonneville Power Administration's "Super Good Cents" program gives builders a *cash* grant of \$1,000 per house for meeting Model Conservation Standards developed by the Northwest Power Planning Council (Randolph, 1988a).

Creating Markets for Conservation

The opportunity for highly profitable investments in energy efficiency has not gone unnoticed by some businesses. If consumers unresponsive to opportunities for are profitable investments conservation, in businesses theoretically could make such investments and share the savings, particularly since a technically expert company could avoid some of the uncertainties facing the typical energy user. Such firms, often referred to as energy service companies, did emerge in the early 1980s. These firms offered a one-stop shopping approach to conservation, combining an energy audit to identify opportunities for savings with installation and financing in exchange for a share of the savings for some fixed period. The owner is not required to assume any risk and is guaranteed that his/her

Box 7-1. The Hood River Experiment

One recent conservation program illustrates the possibility of achieving high levels of efficiency and broad public participation. The Pacific Power & Light Company and Bonneville Power Administration financed what was arguably the most aggressive conservation program in the U.S. in the small community of Hood River, Oregon. The sponsors offered to audit electrically-heated households and implement all cost-effective conservation measures. In two years, 85% of the eligible households accepted improvements, and most of the remainder of the populace received an audit or had previously improved. their homes. Space heating levels were reduced to about half the level expected in pre-project forecasts. However, the cost-effectiveness of the program became difficult to evaluate when electricity consumption dropped sharply shortly before the program went into effect due to price increases in excess of 40% (Cavanaugh and Hirst, 1987).

bill will be no higher than would have been the case without the improvements. Federal and state governments are testing sharedsaving programs to reduce capital spending requirements (see STATE AND LOCAL EFFORTS below).

In practice, the energy service concept has proven to be valuable but not a panacea (Weedall et al., 1986). The negotiation and administration of contract terms can be lengthy and expensive. Relatively large savings are necessary to justify the overhead costs, meaning that privately funded energy service companies have generally been most interested in larger projects, such as commercial buildings. One means of expanding the reach of the energy service companies has been the organization of such services by non-profit groups, which can sometimes operate on a lower margin because they do not pay taxes or return a profit and may also be able to obtain below-market-rate financing. On the other hand, the range of permissible activities for such organizations is usually limited by charter and funding source. Recently, hybrids containing elements of non-profit and forprofit organizations have begun to appear, with possibilities for achieving the benefits of both (Kerwin and Jolin, 1988).

Another innovative approach to reducing the cost of energy service contracting is to pool enough buildings to achieve economies of scale. The Alliance to Save Energy developed a model for this concept after a demonstration program with eight agencies organized by the United Way of Wilkes-Barre, Pennsylvania. However, the project was difficult to implement, and the potential for replication remains to be seen (Prindle and Reid, 1988).

Many other financing mechanisms have been tested or proposed (Lovins and Shepard, 1988). Several utilities offer generic rebates for any demonstrated savings; in one area in Manhattan with exceptionally high cost of service, the utility offers commercial customers rebates of \$500 per kW peak reduction. Another possibility is sliding-scale hookup fees for new buildings, based on the cost of the generating capacity necessary to supply the building's electricity needs (the converse of subsidies for more efficient buildings) (Rosenfeld and Hafemeister, 1988; also see Box 7-2).

Limits to Price-Oriented Policies

Economic incentives could play a critical role in reducing greenhouse gas emissions. Nevertheless, there are often practical and political limits to reliance on price-oriented policies. Demand may be very inelastic due to lack of information, the absence of alternatives in the near term, or shortages of capital. Price increases may also have socially undesirable, disproportionate impacts on particular groups or regions. Price increases may also be politically unpopular relative to other policies.

Box 7-2. Creating Markets Through Demand Side Bidding

Another emerging approach to promoting markets for efficiency is the demand-side bidding concept. Bidding programs for new capacity have been developed in many states as a means of obtaining low-cost supply additions, a concept that may receive further encouragement from proposed rules now being considered by the Federal Energy Regulatory Commission (FERC, 1988a). FERC has invited comment on the possibility of addressing demand-side bidding, and several states have already implemented such programs. Energy service companies have some potential here since they can achieve some economies of scale. However, large commercial and industrial firms may want to bid themselves rather than share savings (Cole et al., 1988). In 1987 Central Maine Power requested bids for investments producing demand reductions from large industrial customers. The utility offered to pay up to 50% of the project cost or a rebate sufficient to reduce the payback to two years, whichever is less; four contracts were produced for a demand reduction of over 11 MW at a cost of \$2.5 million.

Thus, the price necessary to induce change might be so high as to be inequitable, economically impractical, and politically unattractive. Empirical studies illustrate some situations in which increased energy prices have not resulted in nearly the degree of energy efficiency that would be expected from economic calculations. One study at the Energy Analysis Program at the Lawrence Berkeley Laboratory examined the market for more energy-efficient appliances over the

period 1972-1980 (Ruderman et al., 1987). The authors found that consumers demand payback periods of two years or less for investing in more efficient household appliances. Except for air conditioners, the implicit discount rates corresponding to these payback periods are much higher than real interest rates or the discount rates commonly used in life-cycle cost analysis of consumer choice (see Table 7-2). The study suggests several factors are responsible for this underinvestment substantial in energy efficiency: lack of information, lack of access to capital to pay for the added first cost, the relatively small savings, a substantial number of purchases of some appliances by builders or landlords who do not pay operating costs, and manufacturers' decisions to limit highefficiency features to top-of-the-line models that yield higher profit margins.

Studies of small commercial customers and larger industrial customers indicate they also make greater demands of efficiency investments than of alternatives that are considered to be more within their main line of business (Komor and Katzev, 1988; Lovins and Shepard, 1988; Cavanaugh, 1988; Alliance to Save Energy, 1987). Managers of small enterprises may never see the electric and gas bill, have no knowledge of the rate structure for their building, and are largely unaware of which appliances are responsible for most of their bills. Larger companies may demand payback periods of six months to two years for conservation investments, while simultaneously investing in government bonds at an 11% interest rate. Utility companies typically apply investment criteria to new powerplants that are much less demanding than consumer investments to save an equivalent amount of energy (Cavanaugh, 1986).

Some authorities predict that market forces alone are unlikely to prompt continued demand for automobile efficiency improvements because of the declining share of operating costs attributable to fuel as efficiency improves (see Figure 7-5). According to an analysis by the U.S. Department of Energy, a typical automobile costs over \$10,000 and consumes about 370 gallons of gasoline per year (U.S. DOE, 1988; see also Bleviss, 1988; Goldemberg et al., 1987). At \$1.10 per gallon, this implies that annual fuel expenses typically represent only about 4% of the purchase cost and much less than maintenance, and financing insurance, expenses. The result, according to the U.S. DOE, is that "the desire to reduce fuel expenses, even with higher gasoline prices, will not motivate consumers to significantly alter their preferences for automobiles" (U.S. DOE, 1988).⁵ Precise evaluation of this effect is

Years Required to Pay Back Investment in Energy-Efficient Appliances, 1972-1980

Appliance	1972	1978	1980
Gas central space heater	2.98	2.38	2.21
Oil central space heater	2.33	1.70	1.18
Room air conditioner	5.11	4.77	5.25
Central air conditioner	4.96	4.16	5.18
Electric water heater	0.48	0.41	0.41
Gas water heater	1.50	1.07	0.98
Refrigerator	1.35	1.45	1.69
Freezer	0.60	0.67	0.72

Source: Ruderman et al., 1987.

FIGURE 7-5



Figure 7-5. The indicated energy performance is based on computer simulations of an automobile having various fuel economy improvements added in the sequence shown at the top of the graph. The base car is a 1981 Volkswagen Rabbit (gas version). The figure shows that the reduced operating costs associated with various fuel economy improvements are roughly offset by the increased capital costs of these improvements over a wide range of fuel economy.

Source: Goldemberg et al., 1987.

difficult; the high visibility of posted gasoline prices may cause some consumers to focus more attention on this cost than on other operating costs. Moreover, at some higher price, consumers could be induced to change their preferences, but this price might be so high as to be inequitable, impractical, or politically unacceptable.⁶

Economic incentives alone may not serve to reduce trace-gas emissions to acceptable levels. When markets are unresponsive, there may be a need for regulations or other policies to help restrict activities that result in emissions of trace gases. One desirable effect of regulations and other alternatives to direct economic incentives may be to increase the costs of regulated products and activities, thereby creating indirect economic incentives.

REGULATIONS AND STANDARDS

Regulation of energy, CFCs, and forestry could complement pricing and other policies for reducing greenhouse gas emissions. In brief, pricing strategies and other government policies may not always induce changes in consumer behavior effectively, either because there is some major market failure or because of an unwillingness to set prices high enough to bring about the desired change in demand.

Like pricing and economic incentive policies, government regulations should be viewed as simply one tool for promoting the development and adoption of technologies and behavioral changes necessary to reduce greenhouse gas emissions. They are likely to be most effective (and perhaps most acceptable) when they are targeted to specific groups, are no more restrictive than necessary, and are used to complement economic incentives. research and development programs, information programs, and the other approaches outlined in this chapter.

In this section we will discuss possible regulatory strategies for strengthening existing regulatory programs (which have been adopted for reasons unrelated to climate change) to either restrict emissions of greenhouse gases or encourage actions to reduce emissions, as well as concepts for new regulatory programs specifically targeted to reduce emissions.

Existing Regulations that Restrict Greenhouse Gas Emissions

The U.S. federal government already has extensive regulations and regulatory programs that limit greenhouse gas emissions, such as its air pollution control laws, restrictions on the use of CFCs, and regulation of investments and rates charged by utilities. There are also energy-efficiency standards for automobiles, appliances, and fluorescent lamp ballasts. All of these programs could be modified to yield further reductions in greenhouse gas emissions.

Regulation of Chlorofluorocarbons

Chlorofluorocarbons are being regulated because of concern about their impact on stratospheric ozone (see discussion in CHAPTERS IV and V). The potential for introducing substitutes for CFCs to reduce the risks of ozone depletion and global warming has been known for many years. For example, the DuPont Company stated in 1980 that such substitutes could be produced, but the cost would be much higher (E.I. DuPont, Inc., 1980). Without regulation, however, there was no market for these alternative chemicals so they were not produced. The Montreal Protocol on Substances That Deplete the Ozone Layer, signed in September 1987, provides a framework for global reductions in CFC emissions. The subsequent June 1990 London Amendments to the Protocol provide an accelerated framework for global reductions of CFCs and halons, and introduce a schedule for global reductions in methyl chloroform and carbon tetrachloride:

• The use of CFCs-11, -12, -113, -114 and -115 is to be frozen at 1986 levels starting in approximately mid-1989, reduced to 80% of 1986 levels in 1993, and reduced to 50% of 1986 levels in 1995. The reduction from 80% to 50% will take place unless the parties participating in the Protocol vote otherwise.

• The use of halons 1211, 1301, and 2402 is to be frozen at 1986 levels starting in approximately 1992, reduced to 50% of the 1986 levels in 1995, and phased out by 2000.

• The use of methyl chloroform is to be frozen at 1989 levels starting in 1993, and reduced to 70% of 1989 levels by 1995, and reduced to 30% of 1989 levels by 2000, with full phase out in 2005.

• The use of carbon tetrachloride is to be frozen at 1989 levels in 1992, reduced to 15% of 1989 levels in 1995, and completely phased out in 2000.

• The London Amendments also include a non-binding resolution regarding phase out of HCFCs.

• Beginning in 1990, and at least every four years thereafter, the parties will assess the control measures in light of the current data available. Based on these assessments the parties may adjust the control levels and substances covered by the Protocol.

• Each party shall ban the import of the controlled substances (bulk CFCs and halons) from any State not party to the Protocol beginning one year after the Protocol takes effect. The parties shall, in addition, develop a list of products that contain the controlled substances, which will be subject to the same trade restrictions. The feasibility of restricting trade in products manufactured with the controlled substances shall also be assessed.

• Developing countries with low levels of use per capita are permitted to delay their compliance with the Protocol for up to ten years. The parties also agree to assist developing countries to make expeditious use of environmentally safe alternative substances and technologies.

The U.S. Clean Air Act Amendments provide a more detailed reduction schedule for CFCs and halons, accelerate the reduction schedule for methyl chloroform (freeze at 1989 levels starting in 1991 with full phase out in 2002), and for carbon tetrachloride (freeze at 1989 levels starting in 1991 with full phase out in 2000), as well as a phase-out of HCFCs over the 2015 to 2030 period.

On August 1, 1988, U.S. EPA announced a comprehensive regulatory program for these chemicals that will reduce production and consumption in three phases leading to a 50% cut by July 1, 1998 (Federal Register, 1988). The U.S. regulations become effective upon international ratification of the In September 1988, U.S. EPA Protocol. Administrator Lee Thomas stated that recent scientific evidence makes it necessary to consider a complete phase-out of these chemicals. The regulatory approach adopted by U.S. EPA restricts CFCs by granting limited production rights to the five U.S. companies who manufactured them in 1986, and by restricting imports. This is expected to cause an increase in price and an increasing incentive for CFC users to find substitutes.

U.S. EPA was concerned that the added profits for CFC producers could create an incentive to delay the introduction of substitute chemicals. U.S. EPA estimated that CFC producers could earn additional profits between \$1.8 billion and \$7.2 billion by the year 2000. The Agency therefore requested comments on the merit and legality of taxes on CFCs to remove the added profit and potential incentive to delay.

Another concern is that the price rise alone may not be an effective means of reducing demand for some uses of CFCs for which substitutes may be available, but which have a small impact on total product cost. U.S. EPA has indicated it will monitor this possibility and will, if necessary, consider product-specific regulations.

Energy Efficiency Standards

Congress adopted minimum energy efficiency standards in 1987 for refrigerators. water heaters, air conditioners, furnaces, and other appliances. The standards take effect on different dates for different products in recognition of variations in product planning The law defines and production needs. standards for different classes and categories of each appliance and does not prevent the addition of new features that may increase total energy consumption (see Table 7-3). By one estimate, the standards will reduce peak electricity demand in the year 2000 by an amount equivalent to the output of 22 large powerplants (Geller, 1986a). The appliance standards were adopted on the basis of a supported by industry and consensus

TABLE 7-3

Comparison of Energy Efficiencies of Regulated Appliances

Appliance	Average Annu	ual Energy Con New Models	sumption Best Commercial Model	Estimated Cost-Effective Potential ^a	Potential Savings ^b (percent)
Refrigerator ^c	1,500	1,100	750	200-400	87
Central Air Conditioner ^c	3,600	2,900	1,800	900-1,200	75
Electric Water Heater ^c	4,000	3,500	1,600	1,000-1,500	75
Electric Range ^c	800	750	700	400-500	50
Gas Furnace ^d	730	620	480	300-480	59
Gas Water Heater ^d	270	250	200	100-150	63
Gas Range ^d	70	50	40	25-30	64

^a Estimates are made of potential efficiency (by mid-1990s) if further cost-effective improvements already under study.

^b Percent reduction in energy consumption from the average of those appliances in use to the best cost-effective potential.

^c Energy consumption for these appliances measured in kilowatt-hours per year.

^d Energy consumption for these appliances measured in therms per year.

Source: Geller, 1986b.
environmental and consumer groups, demonstrating that a cooperative approach to establish achievable energy efficiency goals is possible. Appliance manufacturers were most interested in preemption of state regulation, while utilities and environmental groups were motivated by energy savings. On November 17, 1989, the Department of Energy published regulations imposing new efficiency standards for refrigerators and freezers. The new standards are more stringent than minimums established by the federal law and by California and are expected to reduce energy use by 25%.

The energy efficiency standard for new U.S. automobiles as of 1988 was a CAFE of 26 mpg. In September 1988, the Department of Transportation set CAFE standards at 26.5 mpg for the 1989 model year, down from a scheduled increase to 27.5 mpg. The standard for the 1990 model year has been set at 27.5 mpg. Automakers are allowed to meet this requirement by offsetting less efficient (usually larger, more powerful) models with more efficient ones; they may also offset their failure to meet the target in one year with credits gained in prior years. However, mpg ratings of domestic models may not be averaged with those of foreign imports. New-car fuel economy has improved markedly since CAFE was adopted (well over 50% since 1973), but its value has been vigorously debated. The research of Greene (1989) indicates that CAFE standards have had about twice the influence of gasoline prices on efficiency Critics of the efficiency improvements. standards, however, argue that the fueleconomy gains have been primarily a response to higher prices and that the regulations have imposed substantial costs on manufacturers and consumers. They argue that fuel efficiency is improving due to market pressures and technological innovation, but that if more rapid improvement is desired, it could be promoted more efficiently by higher gasoline taxes to promote demand for more efficient vehicles and encourage turnover of older, inefficient cars (U.S. DOE, 1988; Crandall et al., 1986). Another problem with efficiency standards is that they may have contributed to the trend toward longer use of older vehicles. Only 12% of vehicles in use in 1969 were more than ten years old, but this figure increased to 29% in 1987, substantially

increasing both fuel consumption and air pollution from what it would otherwise have been.

There is, however, no assurance that market forces alone will produce substantial further improvement in vehicle mileage ratings as long as oil prices are stable or declining in real terms. Higher gasoline taxes would help but may have to be increased sharply to spur demand for efficiency improvements beyond 30 mpg. Exclusively demand-oriented strategies can leave manufacturers with considerable uncertainty about future markets (Bleviss, 1988). Regulations adopted as a supplement to tax increases could give industry a clear target, reducing the need for hedging strategies that dilute efforts and increase investment costs (Bleviss, 1988).

The CAFE approach also could be improved to increase incentives for efficiency improvements and to meet some industry objections (McNutt and Patterson, 1986). The fleet average concept unduly penalizes larger when technologies could cars. allow improvements in all sizes and classes. It requires annual improvements, when improvements are made in steps over longer time periods, and then seeks to provide flexibility with credits that encourage a search for administrative exemption rather than longterm improvement. Lower standards have been set for light trucks, which further undercut the program. Finally, violations of standards are punishable by court-imposed civil penalties, when equivalent economic incentives could achieve the same results more acceptably by imposing fees proportional to the noncompliance (Bleviss, 1988).

Air Pollution Regulations

Some greenhouse gases are already regulated as air pollutants because of their effects on human health and welfare. Under the Clean Air Act, U.S. EPA sets uniform ambient standards for emissions of carbon monoxide (CO), ozone (O_3) , nitrogen oxides (NO_x) , and other pollutants and uniform technology-based standards for major new sources of these pollutants. However, states retain responsibility for compliance with the ambient standards, which may require allocating greater responsibility on some sources than on others. States are also free to set more stringent requirements on stationary sources.

The regulatory strategy for control of air pollutants to stabilize greenhouse gas concentrations is not identical to that for achieving compliance with ambient air quality standards. In the latter case, the objective is to stay below threshold levels that affect human health or welfare. Total as well as peak emissions, however, affect the buildup of greenhouse gases, which implies a potentially different regulatory approach. An area barely in compliance with ambient air quality standards at all times may contribute more to greenhouse gas buildup than an area with occasional air quality violations but extensive periods of much cleaner air.

Substantial progress has been made in reducing total emissions of regulated pollutants since the Clean Air Act was adopted in 1970 (U.S. EPA, 1987). For example, CO emissions from automobiles dropped about 35% from 1970 to 1985 despite a 58% increase in vehicle miles traveled (see Figure 7-6). Emissions of volatile organic compounds from highway vehicles decreased 48% in the same period. However, emissions of NO_x during this period were relatively unchanged.

Passage of the Clean Air Act Amendments of 1990 will result in substantially increased progress toward cleaner air from a health and welfare viewpoint. In addition, it will have substantial greenhouse gas reduction effects. The efforts to achieve attainment and maintenance of National Ambient Air Quality Standards through regulation of carbon monoxide, nitrogen oxides, and volatile organic compounds will reduce tropospheric ozone and methane. Specific targets for sulfur dioxide of 10 million tons below 1980 levels and for nitrogen oxides of 2 million tons below projected year 2000 levels will encourage energy efficiency and reduce greenhouse gas emissions. The provisions of the Clean Air Act and the Montreal Protocol to phase out CFCs, halons, and carbon tetrachloride by 2000, methyl chloroform by 2002, and HCFCs over the 2015 to 2030 period will directly reduce greenhouse

gas emissions as well as protect the stratospheric ozone layer.

Solid Waste Management

The problem of solid waste management illustrates another area in which policies to reduce greenhouse gas emissions may complement other environmental objectives. As discussed in Chapter IV, decomposition of solid wastes is a growing source of methane emissions. In the U.S., governments at all levels have accelerated efforts to promote recycling and reduction of solid wastes for both economic and environmental reasons.

State and local governments have historically been primarily responsible for solid waste disposal. The cost of landfills and public opposition to burning waste has generated substantial interest in recycling and waste reduction. Numerous states have recently adopted stringent programs to reduce the waste stream by a minimum of 25%. How this will be accomplished has yet to be made completely clear, but economic incentives will play a major role in some states. Florida adopted an advance disposal fee on every retail container sold that fails to achieve a 50% recycling rate; the fee increases if targets are not met (Carlson, E., 1988). Similarly, California adopted a system of deposit fees with increases scheduled to take effect if goals are not met.

Federal law (RCRA Sec. 4010(c)) assigns U.S. EPA the responsibility for ensuring the environmental safety of sanitary landfills. As discussed in Chapter V, U.S. EPA proposed minimum standards on August 1, 1988, that would require gas monitoring stations to detect methane and to plan for its removal, and proposed regulations under the Clean Air Act that would require collection of landfill gas at both new and existing landfills. The Agency has also supported a national recycling goal of 25% by 1992.

Another source of methane releases discussed in Chapter V is coal mining. Interest in coalbed methane recovery is increasing for economic reasons, but at this time there are no specific policies to promote such efforts. FIGURE 7-6



Utility Regulation

Regulatory policies also can exert a significant influence on the price and demand Electric companies are for electricity. monopolies whose rates and investments are regulated by state public utility commissions -except for wholesale and interstate transactions, which are approved by the Federal Energy Regulatory Commission. The structure, as well as the overall level of electricity rates, is regulated, and both influence demand (see Kahn, 1988). For example, some states provide relatively low "lifeline" rates for the initial increment of residential demand to meet the basic energy needs of all customers. The consequence is usually an inverted block rate structure, with rates increasing with greater use. Even though rates may be initially set to produce the same total revenue, the result is some reduction in demand because consumers recognize the higher rates associated with greater use. For example. Detroit Edison estimated that a lifeline rate structure imposed in 1981 resulted in reducing demand about 3% (Kahn, 1988).

Where the production of electricity to meet peak power needs is more carbonintensive (e.g., where the marginal fuel is oil and the base fuel has a large percentage of nuclear power), incentives to reduce peak demand and to level loads may be economically justified as a means of supporting greenhouse gas reductions. With time-of-use metering, utilities can charge rates that more accurately reflect costs, potentially promoting energy efficiency as well as cost savings. This is possible because the costs of generating electricity are not uniform throughout the year; when demand peaks, costs are usually highest because the utility must rely on its most costly units to meet the increased demand. Some utilities in the U.S. and in Europe have tested rate structures that give customers incentives to use electricity at times when costs are low, and conversely, disincentives when costs are high. For example, a recent three-year New York experiment gave customers a one-cent-perkWh reduction during hours of normal demand, but above a certain threshold level, customers were charged a rate of 40 cents per kWh, several times higher than the usual rate. On average, customers saved 5 to 10%

annually, reduced their peak period loads over 40% relative to the average customer, and expressed strong support for the continuation of the program (Cole and Rizutto, 1988). The metering costs are currently about \$500 per house, but the overall program is still expected to produce substantial net benefits. Moreover, it is expected that meter costs will drop substantially with large production. (For an example of utility disincentives, see Box 7-3.)

Box 7-3. Disincentives to Utility Conservation

The revenues earned by electric and gas utilities are governed by accounting rules devised to allow utilities to recover operating costs and earn a fair rate of return. These rules were not intended to favor particular types of investments but recent analysis by the Maine and California public utility commissions indicates that they may in fact favor investments in additional supply as opposed to efficiency improvements, even when the less expensive latter is much (Moskovitz, 1988; Cavanaugh, 1988). As long as retail rates exceed shortterm production costs, these studies show that, under traditional regulatory practices, utilities will always earn greater profits by selling more electricity, even if the cost of conservation is zero. Allowing utilities to profit from conservation by allowing equivalent return on such an investments does not rectify the the economic situation. Instead, incentive is to do the most costly conservation investments (to achieve the greatest return) with the least impact (to maintain sales). California and Maine have adopted procedures designed to correct these disincentives as one means of encouraging utility interest in demand-side investments.

Another significant issue in utility regulation is the creation of competitive markets for the generation of electricity. Federal and state policy have encouraged this concept since the enactment of the Public Utility Regulatory Policies Act (PURPA) in 1978. This law requires utilities to buy power from cogenerators and small renewable energy projects and to pay an amount equal to the costs they save as a result. Since the law's adoption, thousands of projects have been developed around the country, despite the absence of a need for new generating capacity in many areas (FERC, 1988c).⁷ FERC compilations indicate cumulative applications from projects equivalent to more than 40 nuclear powerplants (see Table 7-4). In addition, FERC is currently reviewing proposed rules to expand the circumstances and type of projects eligible to participate in competitive bidding arrangements (FERC, 1988a, 1988b). FERC has also asked for comment on the possibility of allowing demand-side reduction efforts to compete with capacity additions.

Existing Regulations that Encourage Emissions Reductions

contrast with In the mandatory regulations discussed above, some regulatory programs stress positive incentives for reduce greenhouse activities to gas concentrations. Such programs could be expanded to encourage greenhouse gas reductions.

Tree Planting

example of A prime regulatory incentives for actions that reduce greenhouse gas concentrations is the Conservation Reserve Program (CRP) created by the Food Security Act of 1985. The CRP gives up to 50% of the cost of establishing approved conservation practices to farmers who agree to take highly erodible cropland out of production for contracted periods of 10-15 years. Under Section 1232(c), at least one-eighth of the number of acres placed in the reserve between 1986 and 1990 are to be devoted to trees. As of the sixth signup, ending February 19, 1988, more than 1.5 million acres had been committed to trees -- less than a third of the Congressional goal -- at a cost to the government of roughly \$58 million (Dudek, 1988).

In recognition of the CRP's broader potential for achieving environmental protection, the program was modified in the sixth signup to allow the inclusion of 66- to 99-foot-wide strips of former cropland along streams and waterbodies, irrespective of the erosion rate.⁸ Tree planting is one allowed use of the land. These so-called "filter strips" provide a buffer zone that absorbs pollutants that would otherwise go into lakes and streams. The Conservation Reserve Program offers a possible model and precedent for further cooperation between U.S. EPA and the U.S. Forest Service to identify opportunities where tree planting may serve multiple-agency goals.

Because the CRP provides such diverse benefits, proposals have been made to expand its scope and coverage. In some states, particularly in the Southeast, aggressive tree planting could become a significant means of offsetting the buildup of carbon dioxide. According to a recent study, most eastern states, with the exception of Florida, appear to have enough erodible acreage to provide the acres needed to offset new CO₂ emissions from electricity production if such acreage is planted with trees (see Table 7-5). Roughly 11-22 million acres of new trees, or about onefourth to one-half of the current CRP goal, would offset projected new fossil-fueled generating plants for the 1987-1996 period, assuming those 11-22 million acres were planted with optimum species (Dudek, 1988). By this estimate, the costs are modest relative environmental requirements to other associated with operating powerplants, on the order of 0.5 cents per kilowatt-hour.

New strategies to promote tree planting may avoid some of the limitations and complications created by the CRP, which must identify farmers willing to withdraw farmland and which must restrict the land for a period less than the time many trees require to reach maturity. Utility companies and large industrial coal users may also wish to sponsor tree planting. The U.S. Forest Service reports that southeastern states -- where most timber industry investments have occurred in the past two decades -- must replant and manage their

Cogeneration Facilities

(No. Filings), [No. of Facilities], and Capacity in kW

	Ne	Św	Ex	isting	В	oth	Tou	al	Qualified and Initial	Facilities Capacity
Coal Natural Gas Biomass Waste Oil Other	(183) (1,264) (122) (51) (47) (38)	10,419,659 25,894,776 1,617,390 2,432,239 324,921 1,258,288	(6) (41) (18) (2) (8) (3)	461,600 1,888,457 570,497 40,875 323,700 56,500	(12) (9) (9) (1) (1) (1)	356,272 694,671 615,000 51,000 5,350 62,250	(201) (1,314) (149) (54) (56) (42)	11,237,531 28,477,904 2,802,887 2,524,114 653,971 1,377,038	[178] [1,269] [138] [50] [56] [39]	10,948,083 26,880,678 2,698,802 2,450,114 653,971 1,311,968
Total Cogeneration	(1,705)	41,947,273	(78)	3,341,629	(33)	1,784,543	(1,816)	47,073,445	[1,730]	44,943,616

NOTES:

1. Under §292.202 of the Commission's rules, "Cogeneration facility means equipment used to produce electric energy and forms of useful thermal energy (such as heat or steam) used for industrial, commercial, heating, or cooling purposes, through the sequential use of energy." Topping-cycle facilities first apply the energy input to electric power production; bottoming-cycle facilities first apply the energy input to a useful thermal application. All but nine filings in this table are topping-cycle facilities. Bottoming-cycle and partially bottoming-cycle facilities are listed below, along with their capacities:

QF80-6-000 New	Petro Coke	75,000
QF82-100-000 New	Coal	10,000
QF82-207-000 New	Coal/Waste	125,000
QF83-220-000 New	NG, FO	6,000
QF84-134-000 New	Petro Coke	27,300
QF84-192-000 Ex.	NG	910
QF85-572-000 New	Waste/Petro Coke	49,900
QF86-23-000 New	NG	2,700
QF86-800-000 New	Hydrocarbon Coke	3,300

2. "Other" includes cogeneration facilities using nuclear or solar energy sources.

Source: FERC, 1988c; Koomanoff, 1989.

State	Megawatts (MW)	CO_2 Emission (10 ³ tons)	Erodible Acres (10 ³ acres)	Offset Average (10 ³ acres)	Percent (%)
Alabama	1,557	10,458.4	2,558.8	697.2 - 2,091.6	27.2 - 81.7
Arizona	710	4,900.3	187.1	326.7 - 980.1	> 100
Colorado	899	6,204.7	6,480.1	413.6 - 1.240.8	6.4 - 19.2
Florida	2,678	15,136.3	670.2	1,009.1 - 3,027.3	> 100
Georgia	1,641	11,325.9	3,072.7	755.1 - 2,265.3	24.6 - 73.8
Iowa	50	201.2	17,833.7	13.4 - 40.2	0.1 - 0.3
Indiana	1,600	10,179.6	5,244.2	678.6 - 2,035.8	12.9 - 38.7
Kentucky	1,095	7,557.5	2,412.7	503.8 - 1,511.4	20.9 - 62.7
Louisiana	540	3,727.0	2,171.0	248.5 - 745.5	11.4 - 34.2
Maryland	753	4,870.3	602.7	324.7 - 974.1	53.9 -> 100
Minnesota	1,251	8,634.2	10,102.0	575.6 - 1,726.8	5.7 - 17.1
Missouri	1,005	6,792.4	7,223.7	452.8 - 1,358.4	6.3 - 18.9
Mississippi	250	1,725.5	3,009.9	115.0 - 345.0	3.8 - 11.4
North Carolina	690	4,762.3	2,476.4	317.5 - 952.5	12.8 - 38.4
Nevada	1,865	12,469.0	79.1	831.3 - 2,493.9	> 100
Ohio	1,300	8,972.4	3,799.8	598.2 - 1,794.6	15.7 - 47.1
Oklahoma	470	2,754.6	3,795.2	183.6 - 550.8	4.8 - 14.4
Texas	5,515	38,063.5	20,417.2	2,537.6 - 7,612.8	12.4 - 37.2
Utah	814	5,577.8	392.6	371.9 - 1,115.7	94.7 -> 100
Wisconsin	60	414.1	4,015.6	27.6 - 82.8	0.7 - 2.1
Total	24,743	164,727	96,544.7	10,981.8 - 32,945.4	11.4 - 34.2

Erodible Acreage Available to Offset CO₂ Emissions From Electricity Production

Source: Dudek, 1988.

dwindling forests to allow their timber industry to keep growing (USFS, 1987).

There are some practical questions to be answered before attempting a large-scale program to offset carbon emissions with tree planting, particularly if implemented on an international basis. For example, there may be difficulty counting net "new" trees in a developing country undergoing deforestation; there must be assurances that the trees are properly cared for and not cut down prematurely. Similarly, counting net energy reductions may be difficult since a factory may have intended to make improvements in any case.

Despite these concerns, the offset concept offers some advantages that make it worthy of further consideration. First, it can be targeted to achieve greenhouse gas reductions, unlike energy regulations, which may not always reduce carbon-intensive fossil fuels. Second, the offset concept is consistent with efficiency and innovation by allowing each developer the flexibility to seek out the least expensive means of reducing his emissions. Third, it can be implemented in a way that promotes international cooperation by allowing reductions to be achieved in developing countries where they can be accomplished most cheaply and also contribute to development. Eligibility for offsets could be limited to countries that join in ап international greenhouse agreement as an incentive for participation.

Other Incentives/Disincentives

The Food and Security Act has another provision that demonstrates the potential use of regulations to promote environmental goals. Under Section 1221, any farmer who produces an agricultural commodity on a wetland converted to agricultural use after the effective date of the Act may become ineligible for many forms of U.S. Department of Agriculture financial assistance. The restriction applies to all of the farmer's land, not only the converted wetland area. The impact of the program obviously depends on the value of the financial assistance, which in turn varies with commodity prices, but the precedent is important (see Tripp and Dudek, 1986).

Another example regulatory of incentives for actions to reduce greenhouse gas emissions is higher rates of return in some states for utility investments in energy efficiency or renewable energy. Utilities are also sometimes allowed to choose whether to amortize their investment and receive a return or recover their expenses in the first year. Some states have also adopted revenue adjustment provisions to prevent reductions in utility profits as a consequence of utilitysponsored conservation programs (Cavanaugh, 1988; Moskovitz, 1988).

RESEARCH AND DEVELOPMENT

Further research and development will be necessary to bring about widespread use of many of the technologies and strategies reviewed in Chapter V. As discussed below, in some areas substantial programs are already in place, while in others existing priorities may not be entirely consistent with the objective of stabilizing greenhouse gas emissions.

Research programs can serve several different purposes. In some cases, such as finding more efficient methods for producing steel and photovoltaics, basic research is needed. In other areas, technologies are nearly commercially ready but their introduction could be accelerated through testing and demonstration (see Box 7-4). Research is important to improve policies and programs as well as hardware; for example, the U.S. has acquired considerable experience with energy conservation programs over the last decade that has yet to be fully evaluated and summarized for use by public and private authorities.²

The importance of government support for R&D is widely accepted; industry often has only a weak incentive to pay for research that will be of widespread benefit or that is long term and high risk (U.S. DOE, 1987c). However, government can create incentives for greater industry efforts. Special efforts are also needed to develop technologies suitable for use in developing countries where local needs and resources may dictate very different solutions.

Box 7-4. Light-Vehicle Fuel Economy R&D

Prototype vehicles designed by Toyota and Volvo have already demonstrated that it is technically possible to produce full-sized vehicles with fuel economy of 70 mpg or better, as discussed in Chapter V. Recent developments in materials technology and other areas suggest that even this level will be greatly exceeded in the near future. The problem therefore is less one of basic science than it is lack of incentives for product development to reduce costs. The relatively low price of oil has diminished incentives to invest in improved efficiency unless it is associated with other features considered more marketable. This is true in both Japan and Western Europe, as well as in the U.S., since the price of oil has declined even more rapidly in these countries because of the relative decline in the value of the dollar.

Barring another large rise in oil prices or some significant government policy intervention, it seems unlikely to expect that consumers will demand, and that manufacturers will produce, vehicles with much higher fuel economy. Indeed, there is some evidence that fuel economy (particularly in U.S.-made vehicles) will stagnate or even decline in the near term as a result of market demand for larger models and increased acceleration and performance capabilities (Bleviss, 1988).

Energy Research and Development

The energy R&D budget is important from a greenhouse perspective in both its total amount and its relative priorities. Research to promote the more efficient use of all forms of energy is desirable from the standpoint of greenhouse gas emissions, as is research to reduce the cost of renewable and nuclear energy relative to fossil fuels. Since fiscal year (FY) 1981, annual appropriations for energy R&D have declined from \$3.4 billion to roughly \$1.4 billion in FY 1988. An examination of R&D expenditures in other western industrialized countries suggests that their research budgets have tended to remain more constant than those of the U.S. As of 1986, the U.S. ranked last among the Organization for Economic Cooperation and Development (OECD) member countries in the percentage of GNP devoted to energyefficiency R&D. However, U.S. expenditures still ranked first in absolute terms (see Table 7-6).

Priorities among energy sources have also shifted during the 1980s as research on renewables and conservation has declined more than research in other areas (see Figure 7-7). The Clean Coal Program is by far the largest energy R&D initiative this decade; President Reagan requested \$525 million for FY 1989 and \$1.775 billion for FY 1990-1992. Clean coal technologies could make an important contribution to reducing CO_2 emissions by substantially improving the efficiency of coal use so that less coal needs to be used to produce a given amount of electricity. Electricity generation is the only major area of primary energy use that has not achieved significant efficiency improvements in the last 25 years (Fulkerson et al., 1989). However, the intent of current policy is also to expand the market for coal here and abroad, thereby helping to improve the U.S. balance of trade (coal exports were worth \$3.5 billion in 1987). Unfortunately, expanded coal use would unavoidably increase carbon emissions relative to other fuels used with equivalent efficiency (U.S. DOE, 1987c; National Coal Council, 1987). The U.S. DOE has suggested the use of alternative fuels and increased domestic production of petroleum. However, these alternatives could exacerbate the greenhouse problem, particularly if alternative fuels were coal-derived.

Total federal spending on R&D is not the only measure of success. Some studies suggest that the variations in funding levels and priorities in U.S. R&D efforts have reduced their effectiveness relative to more .

TABLE 7-6

Country	Efficiency Budget (millions of dollars)	Total R&D Budget (millions of dollars)	Efficiency as Percent of Total
Japan	78	2,311	3
United States	275	2,261	12
Italy	48	761	6
West Germany	21	566	4
United Kingdom	43	378	11
Canada	34	336	10
Sweden	29	79	37
Greece	0	15	0
Denmark	5	14	36
Total OECD*	622	7,133	9

Government Efficiency Research and Development Budgets in OECD Member Countries, 1986

* Total includes minor additional expenditures. Excludes France.

Source: IEA, 1987.

FIGURE 7-7



steady and long-term programs such as those in Japan (Flavin, 1988; Chandler et al., 1988). Federal R&D support may no longer be as important for technologies reaching commercial competitiveness, such as photovoltaics; low energy prices have become a more critical obstacle (Carlson, D., 1988). The largest improvements in energy efficiency often result from changes in processes or products that serve multiple purposes; reduced energy costs may be only a secondary consideration (OTA, 1983). Narrowly focused energy conservation programs may not effectively address this objective. One alternative is to establish research centers for energy-intensive industrial processes. Such centers could research multiple improvements on a cooperative basis with industry and academia, an approach currently incorporated in the Combustion Research Program operated by Sandia National Laboratories (Chandler et al., 1988).

In 1989 the Oak Ridge National Laboratory (ORNL) published a major review of U.S. energy R&D entitled Energy Technology R&D: What Could Make A Difference (Fulkerson et al., 1989). The study was conducted by more than 100 ORNL staff members with additional help from experts from other laboratories and R&D institutions. The authors reviewed both public and private expenditures and concluded that total U.S. expenditure on energy R&D is in the vicinity of \$4 billion to \$5 billion annually, or about 1 to 1.5% of total annual energy expenditures.

The ORNL study evaluated current research budgets and priorities in terms of their adequacy to meet future circumstances, including a scenario in which the greenhouse effect calls for reductions in the use of fossil fuels. The report concluded that from the perspective of global warming "the nation's R&D agenda is not adequate nor balanced. A much greater effort is needed to develop and improve non-fossil sources and to improve the efficiency and economics of end-use technologies. The latter has the greatest potential to reduce the use of fossil fuels in the near to mid-term" (Fulkerson et al., 1989).

The timing and cost of a greenhouseoriented energy R&D policy were also addressed by ORNL: Because of the substantial lead time required [to develop new technologies], it seems imprudent to delay the R&D necessary to provide the options that move the energy system away from fossil fuels at reasonable cost. Furthermore, what will we have lost by taking aggressive action now? ... [Improved efficiency and non-fossil technologies] will be useful in any event, and the cost of achieving them on an accelerated schedule is the increased cost of R&D (Fulkerson et al., 1989).

To meet these goals and to reduce CO_2 emissions, ORNL proposed a program of about \$1 billion annual additional energy R&D expenditures as itemized in Table 7-7. They suggest about \$600 million of this amount could be raised by a tax on fossil fuels at the rate of 0.2%, with the remainder coming from matching funds invested by private firms.

Oak Ridge reviewed many specific areas where the potential for technological improvement is considered very promising. Some of the most important areas for research are crosscutting technologies such as improvements in materials science that would produce benefits throughout the economy (see also Williams et al., 1987).

Federal programs are also not the only large source of energy R&D support. Several states, notably New York, California, and North Carolina, have created state agencies to support energy R&D (see STATE and LOCAL EFFORTS, below). Private sector support is also large: the utility-supported Electric Power Research Institute and Gas Research Institute both have annual budgets in excess of \$100 million, and some of these organizations give high priority to research on efficiency improvements.

Another important consideration is the allocation between basic science and more applied research. The former has received highest priority, but demonstration and technology transfer programs can accelerate acceptance of innovative ideas that have been proven on a small scale but are not yet widely adopted. The U.S. Department of Energy now

Additional Energy Technology R&D Expenditures Needed to be Prepared to Control CO₂ Emissions

(combined public and private sector investments)

R&D Area	Added Cost (million \$ per year)
Improve efficiency and economics of end-use and conversion technologies Phased increase over several years to double the current national level seems warranted by opportunities.	300
Improve nuclear power Prototyping an advanced LWR (ALWR) with passive safety features and an MHTGR which is fully passively safe would probably cost \$3 billion to \$4 billion over the next decade. Prototyping the liquid metal breeder with passive safety features should be initiated in the first decade of the next century.	300-400
Solar and renewables Expanded budgets for biomass, hydroelectric (to capture 50 Gw of remaining capacity) photovoltaics, solar thermal electric, wind, and others (phased increases over several years) seem warranted by the technological promise.	200
Fusion Better international coordination of the \$1 billion to \$2 billion per year expended worldwide is needed.	None, if improved world cooperation achieved
Technologies for less-developed countries This would be the U.S. part of a worldwide effort to develop energy technologies for developing nations.	100-200
TOTAL	900-1100

Source: Fulkerson et al., 1989.

supports some technology transfer activities for conservation and full-scale demonstration of clean coal technologies to provide "proofof-concept" experience (*Clean Coal Synfuels Letters*, 1988; U.S. DOE, 1987c). Some of the technologies with greatest potential to reduce greenhouse gases, such as advanced gas turbines (see CHAPTER V), could also benefit from full-scale demonstration and evaluation (Williams and Larson, 1988).

Energy R&D should also include examination of policy and program issues (IEA, 1987). One very critical question is why so many consumers often fail to invest in energy conservation measures despite very high rates of return; this behavior appears to be irrational in economic terms (Kempton and Neiman, 1987; Aronson and Yates, 1985). Consumers also respond differently to loans, rebates, and other subsidies even though they have roughly equal cost to the government.

Another research need for policy purposes is a more detailed data base on international sources of greenhouse gas emissions. The compilation of such data should be an initial goal of the Intergovernmental Panel on Climate Change.

Global Forestry Research and Development

The benefits of trees for storage of carbon are widely accepted, but the elements of a large-scale forestry program to stabilize greenhouse gas emissions have yet to be fully described (see CHAPTER V). Such a program would seek to maximize global vegetation and storage of carbon. The steps necessary to accomplish this objective may not be entirely consistent with the emphasis and goals of existing governmental and commercial forestry The preservation of research programs. tropical forests, for example, is a critical international environmental problem with considerable impact on global climate change. However, this effort may not be the most costeffective way to increase net global forest cover, because the underlying causes are often closely related to deeply rooted social ills that require very long-term solutions. Large-scale plantation forestry is one alternative, but the economic criteria used in commercial forestry may also have little relationship to maximizing carbon storage.

Traditional forestry research priorities have not emphasized conservation. Recent reviews of forestry research in tropical countries conclude that most projects have focused on the creation of large-scale industrial plantations and other activities to promote the improved industrial use of timber (FAO, WRI, World Bank, and UNDP, 1987). According to the Tropical Forest Action Plan prepared by an international task force, forestry has not received the large-scale, targeted research support devoted to agricultural study of plant breeding and the development of improved crop varieties. The Plan proposed to begin responding to these needs with a five-year, \$1 billion research program.

Efforts to date indicate that forestry research can produce markedly higher yields through genetic improvement and better management practices. For example, a Brazilian paper company was able to double yields from 33 to 70 cubic meters per hectare per year through genetic selection and cloning (WRI, World Bank, and UNDP, 1985). Research and demonstration can also help promote sustainable management practices; a U.S. Agency for International Development (U.S. AID) -funded village woodlot project in Thailand shows that planting fuelwood species can be profitable and environmentally protective (U.S. AID, 1987).

More research on managing public lands, pricing public resources, and other policy aspects of tree planting is also needed. For example, government policies in both the developing and industrialized world have been a major source of pressure on tropical forests, but this relationship has not been thoroughly studied. Excessive consumption of forest products has also sometimes been encouraged by underpricing of public resources in some developing countries (see CHAPTER VIII).

Research to Eliminate Emissions of CFCs

Industry is now making substantial efforts to reduce or eliminate emissions of CFCs as discussed earlier (U.S. EPA, 1988; Cogan, 1988). However, existing regulatory incentives may not be adequate to assure that all users of CFCs will make a serious effort to find substitutes. The demand for some uses of CFCs, such as automotive air conditioning, is highly inelastic because the cost is very low relative to the total cost of the product and there are no obvious short-term alternatives (Federal Register, 1988). U.S. EPA is not only considering regulatory changes to address this problem, but also attempting to bolster industry interest in alternatives through a program of cooperative research on promising technologies (U.S. EPA, 1988; Claussen, 1988). Such efforts could be expanded as part of an effort to phase out all CFC emissions as soon as possible and could serve as a model for programs to reduce emissions of other greenhouse gases.

INFORMATION AND TECHNICAL ASSISTANCE PROGRAMS

The government can facilitate the development and adoption of new technologies and strategies through many forms of information and technical assistance programs. These efforts complement research, pricing, and other policies by making consumers more aware of the value of energy conservation and therefore more likely to respond to investment Information programs can opportunities. serve to improve consumer understanding of the significance of energy costs, which are often underestimated because they occur over time. For example, many consumers do not know the relative energy cost of home appliances or that the cost of operating a refrigerator over its lifetime will be greater than the first cost. Information coming from the government is also frequently perceived to be more credible than similar information coming from utility companies or other private firms (Kempton and Neiman, 1987).

Information and technical assistance programs take a variety of forms to serve a range of specialized purposes. Within the U.S. Department of Energy, R&D results are disseminated to potential users through "technology transfer" programs (U.S. DOE, 1987c). One element of this program is the National Awards for Energy Innovation, which annually recognizes outstanding achievements in conserving and producing energy.

U.S. DOE also operates several energy information services for different audiences (U.S. DOE, 1987b). The Conservation and Renewable Energy Inquiry and Referral Service (CAREIRS) serves the general public through a toll-free telephone number and refers technical questions to one of several hundred laboratories and expert agencies. In FY 1987, CAREIRS responded to more than 40,000 inquiries. General information on energy production and consumption is also available through the National Energy Information Center and the Solar Technical Information Program. More specialized assistance is provided by the National Appropriate Technology Assistance Service (NATAS), which helps evaluate new technologies and suggests approaches to commercialization.

The federal government has also provided consumers detailed information on the comparative energy cost of new cars and appliances through mandatory labeling requirements. These programs improve market forces by making it easier for consumers to make decisions about the value of more expensive but more efficient models.

There is no standardized or widely accepted system for communicating energy cost information for homes and buildings, which may be partly responsible for the slow rate of improvement in this sector (Chandler et al., 1988; Hirst et al., 1986). For example, such a system could be used by lenders to evaluate the expected energy cost of a home as a factor in loan amounts, creating an incentive to improve energy efficiency. Such a system is used on a limited basis now by the Federal National Mortgage Association (U.S. DOE, 1987c). Another model is in use by 12 banks in Seattle (Hirst et al., 1986).

Several federal information programs directed to small-scale energy use have been gradually curtailed but still operate in many states. One is the Residential and Commercial Conservation Program, which requires electric and gas utilities to offer home energy audits to their customers for a minimal charge. The program was not promoted effectively in most parts of the country and participation has typically been very low, although a few states achieved notably better success (Hirst et al., 1986). The Energy Extension Service provides a small amount of federal support for state energy information programs and technical assistance programs targeted to individuals and small energy consumers.

Another approach to improving consumer awareness of energy costs is through the introduction of technology that continually reports electricity costs. Advances in microelectronics and communications now make it possible to provide such information for a cost that could be offset by savings achieved through better energy management and shifts in time of use, and at the same time allow closer tracking of marginal costs (Peddie and Bulleit, 1985; Rosenfeld, 1985).

Federally supported programs have also helped support development of computer models and other analytical methods for evaluating the energy use from new residential and commercial buildings. These analytical tools can be used by designers to lower the energy use of buildings and as a basis for calculating energy use for purposes of minimum standards and incentive programs (Vine and Harris, 1988). Computer models of building energy use were a key product of the Building Energy Federal Performance The Standards began as a Standards. mandatory federal regulatory program in 1976, but Congress subsequently amended the law to require only voluntary guidelines. The standards have yet to be released in final form; however, much has been learned in the process, and interim products have been used by industry and government. The federal government could facilitate use of the final rules by providing additional technical assistance such as materials on compliance methods (U.S. DOE, 1987c; Chandler et al., 1988).

The integration of research, technical assistance, and public information has a long and productive tradition in federal agriculture The federal budget for such programs. activities is about \$3 billion annually, and as of 1984 there were over 3,500 specialist extension agents and over 11,000 county agents (OTA, 1986). As discussed in Chapters IV and V, modifications in some farming practices such as selection of crop varieties and fertilizers, water use, and disposal of crop residues may inhibit greenhouse gas emissions, although more research is needed to establish the As our efficacy of such changes.

understanding of agricultural sources of greenhouse gas emissions iniproves, extension activities could be used to teach farmers how to reduce their emissions.

Information and technical assistance is also an important function of bilateral aid, as discussed in U.S. Bilateral Assistance Programs (see CHAPTER VIII).

CONSERVATION EFFORTS BY FEDERAL AGENCIES

The federal government is the single largest consumer of energy in the United States, accounting for 2.5% of total energy consumption (U.S. DOE, 1987a).¹⁰ The annual energy budget for over 500,000 federal buildings and facilities is about \$4 billion, plus another \$2 billion for federally assisted A Federal Energy Management housing. Program was established 12 years ago to provide leadership in reducing these costs and has achieved some success. According to U.S. DOE, cumulative energy savings over the past 12 years are nearly 1.6 Quads, equivalent to about \$6.5 billion in savings (U.S. DOE, 1987a; see Table 7-8). In FY 1985 a ten-vear performance target for improving the energy efficiency of federal buildings ended, having attained a 16.6% reduction in energy per square foot relative to a 20% target.

The government could use its buying power to test and demonstrate energy conservation and alternative energy sources. Government procurement could help demonstrate new products, acting as an incentive for manufacturers worried about the lack of a market and consumers worried about being first-of-a-kind purchasers (Goldemberg et al., 1987). The Department of Energy expressed support for this role in the 1987 Energy Security report to the President: "The federal government should lead by example in testing and adopting cost-effective technologies that use energy more efficiently, especially those that minimize future reliance on insecure supplies of oil" (U.S. DOE, 1987c).

According to the U.S. DOE, a major obstacle to federal conservation efforts was recently addressed through a change in federal law. Conservation investments, although costeffective, may require a substantial initial

Federal	Energy	Expenditures and Cost Avoidance
		FY 1975-FY 1987

	Annual Energy Cost (\$ Million)	Annual Energy Use Reduction Rel. to FY 1975 (BBtu)	Average Annual Energy Cost (S/MBtu)	Annual Energy Cost Avoidance (\$ Million)
Buildin	gs and Facilities			
1975	1,812.453		2.107	
1976	1,888.673	58,080.4	2.355	136.779
1977	2,162.395	51,847.4	2.675	138.692
1978	2,286.054	66,013.3	2.879	190.052
1979	2,636.361	77,885.9	3.370	262.475
1980	3,168.399	97,947.3	4.157	407.167
1981	3,713.200	99,466.9	4.882	485.597
1982	3,804.965	92,207.3	4.955	456.887
1983	3,863.248	98,559.4	5.073	499.992
1984	3,919.356	64,706.3	4.928	318.873
1985	4,054,799	27,131.1	4.868	132.074
1986	3,828.608	50,877.7	4.731	240.702
1987	3,941,605	6.465.6	4.617	29.852
Total	,	,		3,299.142
Genera	1 Operations			
1975	2.697.494		2.578	
1976	2,310.695	129,389.8	2.520	326.062
1977	2,594,787	115.884.7	2.789	323.202
1978	2,710,483	139.408.6	2.989	416.692
1979	3,705.588	112,222.9	3.967	445.188
1980	6,195.928	94,910.6	6.513	618.153
1981	8,289.325	33,191.0	8.182	271.569
1982	9,828.685	6,669.7	9.454	63.055
1983	8,743,907	9,260.1	8.432	78.081
1984	7,728.081	18,506.1	7.258	134.317
1985	6,336,706	49,557.8	6.358	315.088
1986	4.006.669	63,407.1	4.077	258.511
1987	4,348,108	26,606.8	4.264	113.451
Total	, ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	,		3,363.369
ATT	ENERCY TOTAL			6 662 511

Note: This table incorporates revisions to previously published energy consumption and cost data submitted to U.S. DOE by federal agencies. Energy costs for FY 1975-1981 are estimated, based on data provided by the Defense Fuel Supply Center and U.S. DOE's Energy Information Administration (EIA). Energy costs for FY 1982-1987 are based on annual reports submitted to U.S. DOE by federal agencies.

Source: U.S. DOE, 1987a.

investment in order to achieve energy and cost savings over the long term (U.S. DOE, 1987a).

Agencies may now legally "share the savings" from investments in conservation through contracts for up to 23 years with companies that supply the necessary equipment or services in lieu of paying the full capital cost upfront. Several states already have such programs, which can serve as demonstration programs for other levels of government and the private sector and may facilitate future federal efficiency investments. Texas has implemented an energy performance audit program for 18 major universities enforced by a potential 10% withholding of administrative funds. The audit includes a review of the energy management program, including procedures for tracking and monitoring, use of audit activities, capital outlays, and professional training programs. The entire program has been highly cost-effective and, in addition, has served to increase upper management awareness of the energy management opportunities under their control (Verdict, 1988).

STATE AND LOCAL EFFORTS

State and local governments can make an important contribution to the reduction of greenhouse gas emissions (see Box 7-5). Much environmental regulation and energy policy are, to a considerable degree, state and local responsibilities. For example, state public utility commissions oversee decisions about the need for new generating capacity and the choice of fuel, and they can exercise their discretion to promote or discourage particular fuels to promote environmental objectives (ABA, 1980; Randolph, 1988b).¹¹

A growing number of states have adopted programs to reduce costs and growth in electricity demand through comprehensive planning and conservation efforts supported by electric utilities. There is evidence that the potential impact of such programs is very large and could allow substantial displacement of fossil-fuel generating capacity in the future. At least ten states have statutory requirements and policies requiring that utilities examine efficiency investment opportunities as part of

Box 7-5. Recent State Initiatives On Global Warming

During 1989, several states passed legislation or signed executive orders that applied specifically to global warming. The most common approach has been the creation of procedures to study the feasibility of reducing greenhouse gas emissions by a specific amount by some target date. In Oregon, a bill passed in July requires a state strategy to reduce greenhouse emissions 20% from 1988 levels by 2005. In Vermont, an executive order calls for a similar plan to reduce both greenhouse gas emissions and acid rain precursors by 15% below current levels by the year 2000; additional restrictions on CFCs were adopted by the legislature. A New York executive order accompanying release of a state energy plan in September set a goal of reducing CO_2 emissions 20% by 2008. A study of how to achieve that goal will be conducted jointly by the Energy Office, Department of Environmental Conservation, and the Public Service Commission for presentation to the Governor by April 30, 1990. A New Jersey executive order on global warming requires state agencies to purchase the most energy efficient equipment available "where such equipment or techniques will result in lower costs over the lifetime of the equipment." In Missouri, the state legislature created a commission to study the effects of ozone depletion and global warming on the state and to identify means of reducing the state's emissions; findings and recommendations are due in late spring 1990.

a "least-cost" plan (Machado and Piltz, 1988). However, in recent years some utilities have reduced their commitment to conservation and renewed efforts to promote new demand for electricity in order to reduce the costs of excess capacity.

One of the most comprehensive and thoroughly evaluated programs is in the Pacific Northwest. The Northwest Power Planning Council, a regional planning agency created by Congress in 1980, must by law evaluate conservation as а potential resource comparable to generation, and may not support new plants until after first undertaking less expensive demand-side measures. ľn. cooperation with the Bonneville Power Administration and regional utility companies, the region spent over \$1.1 billion on conservation efforts between 1979 and 1989. Funds went for research, marketing, builder training, promoting the implementation of stronger building codes, and pilot projects. The Council concluded that its conservation programs had achieved energy savings at costs ranging between 1.9 and 2.9 cents per kilowatthour, much less than the cost of generation. The Council has undertaken some conservation programs despite a power surplus because of the potential "lost-opportunity" resource if, for example, new buildings are constructed without cost-effective conservation Savings from improving the measures. efficiency of new buildings alone are estimated at \$700 million over 20 years (NPPC, 1988). Using high economic growth assumptions, the Council estimates that it would need almost 13,000 additional megawatts (MW)of electricity but that more than 2,500 MW could be obtained through additional conservation efforts (NPPC, 1989).

A recent Michigan study focused on opportunities to improve efficiency in the residential sector (Krause, 1988). The study, done by the Lawrence Berkeley Laboratory, examined the technical and economic potential for electricity conservation. Some of the key findings were that 3400 GWh/year, or 680 MW of baseload equivalent, can be reliably saved by 2005. This is about 29% of the forecasted demand for this date and is about two-thirds of the technical potential (see Figure 7-8). The result implies a steady decline in overall residential electricity demand of about 1% per year over the next 20 years. Most of the projected savings could be purchased at a cost of less than 3 cents per kWh assuming utilities pay for the full extra first costs of consumer investments; the *average* cost is about 1.1 cent/kWh, in contrast with short-run marginal costs in Michigan of about 3 cents/kWh and much higher costs for new capacity. The greatest savings are from improving the efficiency of lighting, water heating, and refrigerators. The net present value of implementing these savings over 20 years at a 7% discount rate would be \$545 million.

Some states have undertaken impressive programs to develop alternative energy technologies suited to their climate and energy needs. The North Carolina Alternative Energy Corporation (AEC), for example, is funded by voluntary contributions from electric utilities recovered from ratepayers (Harris and Kearney, 1988). The AEC has contributed almost \$6 million to projects that test or demonstrate either conservation, load management, or renewable energy technologies. New York and California are among the other states with substantial energy research programs.

Local governments also undertake many relevant activities. One traditional local government function is to establish building codes and land-use regulations. Some local governments have implemented stringent energy conservation requirements for new housing. For example, Tacoma, Washington, estimates that compliance with its code adds only \$2,000 to the cost of a new home but saves electricity at a cost equivalent to 2 cents/kWh (much less than anv new generation) and offsets the need for 1 MW of generation (Randolph, 1988a). Seattle, Santa Monica, and several other cities have worked out cooperative arrangements with their utilities in which the utility provides audits or other services on a reimbursable basis -sometimes at a profit (Randolph, 1988a). Two California cities, Davis and Berkeley, require compliance with minimum residential energy standards as a condition for the sale of a home (Randolph, 1988a).

The state and local role in limiting greenhouse gas emissions is not limited to energy regulation. Other state and local



authority that could be exercised to lower greenhouse gas emissions includes management of landfills and regulation of existing stationary sources of air pollution. source of large, Another short-term opportunities may be tree-planting programs. As discussed in Chapter V, urban tree planting can reduce local temperatures, thus reducing summer energy needs for air conditioning, while simultaneously storing carbon dioxide for a relatively modest cost (Akbari et al., 1988). Cities have undertaken large-scale tree-planting programs to improve air quality, lower summer temperatures, and beautify neighborhoods. In Los Angeles, a non-profit group called TreePeople organized a successful effort to plant 1 million trees prior to the 1984 Olympic games. A new initiative announced by Mayor Bradley in October 1988 calls for planting 5 million trees and painting surfaces light colors to save 500 MW of peak power, or the equivalent of a large new coal plant (Lipkis, 1988).

Some states have also taken steps to help reduce emissions of CFCs. For example, Massachusetts recently fined a foam manufacturer for failing to recover CFCs and obtained an agreement from the company that it will reduce emissions in the future (*New York Times*, 1988).

PRIVATE SECTOR EFFORTS

Because of the global nature of the greenhouse problem and the lack of direct economic incentive for solutions, much of the impetus for solutions will have to come from governments. Nevertheless, private corporations, non-governmental organizations, and individuals can make important contributions without waiting for government direction. Indeed, there are already several good examples of private initiatives that will contribute to reducing greenhouse gas emissions.

There have also been a number of important actions by private companies to reduce emissions of CFCs in advance of any government mandate. In September 1986 -- a year before the Montreal Protocol -- the DuPont Company announced that they could produce chemical replacements for ozonedepleting CFCs within five years if governments provided proper regulatory incentives to support the new market. The substitutes either do not contain chlorine, one of the chemicals that threatens the ozone layer, or they contain hydrogen, resulting in a much shorter and therefore less dangerous atmospheric lifetime. As evidence of the risk to the ozone layer mounted, other companies also announced support for efforts to reduce CFC emissions. The food packaging industry, for example, voluntarily agreed to substitute food packaging made with HCFC-22 rather than with CFC-12; HCFC-22 has an ozonedepletion potential roughly one-twentieth that of CFC-12 and a greenhouse forcing potential about one-third that of CFC-12.

Since March 1988, when the National Aeronautics and Space Administration (NASA) Ozone Trends Panel announced its conclusion that global ozone depletion has been detected, several major CFC producers and users have stated their support for an orderly phase-out of all production of CFCs by the turn of the century. Some companies have restricted sales to existing markets, stopped development work on new applications for regulated products, and committed neither to increase production capacity nor to sell technology to others.

It is often the private non-governmental organizations that are uniquely capable of promoting grassroots development and alleviating poverty (World Bank, 1987). The World Bank has supported the involvement of private companies in the design and implementation of projects, particularly projects on social forestry, agroforestry, and the environment. U.S. AID and the Peace Corps have given a high priority to involving private voluntary organizations in community forestry projects undertaken through the Food for Peace Program (Joyce and Burwell, 1985). The Tropical Forestry Action Plan also includes strong support for involving private organizations.

Applied Energy Services (AES) of Arlington, Virginia, a private company involved in cogeneration projects, recently hired a non-profit organization, the International Institute for Environment and Development, to assist in identifying potential reforestation projects capable of providing a carbon sink equal to the emissions from a new 180 MW coal-fired plant in Connecticut. This approach reflects the offset concept discussed earlier. One problem in making this exchange on a voluntary basis was that the company had difficulty obtaining financing despite the small cost of the trees relative to the total project.¹²

Many of the strategies necessary to reduce greenhouse gas emissions require changes in technologies or policies that can only be accomplished by large corporations and governments. However, there are some important exceptions, particularly tree planting. Reviving the tradition of Arbor Day could provide a very effective symbol of individual responsibility for greenhouse gas emissions; one hectare of well-managed Douglas fir trees can absorb the average American's lifetime per capita emissions of CO_2 (about 400 tons, or 5 tons carbon per year for 80 years).¹³ The cost of planting that many trees on a large scale is difficult to estimate, but \$1500 is a reasonable approximation -- a large but not impossible lifetime investment.¹⁴

As these examples suggest, the government can help foster private initiatives. In some cases, regulatory obstacles impede voluntary efforts and government can help remove them. In other cases, the government may be able to help bring parties together and provide technical information or assistance. The important point is that government can help promote voluntary efforts to reduce greenhouse gas emissions.

ADDENDUM TO CHAPTER VII: ANALYSIS OF SPECIFIC PROPOSALS FOR REDUCING GREENHOUSE GAS EMISSIONS

POTENTIAL OPTIONS TO REDUCE GREENHOUSE GAS EMISSIONS

Chapter VII provides a general discussion of policy options for responding to global warming. This addendum uses some specific policy proposals that have recently been analyzed to illustrate how such a combination of policy options might contribute to reducing greenhouse gas Since the specific proposals emissions. discussed in this section reduce different types of greenhouse gases, the effectiveness of each proposal for reducing greenhouse gas emissions will be evaluated on a CO₂equivalent basis using the Global Warming Potential (GWP) of individual gases. The GWP, discussed in Chapter II and the Executive Summary, provides a way to express total greenhouse gas emissions in terms of CO_2 equivalence (we convert all CO_2 values from their full molecular weight to a carbononly basis to follow the convention used in the carbon-cycle literature). Specifically, we have used the 100 year GWPs developed by the Intergovernmental Panel on Climate Change (IPCC).

As discussed throughout Chapters VII and VIII, there are a wide range of policies that could reduce greenhouse gas emissions. Those discussed below are just a few of many options currently under discussion, and in some cases they may not represent the most cost-effective options. They are presented here to serve as a simple illustration of possible policy initiatives that may help to reduce greenhouse gas emissions and how the GWP approach may be used to assess the reductions in emissions resulting from alternative policy options. The discussion of these options does not imply endorsement; additional analysis would have to be conducted before any recommendations could be made.

Tree Planting

Reforestation initiatives can increase the uptake of carbon as the trees mature. A recent proposal would sequester approximately 9 million metric tons of carbon (10^6 t C) per year by the year 2000 and about 45 10^6 t C by 2010 (Moulton and Andrasko, 1990). Congress has approved initial appropriation for this reforestation initiative as a part of a larger conservation program in the 1990 Farm Bill that would set a goal of planting one billion trees per year over a ten to twenty year period, as well as improving forest management practices.

U.S. DOE Energy Efficiency Initiatives

Reductions of 25.3 10^6 t C may be achieved through recent U.S. DOE energy efficiency initiatives (Egan, 1990; Williams, 1990).¹⁵ These initiatives are aimed at increasing energy efficiency in order to decrease demand for electricity generated primarily with fossil fuels, which reduces the amount of CO₂ emissions resulting from energy production. Specific initiatives include:

• Increase Lighting Efficiency in Federal Buildings. An annual electricity savings of 0.05 quads, equivalent to a reduction in emissions of $1.2 \ 10^6$ t C by 2000, is expected if Federal agencies fully comply with the relevant Executive Order. This Executive Order establishes energy efficiency targets for building lighting based on state-of-the-art techniques.

• Increase Lighting Efficiency in Commercial Buildings. Emissions reductions of 2.2 10^6 t C are expected by 2000 if 50% of commercial buildings convert to high efficiency lighting. This is equivalent to an average savings of 25% of electrical demand for lighting, or an electricity savings of 0.125 quads.

• Promote State Least-Cost Utility Planning. A reduction in the need for coal and other fossil fuels for electricity generation of 7.5%, equivalent to a savings of 0.48 quads of electricity, or a reduction in emissions of 8.2 10^6 t C by 2000, may be achieved through state efforts to institute integrated, least cost resource planning for electric utilities to achieve greater end use energy efficiency.

• State Adoption of U.S. DOE Interim Building Standards. Emissions reductions of 7.4 10^6 t C, or 0.43 quads of electricity, may be expected by 2000 if states make current voluntary guidelines for buildings mandatory. Federal buildings currently must meet new U.S. DOE interim building standards beginning in 1989. The energy savings estimate assumes a 50% acceptance rate for new non-federal buildings and a 20% reduction in energy demand per building.

• Expand Energy Analysis and Diagnostic Centers to Increase Energy Audits. Emissions reductions of $5.5 \ 10^6$ t C, equivalent to 0.28 quads, including 0.05 quads of electricity, may be expected by 2000 if the energy audit program is expanded. This initiative assumes that the program is expanded to include 40 energy efficiency engineering centers by 2000. These centers are assumed to audit 3% of the eligible industrial facilities by 2000; 60% of the audit recommendations are assumed to be implemented, which results in a 15% improvement in energy efficiency.

Adoption of U.S. DOE Building Standards by U.S. HUD. The U.S. Department of Housing and Urban Development (U.S. HUD) is currently designing a program to adopt U.S. DOE building standards that, if successful, are estimated to achieve annual efficiency gains of 0.05 quads, or a reduction in emissions of $0.7 \ 10^6$ t C by 2000. If implemented by U.S. HUD in public housing assistance programs, it may provide a 25% efficiency increase in buildings that are refurbished, if 1.4 million units in the 7 major public assistance programs are retrofitted by 2000.

U.S. DOE Renewable Energy Initiatives

An additional $3.8 \ 10^6$ t C of emissions may be reduced by 2000 through implementation of renewable energy initiatives that reduce demand for fossil fuel-fired electricity (Egan, 1990; Williams, 1990). Specific initiatives are:

• Expand Hydroelectric Power. Hydroelectric power would be expanded at both existing and new sites by working with permitting/development authorities to streamline the present complex processes for hydropower development. This initiative may increase the current level of 90,000 Mw to a maximum of 110,000 Mw in 2000. If 25% of the increased potential could be realized by 2000, electricity requirements generated with fossil fuels may be reduced by 0.27 quads, which is equivalent to a reduction in emissions of 6.7 10^6 t C by 2000. (For this analysis this estimate was reduced by 50% to 3.3 10^6 t C).

• Transfer Photovoltaic Technology. By increasing the transfer rate of photovoltaic technology to the marketplace, savings of 0.03 quads of fossil fuel electricity, equivalent to emissions reduction of 0.5 10^6 t C, may be achieved by 2000. This would be accomplished by increasing photovoltaic capacity to 675 MW.

U.S. DOE Appliance Standards

Annual electricity savings of 0.15 guads by 2000, equivalent to emissions reduction of 3.7 10° t C, may be achieved through revised U.S. DOE appliance standards (Egan, 1990; Williams, 1990). The standards, applied to 1993 and subsequent model years, would increase the energy efficiency of refrigerators and freezers, washers, dryers, and dishwashers, assuming consumer purchases continue similar to today's buying and replacement patterns. The standards applying to refrigerators and freezers have already become law, while the remaining standards are still being promulgated.

Clean Air Act Provisions

Emissions reductions of 15.6 10^6 t C may be achieved by 2000 through conservation initiatives implemented as part of the Clean Air Act (CAA) Amendments passed by Congress in 1990. The initiatives concern acid rain and transportation fuels and would reduce emissions of CO₂.

• Acid Rain Controls. Emission reductions of 14.9 10^6 t C would be achieved by 2000 assuming reduction of 5% in end-use demand from current coal-fired generation. Acid rain control provisions require SO₂ reductions at current coal facilities but allow the facilities to determine how the reductions will be met. Some reductions are assumed to occur due to reductions in electricity demand that is generated at older, less efficient coal-fired powerplants. New powerplants must obtain offsetting emission allowances. • Biofuels Program. Emissions reductions of 0.2 10^6 t C would be achieved by the year 2000 by increasing the use of biofuels, particularly ethanol. This would be achieved by replacing 13% of gasoline use with a gasoline mixture of 10% ethanol, which would reduce CO₂ emissions assuming that the ethanol is made from a biomass feedstock that is replaced or recycled. This reduction represents 50% of the expected oxygenated fuel required by the Clean Air Act.

• Natural Gas Program. Emissions reductions of $0.5 \ 10^6$ t C would be achieved by the year 2000 by replacing 1% of the gasoline used with compressed natural gas, resulting in a 20% decrease in CO₂ emissions.

Landfill Regulations

Pending regulations under the current Clean Air Act provisions regarding emissions of methane from landfills would reduce emissions by about 9.0 Tg CH₄ (equivalent to 44 10⁶ t C) by 2000 (U.S. EPA, 1990a). Landfill control regulations will require the collection of landfill gases and the combustion or recovery of these gases. These regulations are primarily directed at reducing emissions of VOCs and toxic air pollutants, but will result in reducing CH_4 emissions simultaneously. There are approximately 6,000 active landfills in the U.S. that generate about 15.5 Tg/yr of methane. About 9.0 Tg of CH₄ is estimated to be recovered, reflecting a recovery rate of approximately 60%. Assuming a GWP of 18, emissions reduction of about 160 10^6 t CO₂ $(44 \ 10^{6} \text{ t C})$ may be achieved by 2000.¹⁶

Montreal Protocol and CFC Phaseout

The Montreal Protocol is assumed to be strengthened by adoption of a total CFC phaseout, which reduces emissions approximately 119 10^6 t C (i.e., on a CO₂equivalent basis) by 2000 (U.S. EPA, 1990b). The Montreal Protocol currently calls for a 50% reduction from 1986 levels in the production of CFC-11, -12, -113, -114, and -115 by 1998, and a freeze on the production of halon 1211, 1301, and 2402 at 1986 levels starting in approximately 1992. A phaseout of controlled CFCs and halons by 2000 was agreed to in principle by the U.S and several other countries in the London Amendments to the Montreal Protocol in June 1990. This would eliminate 95% of the radiative forcing due to CFC emissions in 2000. Included in the phaseout are CFC-11, -12, -113, -114, HCFC-22, CCl₄, HCFC-134, HCFC-141b, and HCFC-124.

How These Options May Reduce Emissions to Current Levels

Table 7-9 shows the emissions reductions in CO_2 and carbon equivalents of the policy options discussed above. If all of these initiatives were implemented, the options have the potential to reduce emissions by approximately 290 10^6 t C by the year 2000. However, these initiatives do not represent a recommended or preferred set of options, but rather are readily-available examples of options to illustrate the potential for reducing carbon emissions.

Table 7-10 provides estimates of greenhouse gas emissions for 1987 as well as projected baseline emissions in 2000 that assume no policy actions (as described above) are taken. These baseline CO₂-equivalent emissions were developed by U.S. EPA and U.S. DOE based on best-available estimates. To demonstrate one possible method for reducing emissions close to current levels, we have also included the potential reductions from the policy options package described above. If the 290 10° t C reduction is achieved successfully by implementing all of these options, greenhouse gas emissions could be reduced to less than 1987 levels by the year 2000, from 2587 10^6 t C to 2250 10^6 t C.

ADDITIONAL POLICY OPTIONS

U.S. EPA has begun investigating a range of additional policy options that would provide additional reductions in greenhouse gas emissions in the future. These options include tax and non-tax initiatives. It should be noted that these additional policy options represent ongoing work at U.S. EPA and therefore the results are considered preliminary. The full economic and environmental impacts of these initiatives have not been fully evaluated.

Emissions Reductions from Current Policy Initiatives by 2000 (in 10^6 metric tons on a CO_2 -Equivalent Basis)^a

		CO_2 as
POLICY OPTION	<u>CO</u> ₂	<u>CARBON</u>
Tree Planting	30.0	9.0
U.S. DOE Efficiency Initiatives	92.7	25.3
Federal Buildings Lighting	4.5	1.2
Commercial Buildings Lighting	8.2	2.2
Promote State Least Cost Utility Planning	30.0	8.2
Interim Building Standards	27.3	7.4
Expand Energy Analysis	20.0	5,5
HUD Adoption of Standards	2.7	0.7
U.S. DOE Renewable Initiatives	14.0	3.8
Expand Hydropower	12.2	3.3
Transfer of Photovoltaic	1.8	0.5
U.S. DOE Appliance Standards	13.6	3.7
Clean Air Act Provisions	57.3	15.6
Acid Rain	54.5	14.9
Biofuels	0.9	0.2
Natural Gas	1.8	0.5
Landfill Regulations	160.0	44.0
CFC Phaseout	<u>693.0</u>	<u>189.0</u>
TOTAL	1060.6	290.0

^a Based on conversion to a CO_2 -equivalent basis using 100-year GWPs.

Emission Estimates for 1987 and 2000 $(10^6 \text{ metric tons carbon})^a$

GAS	<u>1987</u>		<u>2000</u>
		Baseline	Policy ^b
CO ₂	1319	1565	1508
CH ₄	235	252	208
VOCs	71	72	49
NO _x	210	210	193
со	52	52	45
N ₂ O	74	74	74
CFC	<u>463</u>	<u>362</u>	<u>173</u>
Total	2424	2587	2250 [°]

^a Based on conversion to a CO₂-equivalent basis using 100-year GWPs.

^b Includes policies currently under discussion that would achieve about 290 10^6 t C in emission reductions.

^c The difference in 2000 between the Baseline and Current Policy cases is about 337 10^6 t C. This is greater than the total shown in Table 7-9 because the emission reductions attributable to changes in VOCs, NO_x, and CO are not included in Table 7-9.

Sources: Egan, 1990; IPCC, 1990d; Moulton and Andrasko, 1990; Pechan, 1990; U.S. EPA, 1989, 1990a, 1990b, 1990c; and Williams, 1990.

Tax Initiatives

Two sets of tax-based policy options are being evaluated that may reduce CO₂ emissions. The first set of options examines transportation taxes, including a federal gasoline tax and an oil import fee. The second set of options evaluates a general carbon tax on fossil fuels. These options are briefly discussed below.

Transportation Taxes

The effects of a federal gasoline tax and an oil import fee were estimated using the Data Resources Incorporated (DRI) Transportation model (DRI, 1990). These are preliminary DRI model estimates. Results for the transportation taxes are presented in Table 7-11. It was assumed that the taxes were phased in over time. A 0.33/gallon tax is estimated to reduce emissions by 16 10⁶ t C by the year 2000, while a 1.24/gallon tax yields an emissions reduction of 78 10⁶ t C by the year 2000. An oil import fee of 0.00/barrel results in emissions reduction of 30 10⁶ t C by the year 2000.

Carbon Taxes

Three models were used to estimate the effects of carbon taxes by the year 2000: the Manne-Richels *Global 2100* model (Manne and Richels, 1990a, 1990b, 1990c), the DRI national energy model, and the Dynamic General Equilibrium Model (DGEM).¹⁷ A range of taxes was examined: from \$5.00/ton carbon to \$25.00/ton carbon. The results for each model are presented in Table 7-11. For the lowest tax evaluated, i.e., a \$5/ton carbon tax, estimates on the amount of emission reductions are: 9 10^6 t C for the Manne-Richels model; 24 10^6 t C for the DRI model; and 62 10^6 t C for the DGEM model.

Non-Tax Initiatives

Two potential non-tax initiatives, tighter landfill regulations and an increased tree planting initiative, have been evaluated that could provide additional reductions in greenhouse gas emissions. These initiatives are briefly described below.

Tighter Landfill Regulations

As discussed earlier, landfill regulations currently under discussion as part of the Clean Air Act regulations would limit methane emissions from decomposition of organic wastes. If such regulations were tightened beyond these pending U.S. EPA regulations, methane emissions could be reduced by an additional 7.9 Tg, resulting in a 39 10^6 t C reduction on a carbon equivalent basis (U.S. EPA, 1990a).

Increase in Tree Planting

The tree planting initiative discussed earlier is designed to plant one billion trees annually for a ten to 20 year period. If the size of this program were doubled so that an additional one billion trees were planted per year, an additional reduction of 9 10^6 t C may be attained (Moulton and Andrasko, 1990).

Implications of Additional Policy Initiatives

A comparison of the effects of transportation and carbon taxes, as forecast by the DRI model, suggests that a carbon tax is a preferable policy option from the standpoint of achieving CO₂ emissions reductions. A \$5.00/ton carbon tax is equivalent to a \$0.01/gallon gasoline tax, yet the carbon tax vields $25 \ 10^6$ t C of carbon emission reductions, whereas a \$0.33/gallon gas tax yields only a 16 10^6 t C emissions reduction. However, no distributional or equity issues associated with these tax initiatives have been examined. Also, given the range of uncertainty in the estimated effects of tax options, any conclusions based on these initiatives as here should be discussed considered preliminary.

Although these are preliminary results, it is informative to note the effect of these additional options when combined with the policy options discussed earlier. The first set of policy options reduced emissions by 290 10^6 t C, reducing greenhouse gas emissions to about 93% of the 1987 emissions level by the year 2000. As one example of additional options, if we assume a combination of a carbon tax of \$5.00/ton (based on the DRI

Emission Reductions from Potential Tax Initiatives for the Year 2000 (10⁶ metric tons of carbon)

	Carbon Reductions (million tons)
Transportation Taxes	
Gasoline Tax	
\$0.33/gallon	16
\$1.24/gallon	78
Oil Import Fee	
\$6.00/barrel	30
Carbon Taxes (\$/ton)	
Manne-Richels	
\$5.00 \$10.00 \$15.00	9 18 27
DRI	
\$5.00 \$10.00 \$15.00 \$25.00	25 49 74 124
DGEM	
\$5.00 \$10.00 \$15.00 \$25.00	62 124 182 247

Sources: DRI, 1990; Manne and Richels, 1990a, 1990b, 1990c; and Montgomery, 1990.

Model), the tighter landfill regulations, and an increase in tree planting, additional emissions reduction of 73 10^6 t C may be possible. When added to the first combination of options, these additional options would reduce estimated emissions in the year 2000 to 2177 10^6 t C, or about 10% less than 1987 emissions.

IMPLICATIONS IF ONLY CO₂ IS CONSIDERED

The preceding analysis compares emission reductions on a CO_2 -equivalent basis for all of the greenhouse gases. Because all of these gases contribute to the global warming problem, this approach is valuable as one means for comparing the relative contributions of each gas to the problem. However, because CO_2 is the major greenhouse gas and CFCs will be reduced due to the Montreal Protocol and the recently revised London Agreement, much of the national and international debate has focused on the role of CO_2 and policy actions that could be taken to reduce emissions of this gas only.

If only CO_2 emissions are considered for achieving specific targets such as stabilization at current levels, not all of the policies discussed in the previous section would contribute to the attainment of the target. For example, landfill regulations primarily control CH_4 emissions, while the CFC phaseout

focuses on reducing the use of CFCs and related chemicals. Several of the policies would contribute to reducing CO_2 emissions directly, specifically programs that affect energy use or forestry practices, such as the U.S. DOE appliance standards, the U.S. DOE energy efficiency programs, the Clean Air Act proposals, and the tree-planting initiative. If only direct CO_2 emission reductions are considered, reductions estimated for current policy commitments in the year 2000 total about 57 million tons of carbon, which is a reduction of about 4% from estimated CO₂ emissions for 2000; CO_2 emissions for 2000 would still be about 14% higher than 1987 The additional policies discussed levels. above, such as a carbon tax and an increase in a tree planting program, could reduce total CO_2 emissions further. These additional initiatives, however, would not be sufficient to reduce CO₂ emissions to 1987 levels unless reductions of about 190 10⁶ t C could be obtained. This level of reductions is only achievable with a carbon tax of about \$15/t C based on the DGEM analysis. (For further discussion, also see Box 7-6, which discusses the preliminary results of an analysis that evaluates the technology costs for reducing CO_2 emissions from the U.S. energy sector; this analysis evaluates only the technical potential for reducing CO_2 emissions, not the full economic costs that would be incurred to actually achieve the reductions.)

Box 7-6. A Technology Cost Analysis of U.S. Energy Options for Reducing CO₂

As part of its ongoing analyses on greenhouse gas emission reduction options, U.S. EPA has been examining a variety of options for reducing CO_2 emissions from the consumption and production of energy. To assist in this effort, the MARKAL (Market Allocation) model has been employed to analyze least cost options for reducing CO_2 emissions from the energy sector. MARKAL is a dynamic linear programming model of U.S. energy supply and demand by sector developed in the late 1970s at Brookhaven National Laboratory and Kernforschungsanlage Julich in West Germany and recently updated for U.S. EPA. Current research with MARKAL is attempting to identify least-cost strategies for reducing CO2 emissions. MARKAL focuses on technological options for reducing emissions and considers the engineering costs of these options; it does not, however, address the specific policy actions that would have to be implemented to achieve the technological reductions. For example, MARKAL may identify that gasoline use in the transportation sector can be reduced for a certain cost by building more energy-efficient vehicles; it does not evaluate how successfully different policies, such as a gasoline tax or higher CAFE (Corporate Average Fuel Economy) standard, may be at achieving the energy efficiency improvements. In this example costs of achieving specific CO2 reductions will vary depending on the cost of different technologies and future fuel prices. This approach serves as a scoping analysis to identify those areas where emission reductions may be achieved at least cost, although identification of all costs would require further analysis.

Preliminary results using MARKAL have been estimated for three emission reduction targets: 1) stabilization of CO₂ emissions by 2010; 2) 10% reduction in CO₂ emissions by 2010; and 3) 20% reduction in CO₂ emissions by 2010. The table below summarizes the results for these cases.

Estimated Costs to Achieve CO₂ Reductions in 2010

Case	Fotal Reductions (10 ⁶ tons)	Total Costs (10 ⁹ S)	Cost/ton (\$/ton)
Stabilization	56	0.22	3.95
10% Reduction	126	1.22	9.70
20% Reduction	<u>197</u>	<u>3.22</u>	<u>16.35</u> ª
TOTAL	197	3.22	16.35

^a Estimated marginal cost of emission reductions is \$39/ton.

The results presented in the table above are preliminary and do not reflect the total costs of achieving the indicated reductions since only technology costs and energy costs are included in the estimates; they do reflect the estimated costs that consumers would incur once the decision has been made to purchase the more energy-efficient technologies.

Source: Morris et al., 1990.

NOTES

1. U.S. DOE publishes Gas Mileage Guides, which list the fuel economy of all new car models; however, the number of guides distributed has been reduced from 10 million to 3 million annually.

2. The 5160 billion figure is derived by first calculating what total expenditures on energy in 1985 would have been had energy intensities remained constant at 1973 levels and 1985 price levels prevailed, and then subtracting actual expenditures on energy in 1985. For further discussion, see Chandler et al. (1988) and U.S. DOE (1987c).

3. First-cost sensitivity refers to the tendency, common to many consumers, to prefer a product that has a low initial cost to a higherpriced alternative, which might be much more cost-efficient over the long term. In other words, the upfront costs to consumers tend to dominate the purchase decision more than a conventional economic analysis would predict. The use of a hefty excise tax may affect consumer decisions more acutely than would the gasoline expenses for operation of an inefficient vehicle, which occur in smaller amounts and at intervals rather than all at once.

4. The results of these programs have been periodically reported and evaluated by the Electric Power Research Institute, the American Council for an Energy Efficient Economy, and others. See, for example, Berman et al. (1987) and ACEEE (1988).

5. One domestic automotive company reportedly estimates that consumers will seek a 1 mpg improvement in fuel efficiency for every 20 cent increase in gasoline prices (Bleviss, 1988).

6. One expert has noted that "No aspect of America's energy price system is more peculiar, in comparison with other industrial countries, than the absence of a substantial national sales tax on gasoline" (Nivola, 1986).

7. FERC publishes periodic compilations of "qualifying facilities," projects that have formally requested status as entitled to the benefits of PURPA. However, the list is only an approximation of actual activity, since not all projects file such applications; some file after they have already begun operation, and some applications are made for projects that are never completed.

8. Joint Memorandum of the Soil Conservation Service, U.S. EPA, Fish and Wildlife Service, and U.S. Forest Service on the Conservation Reserve Program Filter Strip Initiatives, April 29, 1988.

9. One excellent source of information on technologies, programs, and policies on energy efficiency in buildings is the biennial proceedings of the summer study program organized by the American Council for an Energy Efficient Economy (ACEEE, 1988).

10. Expenditures on energy in FY 1987 were over \$8 billion, or 0.8% of the federal budget.

11. For example, Washington offers utilities a higher rate of return on investments in renewable energy systems, while Texas requires that utilities first consider using renewable energy for new capacity additions and that owners of renewable energy generators under 10 MW who wish to sell power to non-utilities employ retail wheeling (use of transmission lines).

12. The program will cost the company \$2 million for an endowment to finance a 10-year tree planting program by CARE, the Guatemalan forest service, and the Peace Corps to support 40,000 small farmers in planting 52 million trees in plantations and agroforestry systems. Over the 40-year life of the plant, 15 million tons of carbon will be fixed at a total cost of \$14 million cash and contributed labor. AES is considering providing similar offsetting forestry projects for nine other plants. The costs are expected to be only about 0.1 cents per kWh because the projects will take place in developing countries and some labor will be contributed. CARE officials informally estimate that the project could be replicated perhaps 100 times given current institutional capability and land availability (WRI and IIED, 1988).

13. Other species would require more land, but with research it may be possible to do substantially better. 14. A more detailed discussion of the feasibility of large-scale tree planting is provided in Chapter V.

15. Estimates of the amount of energy saved and CO_2 emissions reduced as a result of specific energy efficiency initiatives are sensitive to many assumptions incorporated into the U.S. DOE analysis. The U.S. DOE estimates have been used without extensive review for this illustrative discussion.

16. IPCC (1990a) estimates that CH_4 has a 100-year GWP of 21. In its analysis, U.S. EPA assumed that all CH_4 recovered from landfills would be flared immediately, thereby converting CH_4 to CO_2 in the process. The IPCC indicates that the GWP for CH_4 after it becomes CO_2 in the atmosphere is 3. Therefore, the avoided impact due to recovering CH_4 and flaring it is represented by using a GWP of 18.

17. A thorough description and comparison of these models is contained in Montgomery, D., Effects on Energy Markets and the U.S. Economy of Measures to Reduce CO_2 Emissions from Fossil Fuels, draft report presented at the MIT Conference on Energy and the Environment in the 21st Century, March 1990.

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CHAPTER VIII

INTERNATIONAL COOPERATION TO REDUCE GREENHOUSE GAS EMISSIONS

FINDINGS

• Most of the expected growth in greenhouse gas emissions is from other countries, particularly developing countries, the USSR, and Eastern Europe. Efforts to promote international solutions are therefore essential to achieve global reductions in greenhouse gas emissions.

• Technological solutions and policy strategies for the U.S. and other western industrialized nations may not be equally applicable in other parts of the world. Differences in economic development, energy resources, and economic systems must be addressed when devising international strategies to reduce greenhouse gas emissions.

U.S. leadership has historically made important contributions to other important international environmental agreements, such as the Montreal Protocol on Substances that Deplete the Ozone Layer, the London Amendments to the Protocol, and the Tropical Forestry Action Plan. In the future, U.S. could promote international leadership cooperation to reduce greenhouse gas emissions worldwide. Successful U.S. efforts to reduce national emissions may encourage similar actions by other nations and could serve as a valuable demonstration that reductions are feasible.

• Developing countries could reduce the expected increase in greenhouse gas emissions consistent with economic development and other environmental and social goals. Energy efficiency improvements are already essential to reduce capital requirements for the power

sector, and efforts to halt tropical deforestation will provide many long-run economic and environmental benefits. The U.S. can promote desirable changes in energy and environmental policy in developing countries through judicious use of its bilateral aid programs and its influence on loans extended by multilateral development banks.

• The Soviet Union and Eastern European nations are and will continue to be important contributors to greenhouse gas emissions. The absence of market pricing has hindered efforts to reduce the energy intensity of these economies, but their governments have shown increasing interest in curbing energy use.

There have already been some important first steps toward building a framework for international cooperation to reduce the risks of climate change. In November 1988, an Intergovernmental Panel on Climate Change (IPCC) was initiated under the auspices of two United Nations (U.N.) agencies, the United Nations Environment Programme and the World Meteorological Organization, to assess the science, impacts, and policy responses to global warming and to submit a report by August 1990, prior to the Second World Climate Congress, which was held in November 1990. The United States chairs the Response Strategies Working Group. The IPCC submitted its report in the Fall of 1990. Also, in February 1991 the first meeting of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change, convened by the U.N. General Assembly, was held in Chantilly, Virginia.

INTRODUCTION

The greenhouse problem requires international strategies to promote global cooperation. An important first step has been taken in this direction under the auspices of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). In 1988 these organizations helped organize an Intergovernmental Panel on Climate Change (IPCC) to review the science, impacts, and response strategies associated with climate change. The U.S., Soviet Union, China, Japan, and many other leading nations agreed to participate. Three panels were organized to consider scientific issues (chaired by the United Kingdom), effects of climate change (chaired by the Soviet Union), and policy responses (chaired by the U.S.). The first meetings occurred in early 1989, and the final report was submitted in time for the Second World Climate Congress, held in November 1990.

There is an important relationship between the domestic policies discussed in Chapter VII and the evolution of international cooperation that is the focus of this chapter. U.S. actions can promote further international cooperation and complementary strategies by other countries. Consideration of the domestic policies reviewed in this report demonstrates that the U.S. no longer views the problem as only a scientific concern. Further analysis and consideration of such policies may also convince other nations of the seriousness of the risks and the need for action. U.S. leadership in the United Nations (U.N.) and other international forums can have a major impact on the evolution of international understanding and ultimately agreements, as illustrated by the Montreal Protocol on Substances that Deplete the Ozone Layer.

Special efforts will be necessary to limit the growth in greenhouse gas emissions from developing countries while addressing their need for energy and economic growth. Solutions to the problems of climate change may be linked to other development needs, such as capital shortages and increased recognition of local environmental problems. U.S. bilateral assistance programs and participation in multilateral development banks (MDBs) provide an opportunity to promote policies that reduce greenhouse gas emissions in developing countries consistent with their development needs. Programs should be designed to increase developing countries' stakes in contributing to this global effort, for example, through debt swaps, afforestation programs, and technology transfer agreements that are linked to reductions in greenhouse gas emissions.

The need for international cooperation has already been recognized, and some important first steps have been taken to establish a framework for international cooperation on the scientific aspects of global warming and to discuss policy responses.

THE CONTEXT FOR POLICIES INFLUENCING GREENHOUSE GAS EMISSIONS IN DEVELOPING COUNTRIES

Because of faster growth rates and greater needs for basic materials, the developing countries will contribute an increasing share of greenhouse gas emissions (see Figure 8-1). Any global effort to reduce emissions will therefore have to take into account the very different needs, resources, and other constraints in the developing countries, particularly their need to grow economically so that they can meet basic human needs despite their limited capital resources for meeting development objectives. These issues will have to be addressed in the international forums that are being created specifically to deal with the greenhouse problem. However, the U.S. can also address these concerns in the short term by recognizing the link between emissions of greenhouse gases and the investment choices encouraged by bilateral aid and lending by multilateral development banks. Before we discuss these options, however, it is useful to examine the different context within which developing countries operate to get an idea of the energy and environmental issues they face and the priority of their concerns.

The context for policy formation in developing countries often differs substantially from that in the industrialized countries, reflecting differences in political and economic systems, resources, and societal needs. Some



FIGURE 8-1 Greenhouse Gas Emissions by Region

* RCW = Rapidly Changing World. See Chapter VI for a description of this and other scenarios used to make projections about future levels of greenhouse gas emissions.

Note: These graphs do not include natural emissions.

of the major issues associated with the formulation and implementation of energy and related environmental policies in developing countries include socioeconomic equity, financial viability, institutional structure and management of enterprises, and the burgeoning awareness of environmental concerns. Our understanding of these issues is essential to developing emissions reduction policies that are relevant to developing countries and that take into account the conditions existing in these countries and the issues that are of most concern to them.

Economic Development and Energy Use

Developing countries are a much more diverse group than the member countries of the Organization for Economic Cooperation and Development (OECD). They range from some of the poorest nations, such as Bangladesh and Ethiopia, to some of the richest ones, such as Saudi Arabia and Singapore. Their annual income per capita varies from \$150 to \$7000 (World Bank, 1987). The group includes oil and natural gas exporters and importers at different levels of per capita income. Their economies vary from a centrally-planned one like China to more market-oriented ones like Brazil and South Korea. Each country has a different mix of institutions engaged in the supply of energy, reflecting different degrees of governmental control and foreign involvement. Table 8-1 shows energy use data from selected countries.

Equity concerns play a strong role in the pricing of fuels. Preferential electricity tariffs residential for customers are often accompanied by even lower tariffs for agricultural ones. (This is not unlike the situation in some developed countries where low "lifeline rates" are charged for small amounts of electricity consumption.) On the other hand, gasoline prices in developing countries are typically set high relative to world market prices, since gasoline is used in cars that are primarily owned by the rich. Petroleum taxes represent an important instrument of social policy; they can be adjusted to cushion the impact of energy price increases or to maintain higher prices when international prices decline.

The price of coal in India and China, the two major developing countries that rely heavily on coal, is subsidized, and the amount of the subsidies varies by sector. In China, since the coal price is too low, the government provides subsidies, in amounts from 10 to 27 yuan/ton (or \$2.70 to \$7.20/ton), to coal producers in order to encourage them to produce more coal (Dadi, 1988). Similarly, despite continual increases in the price of coal in India, Coal India Limited (CIL), an Indian government enterprise that produces over 90% of the country's coal, incurred losses equivalent to more than \$8/ton (Hindu Survey, 1988).

Industrial energy use forms a major segment of overall energy use in the developing countries. Because the industries are generally less modern than their counterparts in the developed countries, they tend to be less energy-efficient as well (see Table 8-2). According to the U.S. Agency for International Development (U.S. AID), developing countries can typically save 5-15% of commercial fuel through low-cost measures and up to 25% through cost-effective retrofits (U.S. AID, 1988a). A recent detailed study of the potential for cost-effective electricity conservation in Brazil documented potential savings equal to more than a fourth of currently forecasted needs (Geller et al., 1988; The management of see Table 8-3). government-controlled industries is often inefficient, as a comparison of similar products produced by government-controlled and private-sector industries, even in the same country, will show.

Given adequate capital and technical knowledge, industries in a developing country can operate just as efficiently as comparable ones in a developed country (Schipper, 1981). For example, multinational companies operating in developing countries often use about the same amount of energy per unit of output as the company's comparable plants in the developed countries.

The energy sector is typically owned and operated by government-controlled corporations in the poorer developing countries. These corporations often have little

1985 Population and Energy Use Data from Selected Countries

		CDP	CDP	ELECI	<u> IRICITY</u>	<u>MODERN F</u> h Per Gro Capita R (GJ) (197 (⁴) 7 21.25 2 7.91 2 35.13 3 8.57 4 57.03 7 7.13 9 62.72 9 23.68	ERN FUELS ^b	Diamace	DOMINAN	ANT FUEL	
Country	Population ^a (Millions)	(1985 U.S.\$ Billions)	Capita (1985 U.S.\$)	Per Capita (kWh)	Growth Rate (1970-85) (%)	Per Capita (GJ)	Growth Rate (1970-85) (%)	Use Per Capita (GJ)	Total	% ^c	
China	1,045.3	265.53	254	365	6.7	21.25	5.2	8.83	Coal	79	
India	750.9	177.10	236	166	7.2	7.91	5.5	5.7 9	Coal	56	
Brazil	134.6	155.45	1,155	1,283	10.2	35.13	7.3	16.16	Hydro	46	
Indonesia	165.2	86.20	52 2	74	14.3	8.57	11.2	9.28	Oil	71	
Korea	41.1	86.80	2,112	1,234	13.4	57.03	8.9	2.07	Oil	49	
Nigeria	92.0	48.70	529	68	10.7	7.13	16.4	10.92	Oil	80	
Mexico	75.6	146.87	1,943	929	7.9	62.72	7.2	5.28	Oil	58	
Egypt	47.2	30.06	637	471	9.9	23.68	8.7	NA	Oil	72	
Kenya	20.4	5.02	246	107	10. 9	2.31	-3.3	NA	Oil	93	
U.S.	239.3	3,946.60	16,492	9,719	3.5	325.76	0.7	11.46	Oil	42	

^a Based on several sources.

^b Modern fuels expressed as fossil-fuel equivalent assuming conversion efficiency of 10,000 Btu/kWh.

^c Dominant fuel as a percentage of modern fuels (excluding most biomass).

Source: LBL, 1988.

Efficiency of Energy Use in Developing Countries: 1984-85

Country/Region	Energy Use/ Unit of GDP ²	Average Annual Growth Rate (%)		
North America ^b				
Canada	0.80	-0.5		
United States	0.61	-2.2		
Average	0.62	-2.1		
Oceania ^b				
New Zealand	0.50	+1.8		
Australia	0.45	-0.5		
Japan	0.29	-3.1		
Average	0.32	-2.5		
Furone ^b		41		
Luxembourg	0.65	-4.9		
Turkey	0.56	-1.0		
Portugal	0.49	+1.5		
Greece	0.44	+1.2		
Ireland	0.44	-1.4		
Norway	0.40	-1.4		
Sweden	0.40	-0.6		
Belgium	0.36	-2.2		
Netherlands	0.36	-1.7		
United Kingdom	0.35	-2.0		
Austria	0.33	-1.2		
Italy	0.33	-1.8		
Spain	0.32	+0.3		
Germany	0.31	-1.7		
Denmark	0.27	-1.7		
Switzerland	0.25	+0.3		
Average	0.34	-1.4		

TABLE 8-2 (continued)

Country/Region	Energy Use/ Unit of GDP ^a	Average Annual Growth Rate (%		
Asia ^c				
People's Republic of China	1.40	-1.3		
India	0.79	+1.4		
Pakistan	0.64	+4.2		
Taiwan	0.62	+0.2		
Thailand	0.38	-0.8		
Malaysia	0.36	+0.3		
Indonesia	0.35	+3.3		
Philippines	0.35	-2.7		
Bangladesh	0.27	NA		
Average	0.97	+0.5		
atin America ^c				
Venezuela	1.40	+4.6		
Brazil	0.68	+2.1		
Mexico	0.56	+2.2		
Argentina	0.29	+1.8		
Average	0.57	+2.7		
West Africa ^d				
Senegal	0.49	+3.6		
Morocco	0.27	0.0		
Nigeria	0.18	+9.4		
Cote d'Ivoire	0.13	+2.8		
Average	0.20	+6.5		

Efficiency of Energy Use in Developing Countries: 1984-85

^a Gross domestic product metric tons of oil equivalent per \$1,000 U.S. (constant 1980 dollars).

^b Average annual growth rate for 1973-85; 1985 data.

^c Average annual growth rate for 1973-84; 1984 data.

^d Average annual growth rate for 1977-84; 1984 data.

NA = Not available.

Sources: Sathaye et al., 1987; OECD/IEA, 1987.

End-Use Application	Current forecast (twh)	Savings potential (%)	Savings potential (twh)
Industrial motors	164.8	20	33.0
Domestic refrigerators	24.7	60	14.8
Domestic lighting	16.5	50	8.2
Commercial motors	28.0	20	5.6
Commercial lighting	25.0	60	15.0
Street lighting	16.8	40	6.7
Total	275.8		83.3

Potential for Electricity Conservation in Brazil

Source: Geller et al., 1988.

incentive to invest in reducing their energy costs because they are protected from competition and rewarded more by measures of production than efficiency of service. This problem is compounded by regulated prices that are often not high enough to pay for the companies' expenses and non-payment or delayed payment for fuels purchased from other government companies.

Oil Imports, Capital Shortages, and Energy Efficiency

Most developing countries are largely dependent on imports for commercial fuels. During periods of high oil prices, import costs have resulted in serious hardship in these countries. In some countries oil import costs exceeded 25% of export earnings in 1984 and much more than that in earlier years (see Table 8-4). Future increases in world oil prices may have an even more adverse impact because of the rapid growth in the transportation sector in some countries.

A shortage of capital for large development projects is pervasive in developing country economies and increasingly a constraint on the energy sector. Energy investments in developing countries require a high percentage of available capital (see Table 8-5). The World Bank and, more recently, U.S. AID have reviewed the magnitude of energy shortfalls in developing countries and its implications for economic development (World Bank, 1983; U.S. AID, 1988b; see Table 8-6). U.S. AID estimates that in a current-trends scenario, U.S. AID-assisted countries would need to spend over \$2.6 trillion for the power sector by the year 2008 to meet projected needs. This is an average of over \$125 billion per year, compared with the estimated \$50 to \$60 billion currently being spent annually. Since current expenditures already consume one-fourth or more of development budgets, this is potentially a serious constraint on economic development. Aggressive conservation efforts, however, could reduce capital needs by 40-60% (Williams, 1988; World Bank, 1983).

The added cost of more efficient products is often cited as an obstacle to efforts to improve efficiency in capital-short developing countries. However, the high cost of capital may favor investments in efficiency relative to investments in long lead-time supply projects, such as construction of new powerplants. Because efficiency investments pay off much more quickly, their economic

		(m illio	Net Oil In on U.S. dollar	mports s, current prio	ces)		
	1973	1974	1977	1979	1981	1983	1984
Kenya	1	27	57	113	316	208	219
Zambia	11	30	53	72	63	274	454
Thailand	173	510	806	1,150	2,170	1,740	1,480
Korea	276	967	1,930	3,100	6,380	5,580	5,770
Philippines	166	570	859	1,120	2,080	1,740	1,470
Brazil	986	3,230	4,200	6,920	11,720	8,890	7,470
Argentina	83	328	338	351	302	-	-
Jamaica	71	193	242	309	490	-	-
India	308	1,170	1,750	3,067	-	-	-
Bangladesh	-	92	172	247	509	286	314
Tanzania	47	153	102	174	306	175	156
		Imports as	Percentage o	f Export Ear	nings		
Kenya	0.1	4.1	4.8	10.2	26.9	21.2	20.3
Zambia	2.2	5.1	9.5	8.2	7.8	20.8	21.4
Thailand	11.1	20.9	23.1	21.6	30.9	27.3	20.0
Korea	8.6	21.7	19.2	20.6	30.0	22.8	19.7
Philippines	8.8	20.9	27.5	24.4	36.8	35.4	27.8
Brazil	15.9	40.7	34.7	45.4	50.4	40.6	27.7
Argentina	2.5	8.3	6.0	4.5	3.3	-	-
Jamaica	18.1	27.3	32.4	37.7	50.3	-	
India	10.6	29.7	27.5	39.3	-	-	-
Bangladesh	-	26.5	36.1	37.4	64.6	39.4	33.6
Tanzania	12.8	38.0	20.2	34.8	52.7	47.0	42.3

Net Oil Imports and Their Relation to Export Earnings for Selected Developing Countries, 1973-1984

Source: IMF, 1985, in Goldemberg et al., 1987.

Annual Investment in Energy Supply As a Percent of Annual Total Public Investment (Early 1980s)

Under 20%	20-30%	30-40%	Over 40%
Egypt	Botswana	Ecuador	Argentina
Ethiopia	China	India	Brazil
Ghana	Costa Rica	Pakistan	Colombia
Nigeria	Liberia	Philippines	Korea
Sudan	Nepal	Turkey	Mexico

Source: Munasinghe and Saunders, 1986.

TABLE 8-6

World Bank Estimate of Capital Requirements for Commercial Energy In Developing Countries, 1982-1992

(billions of dollars)

	Middle Income									
	Low Income	Oil Importers	Oil Exporters	All Countries						
Total Required Capital										
Electricity	17.6	35.9	13.1	66.6						
Oil and Gas	12.1	16.7	40.0	68.8						
Coal	5.6	2.8	0.6	9.0						
Total	35.3	55.4	53.7	144.4						
Foreign Exchange Requirements										
Electricity	3.6	11.4	7.2	22.2						
Oil and Gas	4.9	5.9	25.4	36.2						
Coal	1.1	1.0	0.3	2.4						
Total	9.6	18.3	32.9	71.2*						

* Includes \$10.4 billion for refineries that is not included in country group or individual fuel totals.

Source: World Bank, 1983.

advantage increases with interest rates (Geller et al., 1988). However, this comparison is not visible to consumers since they do not pay the marginal cost of new energy supplies, and energy and utility companies may have no interest in efficiency for institutional reasons (Goldemberg et al., 1987).

Greenhouse Gas Emissions and Technology Transfer

The transfer of state-of-the-art technology will be necessary to significantly reduce commercial energy use in developing countries. However, there are many obstacles to the development and dissemination of such technologies from industrialized countries to potential competitors in developing countries.

Even when state-of-the-art technology is made available, developing-country governments or manufacturers may be reluctant to accept it. Such technology will carry a higher capital cost and may produce products of higher quality only at a higher price. Heavily indebted developing countries may not be in a position to secure the additional capital needed for state-of-the-art technology. Developing-country markets tend to be more price sensitive given the lower discretionary income enjoyed by consumers in these countries. A program to reduce the cost of capital for more efficient plants and equipment, and another to induce consumers to purchase products with higher first costs yet lower life-cycle costs, are essential to encourage developing-country consumers to acquire and use state-of-the-art technology.

Most developing countries need technologies that take advantage of abundant but unskilled labor and that minimize the need for capital. Many have more biomass resources than fossil fuels (Goldemberg et al., 1987; Williams, 1988). Improved versions of some low-cost technologies no longer used in the industrialized countries, such as woodburning cookstoves, are therefore a high priority. Developing countries are still rapidly increasing their consumption of basic materials, whereas such consumption is being replaced by high-value-added fabrication and finishing activities in industrialized countries (Williams et al., 1987). This fact implies substantial differences in research priorities,

but there are few institutions and much less money devoted to meeting their needs. The tendency, reinforced by the risk-averse policies of multilateral banks, is to make do with what is tried and true in the industrialized nations.

A recent study of energy research and development (R&D) by the Oak Ridge National Laboratory concluded that U.S. support for R&D should include some efforts aimed specifically at the needs of developing. countries, in recognition of differences in their resources and infrastructure. The study notes that such expenditures may be in the best interests of the U.S. as a contribution to reduce the buildup of greenhouse gases. Additional potential benefits include reducing the expected increased stress on oil markets that would occur with higher demand and the creation of a significant export market for U.S. manufacturers. The study proposes additional annual expenditures of between \$100 million and \$200 million as part of a larger international effort (Fulkerson et al., 1989).

The potential for developing new export markets would become even more important if the U.S. exports of coal (worth \$3.5 billion in 1987) were reduced. The Committee on Renewable Energy Commerce and Trade (CORECT) may be a model for integrating technology transfer efforts with export promotion activities. The Committee was created by an act of Congress in 1983, serves as a vehicle for bringing together developing country officials, donor agencies, and U.S. renewable energy firms, and addresses both development needs and potential export markets. CORECT has organized trade shows, analyzed trade barriers, brought potential foreign buyers to the U.S. to see operating systems first-hand, and recommended measures to improve access to financing.

STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS

Studies of future energy use in developing countries indicate that the industrial sector and power generation sector will retain their large share of total energy demand (Sathaye et al., 1989). However, the mix of fuels is less certain. A slower growth rate would mean continued use of traditional, and therefore, biomass fuels. On the other hand, faster economic growth would reduce biomass consumption, but increase oil consumption as individuals with higher incomes would demand greater mobility and, consequently, more petroleum products. Strategies to reduce carbon dioxide (CO_2) emissions will therefore depend on the rate of economic growth in the developing countries.

Energy-pricing reform is essential to promote efficient use of fuels; existing subsidies and price controls are major barriers to investments in energy conservation. However, as discussed below, the short-term result may not be to reduce CO_2 emissions since many countries have substantial unmet energy needs that would utilize any supplies made available by efficiency improvements. Coal is also the least expensive fuel other than biomass in most developing countries, and market pricing may lead to increasing the share of energy from this carbon-intensive source.

U.S. AID, the World Bank, and other development agencies have actively promoted energy-pricing reform in developing countries. However, a recent U.S. AID analysis concludes that such efforts have often failed because of fears that reforms will be economically and politically destabilizing. Effective pricing reform, however, does not necessarily require radical reorganization of economies. Hungary, has achieved substantial for example, improvements in agricultural productivity by creating economic incentives while maintaining a primary role for cooperatives (Chandler, 1986). Further study may help identify ways to overcome this problem, but a realistic expectation may be gradual price increases and structural reform to reduce future interference in energy markets (U.S. AID, 1988a).

Improvements in energy efficiency in developing countries may not lead to emission reductions in absolute terms because the energy made available may meet unmet needs and pent-up demands. This is consistent with efforts to promote economic growth but highly successful implies that even conservation programs may not prevent substantial emissions growth in these countries. In the long run, however, there will be less emissions than would be the case with continued inefficient use of energy. Similarly,

pricing reform may not always lead to reduced emissions of greenhouse gases. For example, removing subsidies for kerosene and liquified petroleum gas may push some consumers back to inefficient use of traditional fuels (Leach, 1987, 1988). This may promote deforestation and a net increase in CO_2 emissions if the only alternative is wood from freshly felled trees. Continued subsidies for modern cooking fuels for some transition period might be desirable to reduce CO_2 emissions.

Several financial strategies can promote improved industrial efficiency by increasing the capital available for desired investments. One traditional financial approach is to allocate capital for designated purposes, such as improving energy efficiency, sometimes at subsidized rates. Power sector loans also could be tied to stringent conservation targets involve utilities in promoting that conservation, as is currently done in some industrialized countries. Governments also sometimes deliberately seek to increase competition within the industrial sector, sometimes inviting foreign collaboration, as a way of forcing companies to increase capital spending.

becomes As capital expensive. governments have begun to tap into private capital markets by floating bonds in targeted funds (e.g., the Korean, Taiwanese, or Indian funds introduced in international markets). Domestic markets are being tapped as well in Governments could target similar ways. private capital for proven technologies and government funds for investment in novel, yet economic, energy conservation schemes specially targeted to reduce CO_2 emissions. Industrialized countries may help by inducing banks to reduce the interest charged for investment targeted for CO₂ emissions abatement strategies.

Another possible innovative approach is for governments to allow the release of socalled "black money" funds locked away by private individuals to evade taxes, if directed to investments for CO_2 emissions abatement. In some countries black money may account for 30-40% of total gross domestic product (Woodall, 1988). Placing this money in circulation would mean that governments would have to forego or reduce taxes on these would have to forego or reduce taxes on these funds, in effect conceding that they would not collect them anyway without substantial increase in enforcement.

International Lending and Bilateral Aid

The U.S. can help developing countries reduce their greenhouse gas emissions through its foreign aid programs and contributions to the World Bank and other MDBs. Although all such programs (U.S. and foreign) address only a small percentage of total investment in developing countries, they can exert disproportionate influence because they leverage much greater amounts of funds and certify the financial merit of particular technologies and projects.

U.S. Bilateral Assistance Programs

Most U.S. non-military bilateral assistance is administered by U.S. AID, forestry-related including energyand assistance. U.S. AID has attempted to improve its sensitivity to environmental concerns in recent years and estimates that it now spends over \$100 million for activities aimed at conserving natural resources (U.S. AID, 1987). The Agency has expanded the number of environmental professionals and established an Office of Forestry, Environment, and Natural Resources.

Most U.S. AID support for energy is provided through regional and national programs, although a few projects are funded through a central Office of Energy. Some coordination is also encouraged by an Agency Sector Council for Energy and Natural Resources. Energy-related funding for the past five years has averaged slightly less than \$200 million per year; the fiscal year (FY) 1986 budget included \$254 million for energy projects in 23 countries, of which \$180 million was spent for electric power (U.S. AID, 1988a).

U.S. AID has funded some analysis of promising projects for biomass fuels that indicate the possibilities for redirecting some bilateral assistance to more effectively promote rational energy planning and development and adoption of improved technology. The Multi-Agency Working Group on Power Sector

Innovation, coordinated by U.S. AID's Office of Energy, was organized in 1987 to promote cooperation among international institutions involved in power sector development. U.S. AID has proposed using this group and the International Development Assistance Committee to focus greater attention on the energy/environment relationship (U.S. AID, 1988b). Proposals have also been made to expand the scope of the Consultative Group on International Agricultural Research -- a highly successful international consortium of lenders for improving crop yields and production in developing countries -- to agroforestry, bioenergy, and encompass tropical ecology.

Current U.S. AID priorities are to identify projects that utilize indigenous energy resources and that have the greatest potential for replication. U.S. AID will attempt to broker technical and financial assistance for promising projects, emphasizing private sector participation. U.S. AID's funding priorities are also shifting toward the poorest nations, which generally implies countries with lower energy growth rates, although sometimes high rates of deforestation (Gray et al., 1988). U.S. AID is proposing to give greater attention to the environmental implications of the energy sector.

U.S. AID has steadily upgraded its commitment to forestry in recent years, from about \$20 million in 1979 to \$56.2 million for 146 projects in FY 1987 (U.S. AID, 1987; Stowe, 1987; see Table 8-7). Agroforestry has been emphasized along with training and institution building. A large amount of support has been given to tree planting and forestry-related activities through the Food for Peace Program (PL 480). The program is responsible for direct tree planting on an estimated 1.5 million hectares in 53 countries during the early 1980s (Joyce and Burwell, 1985) and for 38 tree-planting projects in 23 countries in FY 1987, mostly in Africa (U.S. AID, 1988c). Combining bilateral and foodaid assistance, U.S. AID's tropical forestry programs exceeded \$82 million in FY 1987. U.S. AID has also been a strong supporter of the Tropical Forestry Action Plan.

If the U.S. seeks to promote reductions in greenhouse gas emissions in developing

Region	Number of Countries With Projects	Number of Projects Active in FY 1987	Number of New Starts	Number Completed	LOP Forestry Obligations ^a (in \$1,000)	FY 1987 Forestry Obligations ^b (in \$1,000)
Africa	23	45	3	3	95,150	13,960
Asia/Near East	11	39	1	6	273,212	17,337
Latin America/ Caribbean	12	46	3	8	140,241	17,398
Central Bureaus	S NA	16	0	0	78,103	7,488
Totals	46	146	7	17	\$586,706	\$56,183

U.S. AID Forestry Expenditures by Region

^a LOP = Life of Project. Many forestry projects are components of larger natural resource and agricultural projects. To determine the forestry component, a percentage of the total LOP funding was estimated for significant forestry activities based on judgments made by U.S. AID staff and contractors. Projects can receive funding obligations at any time during the life of the project.

^b To arrive at estimates for FY 1987 forestry obligations, the total 1987 LOP obligations were multiplied by the percentage estimated for forestry activities.

Source: U.S. AID, 1988c.

countries, U.S. AID would logically play a major role. Section 106 of the Foreign Assistance Act already authorizes U.S. AID programs to promote renewable energy and improvements in energy efficiency. Several proposals have been made for greatly expanded efforts in this area. A working group of the Atlantic Council of the United States and the Member Committee of the U.S. World Energy Conference recommended expanding U.S. AID's energy assistance programs to promote greater private-sector investment. They suggest using the revolving loan fund and grant program administered by the Bureau for Private Enterprise to make energy loans; its current priority is agribusiness (Gray et al., 1988).

Another recent study by the American Council for an Energy-Efficient Economy proposes that U.S. AID's energy budget be increased to \$50-\$100 million per year. The authors would redirect aid programs away from support of specific projects in favor of building the capabilities of individuals and institutions within developing nations. They conclude that increasing private-sector involvement should be a high priority, noting that U.S. companies could be encouraged to market energy-efficient technologies with the assistance of the Overseas Private Investment Corporation, the Export-Import Bank, and the Trade and Development Program (Chandler et al., 1988).

U.S. AID is not the only U.S. agency involved in bilateral assistance. For example, both the Department of Agriculture and the Peace Corps support international cooperative forestry programs. The former has an Office of International Cooperation and Development exclusively devoted to international activities and also funds some research (Stowe, 1987).

Policies and Programs of Multilateral Development Banks

The U.S. contributes over \$1 billion to MDBs annually, an amount that leverages many times as much actual borrowing through co-financing and other arrangements. Much of the activity of these banks is directly or indirectly related to greenhouse gas emissions

through loans for energy projects, forestry, and agriculture (see Table 8-8). U.S. influence on these institutions is substantial, though they are not controlled by the U.S. government. Voting on each bank's board is through a board of directors whose membership is proportional to the size of contributions, giving the U.S. roughly 15% in the World Bank (World Bank. 1987). (U.S. recommendations on specific loans, however, have been outvoted.) The U.S. is the largest contributor to the World Bank, and the World Bank president has traditionally been an American. Congress has directed use of the U.S. "voice and vote" to promote several selected policies, such as human rights concerns and the use of "light capital technologies" (22 U.S. Code Sec. 262f and 262d).

The MDBs are able to influence the policies of developing countries to some degree, because loans and aid tend to be offered on relatively favorable terms and because bank support can help countries obtain credit from lenders. MDB lending has taken on even greater significance as the debt burden and capital requirements of developing countries have grown enormously in recent years. This influence has been used in ways that have had both positive and negative impacts on the energy and forestry sectors. For example, the World Bank has been a strong advocate of energy-pricing reforms (World Bank, 1983; Goldemberg et al., 1988). However, studies have also documented numerous MDB projects that lead directly and indirectly to deforestation, including roads, dams, tree crop plantations, and agricultural settlements (Repetto, 1988).

About one-fourth of World Bank lending, nearly \$4 billion, goes to energyrelated projects. The rate for other MDBs ranges from 9% by the African Development Bank to 34% for the Asian Development Bank (Gray et al., 1988). Traditionally, a majority of this funding has gone for development of very large power projects (see Table 8-9). By one estimate, over 90% of multilateral and bilateral energy assistance has been for large systems for the generation, transmission, and distribution of electricity. New and renewable energy sources have received about 3%, and

Gross Disbursements of Development Banks in Forestry Projects in 1986-1988

BANK	1986	1987	1988
World Bank	122.3	127.0	129.8
African Development Bank	2.7	5.0	1.0*
Asian Development Bank	9.0	11.6	75.0
Inter American Development Bank	8.5	7.5	6.8
TOTAL	142.5	151.1	212.6

(million U.S. dollars)

* Rough Estimate

Source: FAO, 1989.

TABLE 8-9

World Bank Energy Sector Loans in 1987

(million U.S. dollars)

	Eastern & Southern Africa	Western Africa	East Asia & Pacific	South Asia	Europe, Middle East & N. Africa	Latin America & Caribbean	Total
Oil/gas/coal	20.0	15.0	0.0	548.0	0.0	104.4	687.4
Hydroelectric	63.0	6.3	684.8	1,312.0	527.0	423.8	3,016.9
Total	83.0	21.3	6 84.8	1,860.0	527.0	528.2	3,704.3

Source: World Bank, 1987.

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end-use efficiency measures less than 1% of total energy-related loans (Goldemberg et al., 1987; see Table 8-10).

The World Bank has had a major role in financing energy sector expansion in the developing countries that are growing most rapidly and relying most heavily on fossil fuels, including China, India, and Pakistan. Coal resources in these countries are often characterized by low heating values, and the generation and distribution of electricity is typically much less efficient than in the industrialized countries. Bank projects, therefore, represent a large share of carbon emissions from developing countries.

In 1987 the World Bank announced a general commitment to upgrade its support for environmental analysis and programs (World Bank, 1987). The Bank has created a new environmental department, increased environmental staff, and begun a process of preparing environmental assessments on about 30 developing countries. Special attention is being given to identifying regional environmental projects in Africa. Support for tropical forest conservation and development has also been made a high priority; funds will increase from \$152 million in FY 1987 to \$350 million in FY 1989. In September 1989, the World Bank announced a policy to give greater attention to the global warming implications of its projects, although without indicating any change in funding priorities at this time.

Some power sector loans have important conservation components. For example, a recent loan to Zimbabwe includes \$44 million to upgrade generating equipment, rehabilitate transmission lines, and train workers to increase total output (World Bank News, 1988). The Bank has used its influence to support energy-pricing reforms and the elimination of subsidies and has funded a small number of conservation programs through its Energy Sector Management Assistance Program (see Table 8-11). Some industrialization loans may also result in substantial improvements in energy efficiency, although such improvements are not a primary purpose for these loans. The Bank plans to maintain energy loans as a relatively constant percentage of its total lending (Gray et al., 1988). However, recognizing that capital needs for energy in developing countries are expected to grow much faster than available funding, the Bank plans to increase its analytical, policy, and technical advisory roles and to become more of a catalyst for funds from non-Bank sources. The World Bank, like U.S. AID, plans to give more attention to private power generation and other innovative means of financing new power sources.

A World Bank representative at a U.S. Environmental Protection Agency (U.S. EPA) workshop cited several obstacles to increased support for conservation (WRI, 1988). One is that the Bank traditionally has found it difficult to fund relatively small projects; ways must be found to package them as an element of a larger loan. (This was done in the case of a large power loan to Brazil, which included \$2 million for analysis of conservation opportunities.) Implementation of projects that require actions by many individuals is similarly perceived as difficult. Some of the most inefficient industries may be judged uneconomic and, therefore, inappropriate candidates for loans. Finally, the recipient governments have to be interested in conservation and must possess the necessary technical skills to implement conservation programs.

Another problem is the availability of proven technology suited to the needs of developing countries. As discussed above, the technological needs of developing countries differ from those of industrialized countries in many areas. However, lending criteria tend to discourage the search for new or innovative technologies by restricting financing to practices that have been fully proven in practice (Daffern, 1987). This practice reflects an understandable desire to minimize risks, but the effect is often to finance equipment that is not the most efficient. Promising alternatives that would utilize biomass and other local resources are also neglected because the technologies are not widely used in the industrialized countries (Williams, 1988).

Energy-Related Expenditures of Multilateral and Bilateral Aid Institutions

	Conventional Power Generation (Hydro, Nuclear, Thermal), Transmission; Distribution; Power Sector Studies	Fossil Fuels Recovery (includes Studies and Training)	New and Renewable Energy Sources (includes Geothermal, Fuelwood)	Technical Assistance, Energy Planning, Other	Total Energy Aid
MULTILATERAL AID World Bank					
(FY 1978-Dec. 1978)	5,210	305	170	-	5,686
Inter-American Development H (FY 1972-FY 1978)	Bank 2,596	158	4	-	2,758
Asian Development Bank (FY 1972-FY 1978)	1,183	21	0	-	1,204
European Development Fund (to May 1978)	141	•	9	-	150
U.N. Development Programme (to Jan. 1979)	72	23	29	13	137
U.N. Center for Natural Resources, Energy and Tra (to Jan. 1979)	ansport 3	5	4	5	17
BILATERAL AID French Aid (1976-1979)	229	16	30	5	280
Considian International Develop	amont				
Agency	pment				
(1978-1979, 1979-1980)	88	0	2	1	91
German Aid (1970-1980)	1,925	41	81	48	2,095
Kuwait Fund (FY 1973-FY 1978)	437	99	1	-	536
Netherlands-Dutch Developme Cooperation	nt				
(1970-1980)	119	71	7	2	198
U.K. Overseas Devel. Admin. (1973-1980)	146	1	3	-	149
U.S. AID (FY 1978-FY 1980)	403	2	96	46	546
Grand Total	12,719	757	437	121	14,033
Percentage in Each Sector	91	5	3	1	100

(millions of current dollars)

Source: Hoffman and Johnson, 1981, in Goldemberg et al., 1987.

World Bank Energy Conservation Projects: Energy Sector Management Assistance Program Energy Efficiency Initiatives

Industrial Energy Efficiency

- Program Design and Institutional Support (Senegal, Ghana)
- Energy Audits (Syria)
- Training of Local Staff (Tanzania)

Power Efficiency (Many Countries)

- Design of Programs to Reduce Technical and Non-Technical Losses
- Pre-Feasibility Studies for Life Extension and Rehabilitation Projects
- Utility Organization Studies

Electricity Savings in Buildings

- Energy Efficient Building Code (Jamaica)
- Appliance Labeling (Jamaica)

Household Energy Savings

- Household Energy Strategy Studies
- Improved Cookstoves Projects
- Improved Charcoaling

Energy-Environmental Studies

• Energy Supply Options to Steel Industry in Carajas Region (Brazil)

Source: WRI, 1988.

New Directions

The possibility of redirecting bilateral aid and World Bank loans to facilitate energy conservation and other strategies to reduce greenhouse gas emissions was discussed at the U.S. EPA workshop on developing country issues. One proposed remedy is a shift in Bank energy sector lending to general energy programs as opposed to specific projects as a way of facilitating more funding of demandside efforts (Goldemberg et al., 1988). This proposal may be difficult to implement but may receive more attention as capital constraints lead to greater interest in conservation.

A recent study of innovative financing mechanisms by the World Resources Institute (WRI) proposes that the MDBs place greater emphasis on promoting policy reforms in conjunction with loan agreements to protect natural resources. The authors suggest that the international development agencies identify and analyze the effects of tax, tariff, credit, and pricing policies, as well as the terms and administration of concession agreements, on the use of resources (Repetto, 1988).

A possible strategy for creating an economic incentive for protection of tropical forests is to pay affected nations an annual fee for custodial services -- protection from squatters and illegal development -- in proportion to the areas under protection (Rubinoff, 1985). Agreements to protect 100 million hectares, or roughly 10% of the world's remaining moist tropical forest, might cost approximately \$3 billion. The status of reserves would be monitored and payments adjusted accordingly. In this way tropical countries would be paid for some management costs, reflecting some of the benefits thereby provided to the rest of the world.

Section 119 of the Foreign Assistance Act requires U.S. AID to prepare environmental assessments of its major actions, including effects on the global environment.¹ U.S. AID is also specifically directed to consider the impacts of its programs on tropical forests (22 CFR § 2151(a), (p); see also Stowe, 1987).

The importance of these issues is suggested by increasing Congressional interest (Stowe, 1987; Rich, 1985). Section 539 of Public Law 99-591 directs the Secretary of the Treasury to instruct U.S. Executive Directors in each of the multilateral development banks to take a number of steps to support environmental reform measures and also requires the Treasury Department to report on progress toward these objectives (U.S. Treasury Department, 1988). The Department's most recent report provides mixed reviews of the MDBs' responsiveness to environmental concerns. As already noted, the World Bank announced a higher priority for environmental concerns in 1987, but the report states that "The Bank has not moved effectively in the area of energy conservation."

REDUCING GREENHOUSE GAS EMISSIONS IN THE USSR AND EASTERN EUROPE

The Soviet Union is the second largest source of carbon dioxide emissions and together with Eastern European nations is likely to remain a significant contributor to global greenhouse gas emissions in the years to come (see Figure 8-1). The energy policies of these countries will therefore have an important influence on the greenhouse problem.

The Soviet Union has enormous energy resources, although most of them, including half the world's accessible coal, are in relatively remote areas of Siberia. Soviet oil production is roughly equal to the total production of all Middle Eastern countries combined, and the Soviets also rank first in gas production and third in coal production. Coal was the dominant energy source until the late 1950s but declined to less than 30% in 1977 with the growth in oil production (see Table 8-12). Future plans call for increasing reliance on natural gas and nuclear power and renewed growth in coal use; large coal-burning powerplants and coal slurry pipelines are now under construction. Other Eastern European nations, particularly Poland, East Germany, and Czechoslovakia, are even more dependent on coal (WRI and IIED, 1988).

Energy Use in the Soviet Union and Eastern Europe

(petajoules)

]	Liquid Fu	els"	5	Solid Fuels		(Gaseous Fuels ^b		E	lectricity ^c			Total	
		1970	1980	1985	= ==== 1970	1980	1985	1970	1980	======) 1985	=== 1970	1980	1985	= ==== 1970	===== 1980) 1985
Eastern I	Europe															
	Bulgaria	346	575	562	570	615	672	17	148	216	7	49	71	940	1,387	1,521
	Czechoslovakia	371	668	567	1,792	1,861	1,878	79	298	330	25	40	71	2,267	2,867	2,846
	East Germany	483	690	632	2,602	2,523	2,856	22	302	288	8	54	53	3,065	3,569	3,829
	Hungary	223	424	392	496	374	373	121	364	393	13	27	63	853	1,189	1,221
	Poland	301	610	512	2,878	4,230	4,170	222	363	363	7	11	6	3,408	5,214	5,051
	Romania	406	688	760	410	689	813	971	1,507	1,599	1	47	51	1,788	2,931	3,223
ubtotal		2,080	3,655	3,425	8,748	10,292	10,762	1,432	2,982	3,189	61	228	315	12,321	17,157	17,691
J. S.S.R .		9,283	14,770	14,450	12,933	14,440	14,596	6,611	13,209	19,761	442	811	1,257	29,270	43,229	50,065
otal		11,363	18,425	17,875	21,681	24,732	25,358	8,043	16,191	22,950	503	1,039	1,572	41,591	60,386	67,756

* All petroleum products and natural gas liquids.

^b Natural gas, manufactured gas, coke-oven gas, and blast furnace gas.

^c Hydro, nuclear, and geothermal power.

Source: WRI, 1988.

The energy intensity of the Soviet economy changed relatively little between 1970 and 1985, in contrast to the substantial reductions achieved during the same period in the U.S. and other industrialized nations. The government has become increasingly interested in energy conservation because of the growing capital and fuel costs of energy production. More than 20% of national capital investments and 14% of primary energy resources are consumed by the energy supply system (NAS, Oil is also a valuable export 1987). commodity, and at current production rates known reserves may be exhausted by the year 2000. Siberian reserves may be large, but production costs will be much higher (WRI and IIED, 1988).

According to recent reports, improvements in energy efficiency continue to be elusive in the Soviet economy (Gustafson, 1989). Industry does not pay market prices for energy and, therefore, has little economic incentive to conserve. However, the government is gradually increasing fuel costs within the Soviet economy, and recent economic reforms may give industry greater incentive to conserve (NAS, 1987).

Energy pricing and planning in Eastern Europe is complicated by trade agreements with the USSR. These countries have provided labor for construction on Soviet oil and gas projects in return for options to purchase oil at a price equal to the average price paid for Soviet oil exports over the previous five years -- a rewarding arrangement when prices were rising, but unattractive at recent low oil prices (WRI and IIED, 1988).

The Soviet Union and United States currently have cooperative agreements on both climate change and energy conservation. The U.S.-USSR Agreement on Cooperation in the Field of Environmental Protection lists numerous projects on atmospheric science. The first U.S.-USSR Symposium on Energy Conservation was held in Moscow in June 1985, and several meetings followed, the most recent in October 1988. A program of cooperative research has been developed, administered in the U.S. by the National Academy of Sciences (NAS, 1987, 1988). The Soviet Union also has independently expressed strong interest in global climate change problems. At the November 1988 meeting on global climate issues in Geneva sponsored by WMO and UNEP, the Soviet Union agreed to chair a panel on the effects of climate change.

U.S. LEADERSHIP TO PROMOTE INTERNATIONAL COOPERATION

The international and bilateral cooperation already in place has established a solid foundation for discussion of policy responses. However, there is much that needs to be done before this discussion and analysis leads to agreement on necessary actions. Several precedents suggest that U.S. leadership can help achieve agreement on response Two important sources of strategies. greenhouse gas emissions, the use of CFCs and tropical deforestation, have already been the subject of international agreements that should moderate global warming. In both cases, action was taken for reasons largely unrelated to climate change, but examination of the evolution of these agreements may suggest factors conducive to agreement on climate change.

Restricting CFCs to Protect the Ozone Layer

In September 1987, because of growing concern about the effect of CFCs on stratospheric ozone, 24 nations signed an agreement in Montreal (the Montreal Protocol) to reduce emissions of CFCs. As of February 1, 1991, 68 countries had ratified the Protocol. The reductions are to he achieved through a phaseout process, which began with a freeze (effective July 1, 1989, six months after the Protocol went into effect) and requires a 20% reduction of 1986 levels by July 1993. The U.S. ratified the Montreal Protocol on April 21, 1988. U.S. EPA issued regulations consistent with the requirements of the Protocol on August 1, 1988 (Federal Register, 1988). The London Amendments to the Protocol accelerate the reduction schedule, calling for a 50% reduction of 1986 levels by 1995 and a total phaseout by 2000. For a description of the terms of the Protocol and U.S. REGULATIONS AND regulations, see STANDARDS in Chapter VII.

Aside from its direct impact on reducing emissions of important greenhouse gases, the

terms of the Protocol and the process that led up to the agreement offer some valuable insights for cooperation to address climate change. Developing nations, whose current CFC use is only about 15% of total use worldwide, were concerned that emissions reductions might hinder their economic Therefore, to encourage their growth. participation, Article 5 of the Protocol allows countries with CFC consumption less than 0.3 kg per capita to delay compliance by ten years as long as they do not exceed that amount (U.S. CFC consumption was more than 1 The industrialized kg/capita in 1985). countries also agreed to provide technical assistance and financial aid in support of developing countries' efforts to adopt CFC alternatives.

The Protocol was negotiated over a twoyear period, but the foundations were laid over a period of a decade or more. Intergovernmental meetings were first held in 1977 and 1978 (Stoel et al., 1980). A consensus-building scientific process, the Coordinating Committee on the Ozone Layer, was created by the UNEP Governing Council in 1977. The Council decided to convene a working group of legal and technical experts in 1981, and the first meeting took place in January 1982. When agreement on proposals for action at first proved impossible, the participants came to an agreement in March 1985 that provided a framework for scientific cooperation: the Vienna Convention for Protection of the Ozone Layer. The Convention also committed the signatories to hold workshops and exchange information as the basis for further efforts to achieve a protocol.

Some of the factors that facilitated the Protocol may provide some insight into possible strategies for future efforts to achieve agreements to reduce greenhouse gases (Benedick, 1987). The existence of an international scientific consensus report prepared under WMO auspices, Atmospheric Ozone 1985, helped achieve consensus about the underlying seriousness of the problem. The workshop process, which facilitated informal negotiations, proved to be very conducive to consensus building. UNEP served a valuable organizing role and provided a valuable objective international forum.

According to the chief U.S. negotiator, U.S. leadership had a major role: "The treaty as eventually signed was based upon the structure and concept advanced by the United States late last year" (Benedick, 1987). In addition to governmental efforts, such as a series of diplomatic initiatives, the U.S. role includes industry actions to take responsibility and to express support for the proposed emission controls, efforts undertaken by public interest groups to inform the public, and threats of unilateral action and trade sanctions by members of Congress.

International Efforts to Halt Tropical Deforestation

There has also been substantial recent international cooperation on the problem of tropical deforestation. These efforts are of substantial interest because of some of the similar obstacles faced in solving the tropical deforestation problem and the larger greenhouse problem. In both cases, there is a need for industrialized countries to help developing countries implement policy changes that may be costly and difficult. Mechanisms for achieving international cooperation must be found, substantial amounts of financial assistance must be provided to developing countries, and politically difficult policy choices must be made.

The Tropical Forestry Action Plan (TFAP) is a promising response to this challenge (WRI, 1985; FAO, WRI, World Bank, UNDP, 1987). TFAP was developed by a consortium of institutions concerned about tropical deforestation, including the U.N. Food and Agriculture Organization (FAO), the U.N. Development Programme (UNDP), the World Bank, WRI, and representatives of more than 60 tropical countries. The task force that drafted TFAP included Brazil's Secretary of the Environment and one of India's former Secretaries of the Environment. The broad and highly visible sponsorship of TFAP has helped to highlight the important benefits provided by tropical forests and to draw attention to their accelerating loss. Equally important, TFAP offers the broad outlines of a solution, including regional and functional budget proposals. The total budget calls for \$8 billion over a five-year period.

TFAP has become a focal point for cooperative efforts by bilateral aid agencies and has influenced World Bank policies (Wolf, 1988; Stowe, 1987).² Ultimately, TFAP's success depends on the cooperation and support of the affected developing countries, and many of them are preparing national action plans and increasing national support for reforestation (WRI and IIED, 1988).

The International Tropical Timber Organization (ITTO) is another important vehicle for north-south cooperation on tropical forest management. ITTO was created by a March 1985 agreement reached under the auspices of the U.N. Conference on Trade and Development, primarily as a commodity agreement to facilitate economic use of tropical timber: its purposes include "expansion and diversification of international trade," a "long-term increase in consumption," and greater access to international markets. However, unlike traditional commodity agreements, ITTO explicitly recognizes the importance of the premise of sustainable use to conservation efforts and management policies. The connection has thus been made between conservation, economic development, and the export of resources to industrialized countries (Wolf, 1988; Forster, 1986).

The importance given to promoting cooperation between tropical nations and industrialized consumers of tropical hardwoods is evident in the ITTO organization. The headquarters is in Japan, a very large consumer, and the executive director is from Malaysia, an important producer. Another promising sign is that at the first meeting in April 1987, Japan announced a pledge of \$2 million for research on reforestation and sustainable management.

The ITTO also acts as a forum for addressing the link between policies of industrial countries and resource exploitation in developing countries. A recent WRI study concludes that "industrial-country trade barriers in the forest products sector have been partially responsible for inappropriate investments and patterns of exploitation in the Third World Forest industries. [N]egotiations between exporting and importing countries should reduce tariff escalation and non-tariff barriers to processed wood imports from the tropical countries, and rationalize incentives to forest industries in the Third World" (Repetto, 1988).

Looking toward the future, increased international cooperative efforts will be necessary if tropical deforestation is to be halted and reversed. Professor Pedro Sanchez of North Carolina State University has recently outlined a possible framework for a program to achieve this goal (Sanchez, 1988). Dr. Sanchez notes that 12 countries account for three-fourths of the net carbon emissions from clearing primary forests; 10 more account for much of the remainder (see Table 8-13). Efforts could be made to engage the leaders of these countries in a dialogue to discuss specific program agreements targeted to deforestation "hot spots," where technology transfer and government policies would be focused -- an approach that is consistent with the TFAP's emphasis on national planning.

Ongoing Efforts Toward International Cooperation

Some important first steps to promote international action have already been taken in the last few years, and a foundation for international cooperation now exists. Several meetings without formal governmental status established a basis for international scientific cooperation. A conference on the status of the greenhouse problem organized by UNEP, WMO, and the International Council of Scientific Unions was held in October 1985 in Villach, Austria, and was attended by experts from 29 countries, including representatives from several U.S. agencies. Among their conclusions were recommendations that "scientists and policy-makers . . . begin an explore collaboration the active to effectiveness of alternative policies and adjustments." response In to the recommendations, a small task force was created to advise on needed domestic and international actions and to evaluate the need for a global convention.

The government of Canada convened a non-governmental meeting on "The Changing Atmosphere" in June 1988, which was attended by more than 300 experts from 46 countries and several United Nations' organizations. The Conference Statement that came out of

Countries Responsible for Largest Share of Tropical Deforestation

Country	Net Carbon Emissions in 1980 From Primary Forests (million tons)
Brazil	207
Colombia	85
Indonesia	70
Malaysia	50
Côte d'Ivoire	47
Mexico	33
Thailand	33
Peru	31
Nigeria	29
Ecuador	28
Zaire	26
Philippines	21

Source: Sanchez, 1988.

the meeting urges development of an Action Plan for the Protection of the Atmosphere, in addition to several specific proposals for government policy, including the following:

• reduce CO_2 emissions by 20% of 1988 levels by the year 2005, half by reducing energy demand and half by changing the sources of energy;

• direct energy R&D budgets to energy options that would greatly reduce CO_2 emissions;

• initiate development of a comprehensive global convention as a framework for protocols on the protection of the atmosphere; and

• establish a World Atmosphere Fund, financed in part by a levy on fossil-fuel consumption in industrialized countries, to help finance the Action Plan.

UNEP and WMO have continued their activities since the 1985 Villach meeting. The IPCC, organized by UNEP and WMO, met in November 1988 with representatives from over 40 countries. Participants agreed to establish three committees: the first, chaired by the United Kingdom, was to assess the state of scientific knowledge on the greenhouse issue; the second, chaired by the Soviet Union, was to assess social and economic effects from global warming; and the third, chaired by the United States, was to evaluate potential response strategies.

1989 Ĭn October the Response Strategies Working Group identified an emerging consensus on the value of a framework climate convention to be modeled after the Vienna Convention on the Protection of the Ozone Layer. There was, however, disagreement concerning the timing of such a convention and the extent to which it should be more specific concerning goals and obligations, particularly provisions to address financial aid and technology transfer. These issues and provisions to reduce greenhouse gas emissions may be left for later protocols as was also done in the Vienna Convention. In the Fall of 1990, the IPCC submitted its report.

Outside the IPCC process, global warming has been addressed in several other important international forums such as the U.N. General Assembly, which convened the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change. The first meeting was held in Chantilly, Virginia in February 1991. A communique that arose out of the July 1989 Paris meeting of the seven heads of state of the seven largest western economies (the "G-7") also included statements about the need to address global warming. The government of the Netherlands convened in November 1989 a conference of environmental ministers who addressed the problems of atmospheric pollution and climatic change. Their statement recognized the need to stabilize emissions of greenhouse gases from industrialized nations "as soon as possible, at levels to be considered by the IPCC and the Second World Climate Conference of November 1990," noting that many nations support the goal of stabilizing CO_2 emissions at the latest by the year 2000 (See Box 8-1).

The U.S. also has important bilateral cooperation with some of the other nations that emit large amounts of greenhouse gases, particularly the USSR and the People's Republic of China. (These three countries account for over 40% of the current commitment to global warming.) U.S.-Soviet cooperative efforts include studies of future climates, climate studies in the Arctic, measurements of methane and ozone change in the polar regions, and analysis of possible response strategies. The joint communique released after the Reagan-Gorbachev Summit emphasized the high level of interest in cooperation on the greenhouse issue:

The two leaders approved a bilateral initiative to pursue joint studies in global climate and environmental changes through cooperation in areas of mutual concern . . . there will be a detailed study on the climate of the future. The two sides will continue to promote broad international and bilateral cooperation in the increasingly important area of global climate and environmental change.

Box 8-1. Sweden's Policy on Global Warming

Sweden is one of the countries that is most committed to reducing its emissions of greenhouse gases. Sweden has banned the use of CFCs by 1994, much faster than the 50% reduction required in 1995 by the London Amendments to the Montreal Protocol, and in 1988 decided that CO_2 emissions should not increase above current levels. The CO_2 cap will be particularly difficult to maintain because Sweden has also decided to phase out its nuclear reactors -- 50% of its electricity supply -- by 2010. Increased hydropower is also not permitted. To support the necessary research and changes in economic activities, the government created an Environmental Charge Commission to assess possible implementation of charges on air pollutants. In October 1989, the Commission presented an interim report proposing that emissions of CO_2 be subject to a charge amounting to 3.8 cents per kilogram of CO_2 . The charge would apply to all fossil fuels, including gasoline. Other energy taxes would be reduced. The Commission estimates that the tax would reduce CO_2 emissions by 5-10 million tons by the year 2000 relative to what they otherwise would have been.

Source: Garding, 1989.

The U.S. and Soviet Union are also engaged in some cooperative activities designed to promote energy conservation. For example, the U.S. National Academy of Sciences and the Soviet Academy of Sciences have a cooperative program on energy conservation that includes some comparative evaluation of building codes and other energy conservation programs in addition to exchange of technical information.

The U.S. government has also initiated cooperative research on climate change with the People's Republic of China, now the world's largest user of coal. Potential areas for cooperative research include exchange of information and development of data on future energy development paths, emissions from rice fields and other sources, and concentrations of trace gases in remote regions.

CONCLUSION

Responding to the risks of climate change will require unprecedented global Recent experience with cooperation. negotiations to protect the ozone layer, the Tropical Forestry Action Plan, and programs of U.S. AID's Office of Energy and the World Bank's Energy Sector Management Program provides a helpful starting point. A series of international meetings over the last two years have built a consensus that a convention on climate change is desirable, and the Intergovernmental Panel on Climate Change is playing an important role in assessing climate science, the potential impacts of climate change, and the available policy options. U.S. leadership has played, and will continue to play, an essential role.

NOTES

1. U.S. AID procedures for preparing environmental assessments are published in the Code of Federal Regulations, Volume 22, Part 216.

2. Periodic reports on progress implementing the Action Plan are available from the TFAP Coordinator, FAO Forestry Department, Via delle Terme di Caracalla, 00100 Rome, Italy.

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Daniel Lashof, co-editor of *Policy Options for Stabilizir,g Global Climata, Report to Congress* (U.S. Environmental Protection Agency, Washington, D.C., 1991), is now with the Natural Resources Defense Council.

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