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Strategic Studies Staff
Office of Policy and
Resources Management
Washington, DC 20460

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EPA

# Can We Delay A Greenhouse Warming?

COVER—APOLLO 13 VIEW OF EARTH WITH SOUTHWESTERN U.S. AND NORTHERN MEXICO VISIBLE
NASA PHOTO

# CAN WE DELAY A GREENHOUSE WARMING?

## The Effectiveness and Feasibility of Options to Slow a Build-Up of Carbon Dioxide in the Atmosphere

STEPHEN SEIDEL
U.S. Environmental Protection Agency

and

DALE KEYES
Consultant

Strategic Studies Staff
Office of Policy Analysis
Office of Policy and Resources Management
Washington, D.C. 20460

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## EXECUTIVE SUMMARY

Evidence continues to accumulate that increases in atmospheric carbon dioxide ($CO_2$) and other "greenhouse" gases will substantially raise global temperature. While considerable uncertainty exists concerning the rate and ultimate magnitude of such a temperature rise, current estimates suggest that a 2°C (3.6°F) increase could occur by the middle of the next century, and a 5°C (9°F) increase by 2100. Such increases in the span of only a few decades represent an unprecedented rate of atmospheric warming.

Temperature increases are likely to be accompanied by dramatic changes in precipitation and storm patterns and a rise in global average sea level. As a result, agricultural conditions will be significantly altered, environmental and economic systems potentially disrupted, and political institutions stressed.

Responses to the threat of a greenhouse warming are polarized. Many have dismissed it as too speculative or too distant to be of concern. Some assume that technological options will emerge to prevent a warming or, at worst, to ameliorate harmful consequences. Others argue that only an immediate and radical change in the rate of $CO_2$ emissions can avert worldwide catastrophy. The risks are high in pursuing a "wait and see" attitude on one hand, or in acting impulsively on the other.

This study aims to shed light on the debate by evaluating the usefulness of various strategies for slowing or limiting a global warming. Better information is essential if scientific researchers, policymakers, and private sector decisionmakers are to work together effectively in addressing the threat of climate change.

## FOCUS OF STUDY

Because increases in atmospheric $CO_2$ primarily result from the use of fossil fuels, one logical response to the threat of climate change is to reduce global dependence on these energy sources. This study takes a first look at whether specific policies aimed at limiting the use of fossil fuels would prove effective in delaying temperature increases over the next 120 years. Specifically, it examines whether a tax on the use of fossil fuels or a ban on the use of coal, shale oil, or synfuels could be effective in delaying a greenhouse warming. These policies are also evaluated for their economic and political feasibility. To put our findings in perspective, alternative, nonenergy approaches to limiting a greenhouse warming are also reviewed.

## METHODOLOGY

Evaluating the effectiveness of energy policies to reduce levels of $CO_2$ requires the estimation of future patterns of energy use, the effect of these patterns on $CO_2$ emissions, the fate of $CO_2$ once emitted, and the relationship between levels of atmospheric $CO_2$ and temperature. Three models were used in the estimation process:

- a world energy model to project future supply and demand for alternative fuels and to estimate $CO_2$ emissions based on fuel use mixes;
- a carbon cycle model to translate $CO_2$ emissions into increases in atmospheric $CO_2$ concentrations; and
- an atmospheric temperature model to estimate changes in temperature based on increases in atmospheric $CO_2$ and other greenhouse gases.

We used these models to explore a range of possible assumptions about energy demand and technologies, atmospheric responses, and policy alternatives.

We evaluated both medium-run (by the middle of the next century) and long-run (by 2100) effects, placing greater confidence in the shorter run results. The timing of a 2°C rise is employed as the measure of medium-run effectiveness. A temperature increase of this magnitude by mid-century would represent a dramatic departure from historical trends -- a rate of increase equal to roughly 0.3°C per decade, compared with a rise of 0.04°C per decade during the past 100 years. Over the long run, the absolute temperature rise in 2100 is used as the measure of effectiveness. Rough estimates of technical constraints, costs, and the need for political cooperation are used to judge feasibility.

## BASELINE TRENDS

We developed the Mid-range Baseline scenario as a "best guess" of future energy patterns. Under this scenario, atmospheric $CO_2$ levels would reach 590 ppm, or double pre-industrial levels, by 2060, and a 2°C temperature rise would occur around 2040. By 2100, global warming would approach 5°C. These estimates are particularly sensitive to (1) the assumed temperature response to a doubling of $CO_2$, and (2) the rate of increase of greenhouse gases other than $CO_2$ (i.e., methane, nitrous oxide, and chlorofluorocarbons). By varying these factors within reasonable ranges, the projected date of a 2°C warming shifts from roughly 2015 to 2095. In direct contrast, changes in the projected costs of alternative fuels or in fuel users' behavior (i.e., the degree of conservation in response to rising energy prices and other factors) has almost no effect on the estimated timing of a 2°C rise in temperature. Specifically, scenarios reflecting significant reductions in the future cost of nuclear power and renewable energy, increased conservation, and expanded electrification have little influence on the date of a 2°C warming, and only a minor effect on the temperature rise in 2100 (5-10 percent). Similarly, significant reductions in the baseline costs of shale oil or synfuels fail to accelerate a projected 2°C warming, and estimated temperature in 2100 increases by less than 5 percent. These findings attest to the substantial momentum built into temperature trends, due to the effect of other greenhouse gases and to the difficulty in changing fuel-use patterns.

## SUMMARY OF FINDINGS

Our analysis of energy and nonenergy policies to slow or limit a global warming produced the following results:

### Only One of the Energy Policies Significantly Postpones a 2°C Warming

- Worldwide taxes of up to 300% of the cost of fossil fuels (applied proportionately based on $CO_2$ emissions from each fuel) would delay a 2°C warming only about 5 years beyond 2040.
- Fossil fuel taxes applied to just certain countries or applied at a 100% rate would not affect the timing of of a 2°C rise.
- A ban on synfuels and shale oil would delay a 2°C warming by only 5 years.
- Only a ban on coal instituted by 2000, would effectively slow the rate of temperature change and delay a 2°C change until 2055. A ban on both coal and shale oil would delay it an additional 10 years -- until 2065.

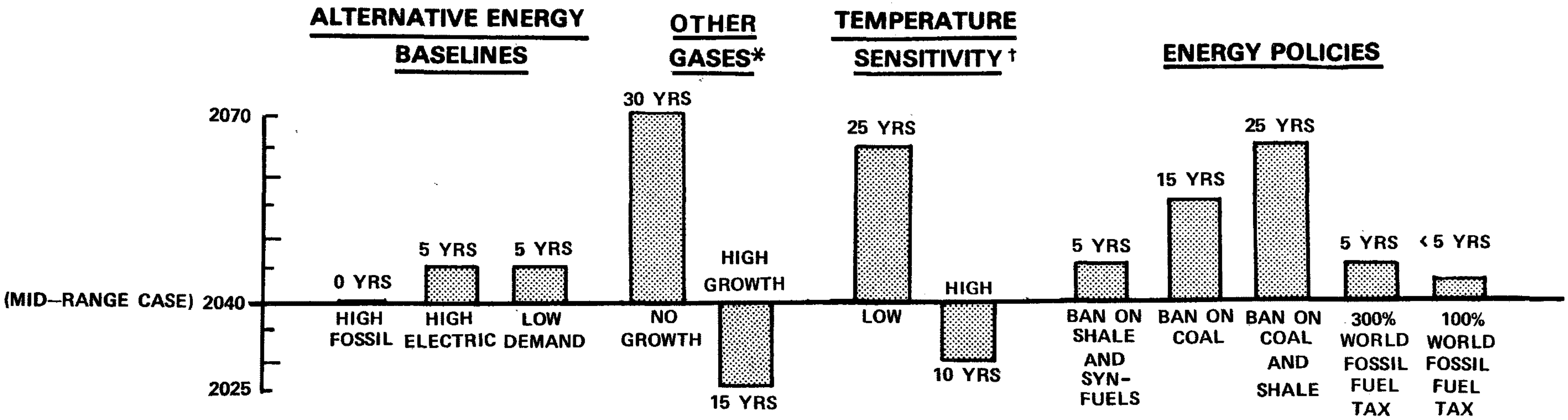
### Major Uncertainties Include Growth of Other Greenhouse Gases and Temperature Sensitivity of the Atmosphere, but Not Baseline Energy Scenarios

- Uncertainties concerning the rate of growth of other greenhouse gases could advance the date of a 2°C warming by 15 years or delay it by 30 years.
- The plausible range of sensitivity of the atmosphere to increases in greenhouse gases creates a 35-year band of uncertainty around the projected year (2040) for a 2°C warming.
- In contrast, alternative energy futures, including significant shifts in the relative costs of fuels, changes in energy demand, and reduced economic growth, cause only minor (i.e., five years or less) changes in the date of a 2°C warming.

These findings are illustrated in the following chart. Each bar represents the number of years the 2°C date is delayed (bar above line) or advanced (bar below line), compared with the Mid-range Baseline projections.

# CHANGES IN THE DATE OF A 2° C WARMING

(PROJECTED DATE IN MID-RANGE BASELINE: 2040)



*REFERS TO GREENHOUSE GASES OTHER THAN $CO_2$: NITROUS OXIDE, METHANE, AND CHLOROFLUOROCARBONS.

†REFERS TO THE TEMPERATURE RISE IN RESPONSE TO A GIVEN INCREASE IN GREENHOUSE GASES ONCE AN EQUILIBRIUM HAS BEEN REACHED.

## Bans on Coal and Shale Oil Are Most Effective in Reducing Temperature Increases in 2100

- A worldwide ban on coal (and thus coal-derived synfuels) instituted by 2000 would reduce temperature change by 30% (from 5°C to 3.5°C).
- Together, a ban on shale oil and coal would reduce the projected warming in 2100 from 5°C to 2.5°C.
- Bans on shale oil alone or synfuels alone would be less effective.
- A 100% worldwide tax would reduce warming by less than 1.0°C in 2100.

## A Ban on Coal Seems Economically and Politically Infeasibile

- Though detailed estimates of total costs of a ban on coal were beyond the scope of this study, initial approximations based only on asset losses and increases in prices of alternative fuels suggest that a coal ban is economically infeasible.
- A worldwide ban on coal also appears to be politically infeasible. Because the burden would be unevenly distributed (e.g., most of the world's coal is concentrated in only three nations, and use of coal varies dramatically between developed and developing nations), worldwide cooperation required to ban coal is unlikely.

## At Best, Nonenergy Options to Limit Global Warming Are Highly Speculative

- Scrubbing $CO_2$ emissions from power plants is of limited effectiveness and prohibitively expensive.
- Capturing ambient $CO_2$ through massive forestation would place too great a burden on land, fertilizer, and irrigation requirements.
- In theory, adding $SO_2$ to the stratosphere might counterbalance the greenhouse warming effect, but at great cost. Moreover, the effectiveness and potential adverse environmental consequences of this proposal require much additional research.

## IMPLICATIONS OF FINDINGS

The implications of our findings point to action directed in the following three areas:

Accelerate and Expand Research on Improving Our Ability to Adapt to a Warmer Climate -- This research should focus on enhancing the positive and minimizing the negative aspects of a greenhouse warming. It should also address problems likely to occur during the transitional stage when social and economic systems are adapted to the consequences of increased $CO_2$ and temperature. A key element of this research must be developing regional climate scenarios that can be used to evaluate the costs and benefits associated with possible changes in climate and that can serve as a baseline against which possible adaptive actions can be evaluated.

Narrow Uncertainties About the Future Effects Greenhouse Gases Other Than $CO_2$ -- Research relating to other greenhouse gases should focus on developing a better understanding of the natural and man-made sources and sinks of these gases, of their interactions with other atmospheric gases, (especially their effects on atmospheric ozone), and of possible strategies to mitigate their influence on future global warming.

Reducing Uncertainty About the Thermal Sensitivity of the Atmosphere -- Narrowing the range of uncertainty regarding the temperature sensitivity of the atmosphere to increases in greenhouse gases will depend on expanded modeling efforts. Cloud formation and ocean systems must be more realistically represented in climate models, and our ability to use these models in predicting transient warming effects must be improved.

Our analysis underscores the need to reduce remaining scientific uncertainties as quickly as possible. Substantial increases in global warming may occur sooner than most of us would like to believe. In the absence of growing international consensus on this subject, it is extremely unlikely that any substantial actions to reduce $CO_2$ emissions could or would be taken unilaterally. Adaptive strategies undertaken by individual countries appear to be a better bet. But for these strategies to succeed, much more precise and detailed information will be needed on the timing and regionally disaggregated consequences of a global warming.

## CHAPTER 1

## $CO_2$ AND THE GREENHOUSE EFFECT: STUDY OVERVIEW

The scientific community is growing increasingly concerned about the build-up of carbon dioxide ($CO_2$) in the atmosphere. Resulting primarily from the use of fossil fuels, $CO_2$ emissions may alter the radiative balance of the earth, increasing global temperature, and dramatically changing global climate. Although much uncertainty remains concerning the magnitude, timing, and possible effects of rising levels of $CO_2$, this issue is considered to be one of the most important facing the scientific community, and one that raises significant questions for policymakers.

This study explores one particularly important aspect of the $CO_2$ issue -- the potential effectiveness and feasibility of alternative public actions aimed at limiting or delaying a $CO_2$-induced rise in temperature. It focuses on policies to reduce the use of fossil fuels, including energy taxes and bans on the use of synfuels, shale oil, and coal. It also reviews other approaches to delaying temperature change. These include removing $CO_2$ from flue gases after fuel combustion, sequestering $CO_2$ from the atmosphere by planting trees, and seeding the atmosphere with $SO_2$ to block incoming solar energy. By providing new information on both energy and nonenergy approaches to modifying the greenhouse effect, we hope to focus current and future discussions on what to do about rising $CO_2$.

## BACKGROUND TO THE GREENHOUSE EFFECT

The "greenhouse theory" -- that increases in $CO_2$ will warm the earth -- was first developed by scientists before the turn of the century (Arrenhius, 1896). This theory holds that certain "greenhouse" gases in the atmosphere allow the sun's ultraviolet and visible radiation to penetrate and warm the earth, but then absorb the infrared energy the earth radiates back into the atmosphere. By blocking the escape of this radiation, these gases effectively form a thermal blanket around the earth. To rebalance the incoming and outgoing radiation, the earth's temperature must increase. Based on the current level of $CO_2$ in the atmosphere, the average global temperature now stands at 288°K, approximately 35°K warmer than it otherwise would be (Chamberlain, et al., 1982).

Carbon dioxide is the principal greenhouse gas. Methane, chlorofluorocarbons, and nitrous oxide, along with water vapor, also exhibit greenhouse properties. Increases in the atmospheric levels of these other trace gases could add significantly to any future $CO_2$-induced global warming.

Since the onset of the industrial revolution, increases in atmospheric $CO_2$ levels have been small, but significant. From 1860 to the present, the concentration of $CO_2$ has grown from about 270-290 parts per million (ppm) to 339 ppm (Keeling, 1982). Our increased reliance on fossil fuels is directly responsible for most of this growth. By burning large quantities of these fuels every year, we are shifting enormous quantities of carbon -- roughly 5 billion metric tons annually -- to the atmosphere from the earth where it had been inactive over millions of years (Rotty, 1983).

## CURRENT UNDERSTANDING OF THE POTENTIAL FOR GLOBAL WARMING

The greenhouse theory assumes that, holding everything else constant, altering the composition of the atmosphere by adding large quantities of $CO_2$ and other greenhouse gases will warm the earth. While the physical laws underlying the theory are well established and straightforward, the assumption that all else will remain constant is not reasonable.

The global climatic system is extremely complex. It consists of many interrelated components that, in themselves, are only partially understood. Changing one of these components -- in this case, increasing the quantity of atmospheric greenhouse gases -- will undoubtably have repercussions throughout the natural systems that determine global climate.

To identify the extent to which increases in $CO_2$ would raise atmospheric temperature or, conversely, to isolate the nature and magnitude of countervailing forces, the National Academy of Sciences (NAS) convened a study panel chaired by Dr. Jule Charney in 1979. After reviewing the existing scientific evidence, this panel concluded that a doubling of pre-industrial atmospheric $CO_2$ levels would most likely increase global climate $3.0 \pm 1.5°C$

(Charney, 1979).* Recognizing that these findings would be "comforting to scientists but disturbing to policymakers," the panel further stated:

> To summarize, we have tried but have been unable to find any overlooked or underestimated physical effects that could reduce the current estimated global warmings... to negligible proportions or reverse them altogether.... It appears that the warming will eventually occur.... (Charney, 1979)

A second NAS panel, convened in 1982, reexamined these conclusions in light of more recent research. It concluded: "The present study has not found any new results that necessitate substantial revision of the conclusions of the Charney report" (Smagorinsky, 1982).**

Several investigators have projected that $CO_2$ will double by the middle of the next century (e.g., Anderer, 1981; Nordhaus, 1977). When viewed in the context of historical changes in temperature, the projected temperature rise must be considered substantial.

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* The NAS panel examined increases in temperature due only to $CO_2$. Other greenhouse gases could further increase global warming by 50% - 100% (see Chapter 2).

** Despite reaffirming the first panel's conclusions, considerable uncertainty remains. For example, while the second panel agreed that a temperature rise of $3.0 \pm 1.5$°C is the most likely response to a doubling of $CO_2$, it hedged this projection with a footnote that the first panel intended the true value would fall within this range with only a 50% probability.

Temperature changes of 5.0°C cover the entire temperature range experienced during the past 125,000 years, which extend from the last interglacial period to the present one (Mitchell, 1977). The projected warming induced by increases in $CO_2$ thus could equal historical changes in climate in a matter of only 120 years.

The possible magnitude of temperature change tells only part of the story. The rapid occurrence of this change must be emphasized to more clearly put it in historical perspective. Although the earth has experienced significant changes in temperature, they generally have occurred over tens of thousands of years and must be viewed in terms of geologic time, instead of the several decades during which an equivalent $CO_2$-induced warming is likely to occur. As a result, we will soon experience climatic trends that significantly deviate from the past (see Figure 1-1).

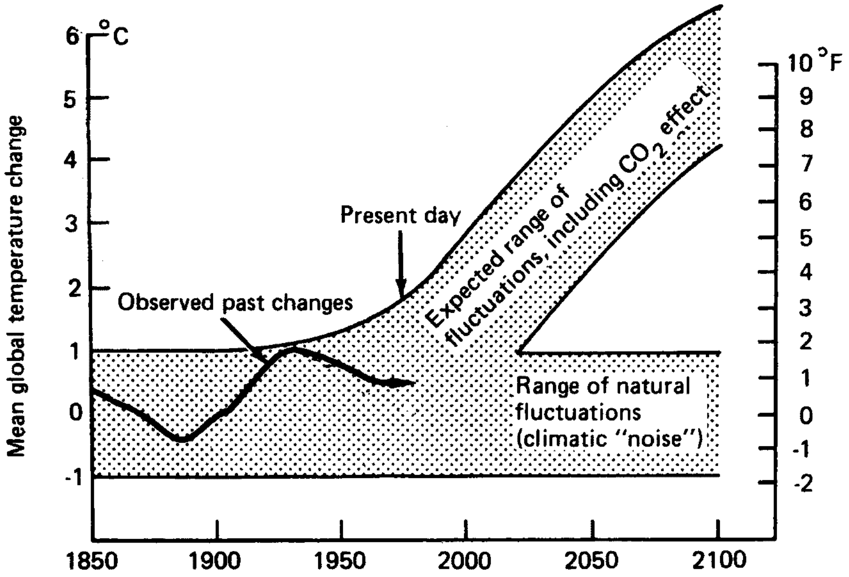
Chapter 2 of this report explains in greater detail the scientific basis and uncertainties surrounding projections of a greenhouse warming.

## IMPLICATIONS OF THE GREENHOUSE EFFECT

Warmer global temperatures are just one aspect of $CO_2$-induced changes to the natural environment. A rise in sea level, changes in precipitation and water availability, altered storm patterns and frequencies, and changes in growing seasons are all significant climatic events likely to accompany a greenhouse warming. Many parts of the world are likely to suffer from these changes, yet others are likely to benefit.

FIGURE 1-1

RANGE OF GLOBAL-SCALE MEAN TEMPERATURE, WITH AND WITHOUT THE PROJECTED $CO_2$ EFFECT



Source: CEQ (1981). Based on J.M. Mitchell, Jr., (1977) "Some Considerations of Climate Variability in the Context of Future $CO_2$ Effects on Global-Scale Climate," in Elliot and Machta, Carbon Dioxide Effects Research and Assessment Program: Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels.

Given the limited knowledge of specific regional effects resulting from higher levels of $CO_2$, it is now impossible to predict the net effect of such changes. Moreover, the analysis of ultimate effects must also account for difficulties encountered during the transitional period when climate is changing, and for the possibility that some negative effects will be mitigated, depending on the success and speed of efforts to adapt economic activity to altered climatic conditions.

## POSSIBLE ADVERSE CONSEQUENCES

A warmer climate could dramatically change existing ecosystems, affect the habitability of many areas of the world, and alter the relationship between developed and developing nations. Adverse impacts will result primarily from increases in temperature, changes in precipitation, changes in storm patterns, and increases in sea level.

A warmer climate will raise sea level by warming and expanding the oceans, and by melting ice and snow now on land. By itself, thermal expansion could raise sea level significantly. Further in the future, this rise may be enhanced by significant ice melting and discharges from land-based glaciers. Given current uncertainties, an initial effort to estimate the range of possible sea level rise concluded that increases of anywhere from about 48 to 380 cm (2 to 12 ft.) are possible in the next 120 years (Hoffman, 1983). An increase of of even 48 cm could flood or cause storm damage to many of the major ports of the world, disrupt transportation networks, alter aquatic ecosystems, and cause major shifts in land development patterns.

The consequences of climate change will differ depending on whether or not adjustments are feasible. For example, changes in climate will require significant adjustments in agricultural practices (e.g., breeding new strains of seeds adapted to changed $CO_2$ levels and climate) and in land-use patterns (e.g., shifting away from coastal areas). To the extent that these adjustments are made in a timely manner, many of the adverse consequences of a $CO_2$ warming can be minimized. In other situations, however, adjustments simply may not be feasible and a total loss may result. For example, despite adjustments to agricultural practices, some currently productive land may no longer be suitable for farming because of significant changes in the length of the growing season or in rainfall patterns. Similarly, if water resource planning does not anticipate shifts in rainfall patterns, water shortages could reach catastrophic proportions.

Recent changes in weather conditions experienced throughout many parts of the world (attributed by some to the El Nino meteorologic phenomenon) give some indication of the economic and social consequences of dramatic shifts in climate. Initial estimates place damages due to droughts and floods at over $8 billion and deaths at over 1,000 (Washington Post, 1983).

## POSSIBLE BENEFICIAL CONSEQUENCES

In contrast to these negative effects, increases in atmospheric $CO_2$ are likely to enhance photosynthesis and decrease moisture requirements for plant growth -- both of which should increase agricultural productivity. A global warming could also improve climate for high latitude areas, increase precipitation for some parts of the world, and reduce heating costs worldwide.

To a limited extent, these altered conditions, by themselves, will enhance certain economic activities. For example, without any changes in agricultural practices, higher $CO_2$ levels will enhance the productivity of many crops. However, some plants will respond to this stimulus more than others. Only by taking steps to identify and expand the use of those plants that benefit the most will nations be able to maximize the advantages of higher levels of $CO_2$.

## NET EFFECTS AND TRANSITIONAL PROBLEMS

Even areas that directly benefit from or that ultimately adapt to altered conditions may experience difficulties redirecting their economies to meet the challenges of rapidly changing climatic conditions. Decisions concerning agricultural practices, land-use patterns, and coastal structures often assume that climatic conditions will be roughly the same as in the past. For example, many decisions about tree selection, road and bridge construction, and coastal development have been based on a continuation of historical climate trends during the useful life of these activities, which is 50 years or more. Future damages can be minimized only if these assumptions are changed for the next generation of decisions. Of course, the precision and detail of the predictions of climatic change must be greatly improved if they are to be used in public works and resource planning.

Whether an individual country benefits or is harmed will depend on its location, its resource and industrial base, and, most importantly, its ability to prepare and adapt to changing climatic conditions. If climate dramatically changes, it will likely affect nearly the entire range of human activity. The magnitude of these effects, and whether they are positive or negative, depends to a large extent on how quickly these changes occur -- or on our ability to delay climatic change -- and how successfully global society anticipates and adjusts to them.

## DEFINING THE APPROPRIATE RESPONSE

Given the potential magnitude of the $CO_2$ problem, it is not surprising that many have raised the question: What can be done? Are there steps that we can and should take to prevent $CO_2$ from rising to some unacceptable level? Or, instead, should we explore actions aimed at minimizing the costs of adapting to $CO_2$-induced changes? In either case, how soon do we have to act?

While there are no simple answers to these questions, a growing body of experts is calling for action now. For example, in its 1979 report, the National Academy of Sciences warned against further delay in responding to the $CO_2$ problem -- "A wait and see attitude may mean waiting until it's too late" (Charney, 1979).

Along similar lines, a report by the President's Council on Environment Quality concluded: "If a global response to the $CO_2$ problem is postponed for a significant time, there may not be time to avoid substantial economic, social, and environmental disruptions once a $CO_2$-induced warming trend is detected" (CEQ, 1981).

Calls for an immediate response have also been voiced at Congressional hearings, in newspaper editorials, and in news magazines across the nation. Such calls for action are not surprising, given the magnitude of the potential climatic changes that might accompany further increases in atmospheric $CO_2$. In the minds of many, concern about these changes far outweighs remaining uncertainties surrounding their exact nature and timing.

Two very different strategies could be employed to respond to this call for action.* The first approach is an adaptive strategy. Rather than seeking to limit $CO_2$ increases, it focuses

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* For another discussion of these strategies, compare "Reduction at the Source," Scroggin and Harris, and "A More Feasible Soical Response," Lave, both in Technology Review, Nov./Dec. 1981.

on steps that would minimize the negative and maximize the positive effects of $CO_2$. For example, land development would be directed in-land to avoid damage from the rise in sea level, and agricultural practices would be shifted to take advantage of increases in photosynthesis.

In contrast, a prevention strategy seeks to delay or limit the build-up of greenhouse gases in the atmosphere. Since $CO_2$ results primarily from the burning of fossil fuels, this strategy necessarily implies a shift in current patterns of energy use.

These two alternatives are, of course, not mutually exclusive. By limiting use of fossil fuels and, slowing the rise of $CO_2$, we would be buying more time to design and implement adaptive actions.

Given the large uncertainty in projecting likely climatic changes and resulting socioeconomic effects, any comparison of the costs and benefits of these alternative approaches would now be little more than guesswork. Although researchers have called for development and evaluation of regional scale scenarios that could be used for analyzing the impacts of $CO_2$, with few exceptions, these projects remain as items on future research agendas (Kellogg, 1981). Only after initial estimates are developed of the economic effects of rising $CO_2$ levels will researchers be able to quantitatively compare the desirability of adaptive versus preventive approaches to dealing with the $CO_2$ problem.

Nevertheless, by focusing specifically on the potential effectiveness of alternative policy actions aimed at delaying or limiting a rise in atmospheric $CO_2$ levels, we can provide useful insights into whether "adaptation or prevention" or some combination thereof is the appropriate response. This study contributes to that goal.

## EVALUATING THE PREVENTION STRATEGY

Two general approaches to slowing or limiting $CO_2$ increases have been mentioned -- one that relies on altering patterns of energy use, and one that employs nonenergy strategies. The first approach attempts to mitigate the $CO_2$ problem indirectly. Burning less coal, oil, and gas, would slow the rate of increase in $CO_2$ emissions. Shifting away from fossil fuels, however, would entail a radical change in the energy foundation upon which current economic activity rests. Under the second approach, $CO_2$ is captured either before or after emission to the atmosphere (i.e., removed from flue gases using scrubbers or sequestered from the ambient air using trees), or the amount of incoming solar radiation absorbed by the earth is reduced via novel schemes. Chapter 6 of this analysis examines the effectiveness, costs, and feasibility of these options.

Altering fuel-use patterns has been the most commonly discussed approach to preventing a global warming. However, such an approach carries with it several potentially severe effects.

These include:

- reducing the value of the vast global fossil fuel resources;
- making prematurely obsolete some portion of the capital infrastructure that supports current patterns of production, transportation, and use of fossil fuels; and
- increasing the percentage of total capital invested in the energy sector to pay for more expensive energy alternatives.

The magnitude of these economic disruptions would depend on how rapidly alternative energy sources must substitute for fossil fuels. The acceleration of the rate at which fossil fuels are displaced will, in turn, depend on the shift to nonfossil fuels due to market forces alone, and on the rate of acceptable climatic change. Furthermore, the shift away from fossil fuels perhaps could be instituted more gradually and therefore less expensively if energy policies were adopted now rather than several decades later.

## METHODOLOGICAL APPROACH

Determining the effectiveness and feasibility of shifting energy consumption to prevent or limit a rise in temperature involves modeling the complex interaction among energy technologies and resources, world economies, the carbon cycle, and atmospheric physics. For this analysis we used three models: the world energy model of the Institute for Energy Analysis, the carbon cycle model of the Oak Ridge National Laboratory, and the atmospheric temperature model of the Goddard Institute for

Space Studies. By integrating these models, we developed a method for (1) estimating the likely global warming for a range of alternative energy futures, and (2) evaluating the effectiveness of alternative policies to delay or limit that warming. Chapter 3 explains each of these models and their underlying assumptions in greater detail.

We evaluated the nonenergy strategies less rigorously, although still quantitatively. Using simple conceptual models and extrapolating from literature reports, we made first-order estimates of the effectiveness and feasibility of each of the three strategies.

## BASELINE SCENARIOS

The energy scenarios examined as part of this study start with a baseline that assumes mid-range estimates for alternative fuel costs, economic growth, and other key parameters. In addition, alternative future scenarios examine $CO_2$ and temperature changes that would result if the costs of nonfossil alternatives (e.g., nuclear or solar) prove to be lower than expected, if projections of energy conservation or future energy demand prove to be high, or if, on the other hand, mid-range estimates of the costs of new fossil fuel technologies prove to be low. Together, these alternative baselines provide a range of possible energy futures against which various policies aimed at reducing fossil fuel use can be examined.

## POLICY OPTIONS

Two basic energy policy options are examined in Chapter 4 of this study:

- fossil fuel taxes based on the relative quantity of carbon emissions from each energy source; and
- bans on future worldwide consumption of coal, synfuels, and shale oil in various combinations.

The $CO_2$ tax option is first applied to the United States to determine the effects of unilateral actions, next to OECD countries, and finally on a global-scale to determine the need for international cooperation. All fuel ban policies are applied worldwide.

Chapter 5 discusses the nonenergy policy options for mitigating a greenhouse warming: $CO_2$ emission controls, forestation programs for sequestering atmospheric $CO_2$, and injecting $SO_2$ into the stratosphere to increase atmospheric reflectivity. Each option is assessed for effectiveness and feasibility.

## MEASURES OF EFFECTIVENESS

The effectiveness of each energy policy option is measured in terms of delaying or limiting temperature increases. If a policy is not effective, costs and future feasibility are of little significance.

The primary measure of effectiveness is the number of years a particular option delays a temperature increase of 2°C. A 2°C temperature rise was selected because it represents a global warming significantly beyond the historical change for any 120 year period, and one guaranteed to produce substantial climatic consequences. As noted earlier in this chapter, 2°C is significant in comparison with temperature changes that produced ice ages. Moreover, a 2°C change by the middle of the 21st century would produce an average warming of about 0.3°C per decade. During the past 100 years, the average change has been only 0.04°C per decade. In addition, temperature serves as a useful indicator of changes in overall climatic conditions (e.g., storm frequency, precipitation, wind direction), which are largely determined by spatial temperature gradients.

A secondary measure of effectiveness is how much the estimated temperature in the year 2100 is lowered. Because these estimates span a far longer time frame, the conclusions they support are substantially more speculative than conclusions based on a 2°C temperature change.

Earlier studies examining possible options to reduce the rise in $CO_2$ focused primarily on the steps necessary to prevent a doubling of pre-industrial levels of atmospheric $CO_2$ (Nordhaus, 1977). In addition, most climate models have been employed to estimate the temperature effects of doubled atmospheric $CO_2$. The different focus here -- the timing of a 2°C temperature change rather than a doubling in $CO_2$ -- offers several advantages. First, it allows other greenhouse gases and their effects on temperature to be considered as part of the analysis. Second, it allows the range of current uncertainty in predicting temperature change (3.0 ± 1.5°C) for doubled $CO_2$ levels to be incorporated into the analysis. Third, it highlights the significance of time lags between $CO_2$ and temperature rises. Finally, it shifts attention away from what has become simply a convenient convention for analysts to a more meaningful measure of the greenhouse effect -- global temperature.

Measures of effectiveness employed in the analysis of non-energy strategies are less specific, largely because our findings are extrapolated from other studies. In general, we compared either projected annual reductions in $CO_2$ with current emission rates, or projected reductions in temperature with expected $CO_2$-induced increases.

## MEASURES OF FEASIBILITY

If a policy is to prove desirable, it must be technologically, economically, and politically feasible, in addition to being effective. Unlike effectiveness, no simple and direct measure exists to determine the feasibility of the policy options examined in this study. The world energy model used in the study does not contain a sophisticated enough structure of regional economies nor complete enough representation of cost factors in the energy sector to provide a reliable basis for evaluating economic feasibility. In addition, considerations of international cooperation fall far beyond the model's scope to support an evaluation of political feasibility. As an alternative analytical approach, Chapter 6 of this study uses a series of examples to illustrate the potential economic and political ramifications of adopting policies that limit fossil fuel use.

## FINDINGS AND CONCLUSIONS

Finally, Chapter 7 brings together the previous discussions of effectiveness and feasibility and presents a summary of findings and conclusions. It also highlights critical uncertainties and areas for future analysis.

# CHAPTER 2

# SCIENTIFIC BASIS FOR A GREENHOUSE WARMING

This chapter discusses the scientific evidence linking increases in carbon dioxide and other greenhouse gases to climatic change. Although many aspects of this linkage need to be further resolved and clarified, much is now known from past and ongoing research efforts.

## ROLE OF GREENHOUSE GASES

The temperature of the earth is determined by a balance between the radiation it absorbs and emits. By reflecting or absorbing and then reradiating certain wavelengths of the sun's radiation as it enters the atmosphere, some atmospheric constituents reduce the amount of energy reaching the earth's surface and thus decrease global temperature. Volcanic aerosols and certain forms of particulate matter are examples of atmospheric components with these characteristics.

Other atmospheric components, commonly referred to as greenhouse gases, have the opposite effect. These gases allow visible and ultraviolet radiation from the sun to penetrate to the planet's surface, but absorb some of the infrared energy that is reradiated from the earth. In a sense, greenhouse gases form a "thermal blanket" around the earth. As these gases increase in concentration, incoming radiation temporarily exceeds that leaving the earth. In reestablishing a radiation balance, the earth-atmosphere system increases in temperature.

Several gases found in the atmosphere exhibit the properties of a greenhouse gas. Carbon dioxide is the most abundant and best known. Other potentially significant greenhouse gases include methane, nitrous oxide, and chlorofluorocarbons. In addition, water vapor demonstrates a sizable greenhouse effect. Thus, increasing levels of water vapor from evaporation and melting, which will accompany a $CO_2$-induced global warming, further enhance the greenhouse effect.

Because of the complexity of the natural systems involved, experiments to further test and clarify the greenhouse effect are not feasible. In fact, the only meaningful field experiment that could be conducted is the uncontrolled one now taking place as we burn large quantities of fossil fuels. The nature of this experiment was best expressed in an early article written by Revelle and Suess in 1957:

> ....Human beings are now carrying out a large-scale geophyscial experiment of a kind that could not have happened in the past, nor be repeated in the future.... The experiment, if adequately documented, may yield a far-reaching insight into processes determining weather and climate....

The challenge facing researchers and policymakers today is to determine a course of action in which we maintain the flexibility to respond in a timely and effective manner as this ongoing experiment unfolds.

There are, however, at least two approaches to obtaining insights into how increases in greenhouse gases might affect atmospheric temperature and climate. First, we can investigate the relationship between the chemical composition and temperature of the atmosphere surrounding different planets for clues of how greenhouse gases influence temperature. Second, global climate models can be manipulated to simulate the climate of a world with higher levels of atmospheric $CO_2$.

## COMPARISONS WITH OTHER PLANETS

Recent space probes to other planets have provided information on atmospheric composition and temperature that substantiates the greenhouse theory. From them, we have learned that the atmosphere of Venus is composed of approximately 97 percent carbon dioxide, and its surface temperature is about 700°K. In contrast, the atmosphere of Mars contains only a small amount of $CO_2$ and therefore does not block the escape of infrared radiation. Its temperature is approximately 220°K. The earth's atmosphere contains about 0.03 percent $CO_2$ (and more water vapor than Venus or Mars),and its observed temperature is 288°K.

Taking into account differences in solar radiation received by these planets and differences in their albedos (i.e., ground and cloud cover, which influences the reflectivity of the planet's surface), their estimated surface temperatures based on the hypothesized effects of greenhouse gases are very close to observed values. Although this analysis by analogy falls far short of verifying estimates of future atmospheric warming on earth, it does provide fundamental evidence supporting the validity of the greenhouse theory.

## EVIDENCE FROM CLIMATE MODELS

Efforts are now under way to better understand the relationship between atmospheric composition and temperature on our planet. The principal approach involves developing mathematical models of the geophysical conditions that produce global climate. To various degrees of complexity, these models simulate radiation from the sun as it penetrates the various layers of the atmosphere, the distribution of energy over the earth's surface, the radiative effects of greenhouse gases, the effect of the earth's albedo, reradiation of energy from the earth back into the atmosphere, and the flux of heat from the atmosphere to the earth and into the oceans -- all of which interact to produce circulation and climate patterns within our atmosphere.

In effect, the more elaborate three dimensional general circulation models (GCMs) represent, in simplified mathematical form, the physical processes that combine to create short-term weather patterns. These patterns, over time, produce climate. The most advanced of these models provide output for time intervals as short as 15 minutes and for relatively small areas (thousands of square kilometers). In contrast, relatively simple one-dimensional radiative-convective models (referred to as 1-D RC models) can be used to calculate long-term trends in globally averaged temperature changes.

Despite the complexity of the tasks, climate models have demonstrated considerable accuracy. For example, a National Academy of Sciences (NAS) review of these models concluded that attempts at recreating existing climate patterns have produced "a reasonably satisfactory simulation of the present large-scale climate and its average seasonal variation" (Smagorinsky, 1982). In addition, consistency has been demonstrated both among different GCMs, and between GCMs and 1-D RC models. These models have also successfully recreated past climates.

In 1979, and again in 1982, NAS reviewed the state-of-the-art in climate modeling. It concluded that temperature could rise 3.0 ± 1.5°C for a doubling of preindustrial atmospheric $CO_2$ levels (Charney, 1979; Smagorinsky, 1982). These conclusions were based, in part, on the experimental results of two GCMs that predicted a 2°C change (Manabe, 1980) and close to a 4°C increase (Hansen, 1983) with a doubling of $CO_2$.

The differences in these results can be explained by examining how each of the models treats various components and feedbacks of the climate system. Specifically, the Hansen model shows a small increase in mean cloud height and a slight decrease in cloud cover for runs with doubled $CO_2$. Both of these feedbacks increase convective warming, and in so doing increase temperature approximately 1.3°C. In contrast, the Manabe model holds cloud altitude and cover constant. The two models also differ in their treatment of heat transport by the oceans and changes in sea ice.

Climate models provide an essential analytical tool for understanding the potential changes in climate brought about by increases in greenhouse gases. Their usefulness is likely to increase over time as the models are further refined and as existing uncertainties are reduced. Critical areas requiring more sophisticated treatment include the storage and transport of heat by the oceans, the role of clouds in determining climate, and possible changes to clouds as the earth warms. To improve these components of climate models, additional observational efforts will be required to close existing gaps in data bases.

The deficiencies in and disagreements among climate models described above should not obscure the large amount of useful information and the extent of agreement that exists in this field. In the absence of unambiguous empirical evidence of the relationship between atmospheric $CO_2$ and temperature, climate models provide the next best tool for characterizing this relationship.

## TIMING OF TEMPERATURE RISE

To date, GCMs have not been used to estimate the timing of global warming or climatic change. Instead, these models have been run assuming that atmospheric levels of $CO_2$ have doubled and that temperature has reached its equilibrium level.

The actual nature of the warming process will be quite different. Additional emissions of $CO_2$ will cause atmospheric concentrations of this gas to increase gradually and continually.

Futhermore, due to the capacity of the ocean to absorb and distribute the heat produced by the greenhouse effect, temperature rises should lag $CO_2$ increases by several decades (Smagorinsky, 1982). A proper accounting of the transitional period, as $CO_2$ levels increases, must consider nonequilibrium conditions and time lags due to the carbon cycle and heat exchange processes.

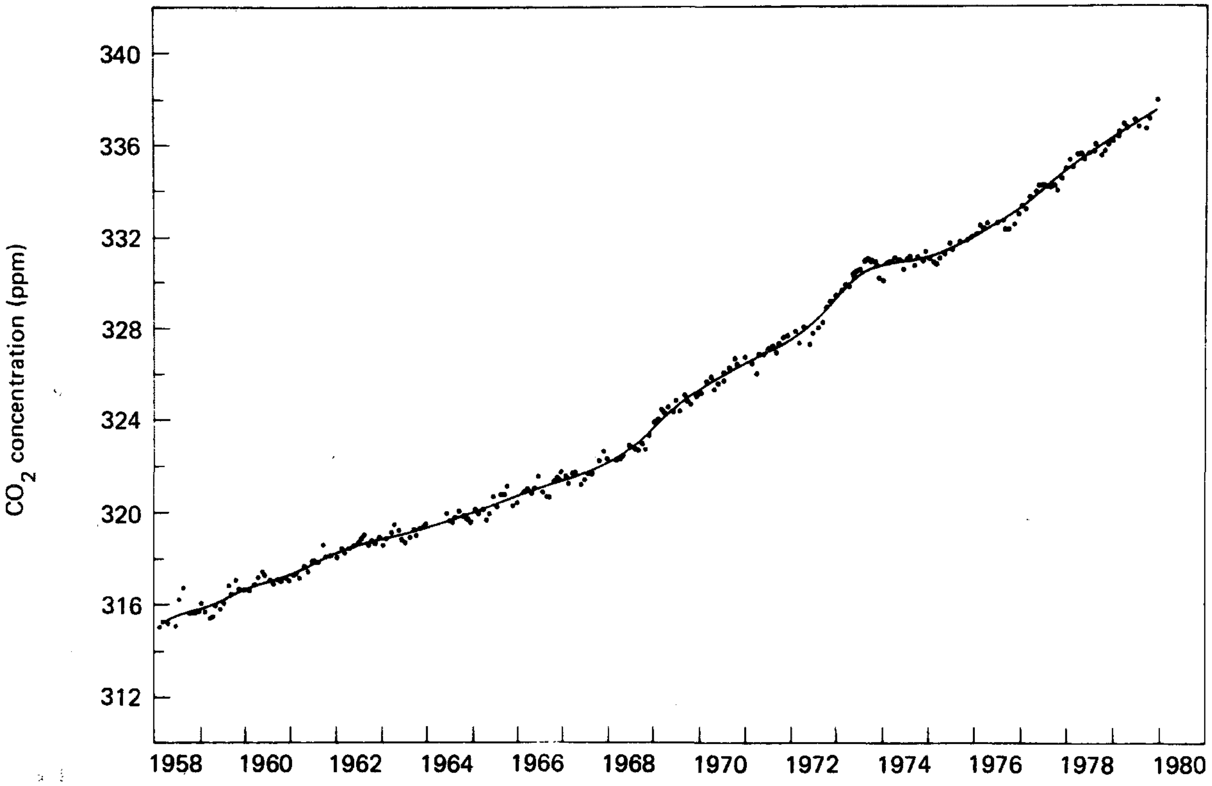
## THE ORIGIN AND EXCHANGE OF $CO_2$ IN THE ENVIRONMENT

Unlike the uncertainty surrounding climate model estimates, the trend in atmospheric $CO_2$ levels since the Industrial Revolution is well documented. Around 1890, at the beginning of the industrial period, atmospheric concentrations are estimated to have been in the 280 to 290 ppm range (Barnola, 1983). Precise measurements of atmospheric $CO_2$ were initiated at Mauna Loa, Hawaii, in 1958 (see Figure 2-1). At that time, these readings registered $CO_2$ levels of 315 ppm or approximately a 12.5 percent increase since the 1890s.

The most recent readings place $CO_2$ levels at 339 ppm, an additional 7 percent increase in just over 20 years (Keeling, 1982). This increase is due in large part to the approximately 160 gigations of $CO_2$ emitted from fossil fuel consumption since 1900 (Rotty, 1983). Although not all of those emissions have remained in the atmosphere -- considerable controversy surrounds this question -- a large percentage has.

FIGURE 2-1

MONTHLY ATMOSPHERIC CARBON DIOXIDE CONCENTRATION AT MAUNA LOA OBSERVATORY*



*Seasonal effects have been normalized.

Source: CEQ (1981), based on data derived from Keeling, Scripps Institute of Oceanography.

## THE CARBON CYCLE: PAST, PRESENT AND FUTURE

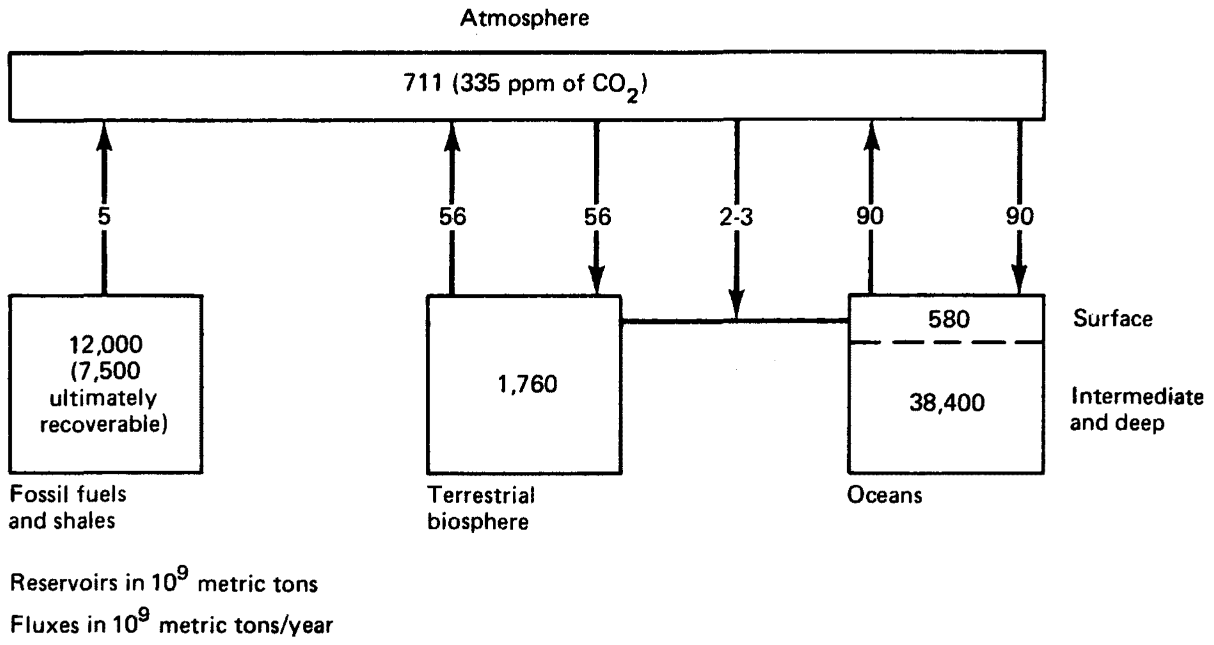
Figure 2-2 depicts the stocks of carbon in each natural reservoir and the annual flows that take place among reservoirs. Taken together, these stocks and flows constitute the carbon cycle. Carbon distributed through this cycle plays an important role in the ecological balance of the atmosphere, biosphere, and oceans.

Fossil fuels are merely preserved forms of carbon (and other elements) previously created in the biosphere. Thus, burning fossil fuels simply redistributes carbon from one reservoir to another. In effect, however, it represents a substantial new flow due to man's activities alone. Carbon stored over hundreds of thousands of years in fossilized forms may be released into the atmosphere in a matter of a few centuries.

Carbon also enters the atmosphere through deforestation. Exact estimates of the magnitude of the flow vary because of a lack of consensus regarding the amount of carbon stored in the soil and rivers, and the countervailing rates of deforestation and reforestation. Early estimates suggested that changes in land-use patterns released as much as 20 gigatons of carbon annually during this century (Woodwell, 1978). Recent estimates have lowered that figure considerably, with some researchers now suggesting that changes in land use offset each other (deforestation and reforestation), resulting in no net increase in atmospheric carbon (Olson, 1982).

FIGURE 2-2

EXCHANGEABLE CARBON RESERVOIRS AND FLUXES



Source: CEQ (1981), as shown in World Meteorological Society, "Report of the Scientific Workshop on $CO_2$," Report 474, Geneva 1977.

## FRACTION OF $CO_2$ FROM FOSSIL FUELS THAT REMAINS AIRBORNE

The amount of carbon emitted from fossil fuels retained in the atmosphere is critically important to the pace and magnitude of global warming. This percentage is called the airborne fraction or retention ratio. If the airborne fraction is high, more $CO_2$ emitted into the atmosphere will remain there, and climatic change is likely to occur sooner than if it is low. Scientists have used recent data on worldwide fuel usage, rates of deforestation and reforestation, and increases in atmospheric $CO_2$ to obtain an estimate of 0.4-0.6 for the historic airborne fraction (Clarke, 1982).*

In the future, an increasing percentage of $CO_2$ from fossil fuel emissions is likely to remain in the atmosphere. This is based on the belief that the top layers of the ocean, which serve as the primary repository of carbon not retained in the atmosphere, will become saturated. Moreover, as temperatures rise, the capacity of the ocean to absorb $CO_2$ is diminished. On the other hand, rising $CO_2$ may stimulate plant growth thus enhancing the biosphere's carbon retention capacity.

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* Considerable uncertainity exists concerning the historic atmospheric levels of $CO_2$. Researchers are unsure of the contribu- of past deforestation. To the extent that deforestation has been significant, its contribution to airborne $CO_2$ would be higher than previously estimated, and the fraction of fossil fuel emissions retained in the atmosphere consequently lower.

Given these uncertainties, one recent estimate of the likely future airborne fraction concluded that it would fall somewhere within the 0.38 - 0.72 range. If existing carbon cycle models are accurate, the actual fraction is likely to be closer to the higher level of that range (Oeschger, 1983).

## INCREASES IN OTHER GREENHOUSE GASES

Human activities may also be responsible for increasing the atmospheric content of other greenhouse gases. These gases are principally nitrous oxide, methane, and chlorofluorocarbons. Although they have generally received less attention and are present in the atmosphere in smaller concentrations than $CO_2$ (and are sometimes called "trace gases"), their increase may contribute significantly to global warming.

### NITROUS OXIDE

Nitrous oxide ($N_2O$) emissions result primarily from biological dentrification processes in soil and in the oceans. By increasing the use of nitrogen fertilizers and by adding nitrogen-rich sewage to water bodies, we are indirectly adding nitrous oxide to the atmosphere. Measurements of $N_2O$ concentrations from 1970 to 1980 show an increase of 6 parts per billion (ppb) to a level of 295 ppb (Lacis, 1981). Estimates suggest that a doubling of nitrous oxide would directly increase temperature by 0.30-0.44°C (Donner and Ramanathan, 1980; Wang and Sze, 1980).

In addition, increases in $N_2O$ may indirectly contribute to an even greater warming. Through various reactions with other gases in the atmosphere, greater amounts of $N_2O$ may lead to higher levels of ozone in the lower stratosphere and upper troposphere. Wang and Sze have calculated that the resulting indirect greenhouse warming could raise temperature another 0.18°C for a total increase of 0.48-0.62°C due to a doubling of $N_2O$ (Wang and Sze, 1980).

As greater demands are placed on world food supplies, increased use of nitrous oxide-producing fertilizers is likely. However, because the natural sources and sinks of this trace gas are not well understood, more research is required before reliable projections can be made of future levels.

### METHANE

Methane ($CH_4$), is a second important trace greenhouse gas. The known sources of $CH_4$ are anaerobic fermentation in rice fields and swamps, and enteric fermentation from termites, cows, and other animals. As the need for food from livestock and rice fields increases over time, atmospheric levels of $CH_4$ are likely to increase. In addition, increases in carbon monoxide (from fuel combustion) in the troposphere will lower the concentration of compounds that destroy methane. Based on current estimates of a 2 percent per year increase in concentration, by the middle of the next century $CH_4$ could increase global warming by about 0.2-0.3°C (Lacis, 1981).

Future increases in methane could, however, be far higher than the estimated 2 percent per year of the recent past. As the earth warms, extensive peat bogs containing as much as 2000 gigatons of $CH_4$ in the form of methane hydrates now frozen in northern latitudes may thaw, releasing considerable quantities of this gas into the atmosphere. While much of this methane is buried 250-1,000 meters under the ground and therefore, unlikely to be released for several centuries, a contribution of eight gigatons per year from methane hydrates under shallow water is possible within the next 100 years (Bell, 1982).

### CHLOROFLUOROCARBONS

Entirely a product of human activity, chlorofluorocarbons have only recently appeared in significant quantities in the atmosphere. Although the shift away from gas-propelled spray cans in many countries reduced one important source of CFCs, they are still used in refrigeration equipment and insulated packaging materials.

Based on the known rates at which CFCs are destroyed in the stratosphere, one study estimated that the direct effects of CFCs should increase temperature by approximately 0.3°C if annual production were maintained at 1973 levels (Wang and Pinto, 1980). This estimate is probably high, since CFCs reduce the concentration of ozone, another greenhouse gas. On the other hand, future emissions of CFCs may be higher or lower than 1973 levels depending on the effects of the U.S. ban on aerosol propellants, and the extent to which a ban is applied to other uses and in other countries.

## COMBINED TEMPERATURE EFFECTS: 1970-80

Researchers at the Goddard Institute for Space Studies used a one-dimensional radiative-convective model to estimate the temperature increase from the rise in $CO_2$ and other greenhouse gases during the 1970s. They assumed the temperature rise for a $CO_2$ doubling was 2.8°C. For this ten-year period, they found that temperature increased a total of 0.24°C. Of that increase, 0.14°C was attributed to a 12-ppm rise in $CO_2$.

The researchers attributed the remaining 0.10°C to the other greenhouse gases ($N_2O$, $CH_4$, and CFCs) included in their analysis. Given the uncertainties in their analysis, they concluded that the other greenhouse gases were responsible for an additional 50-100 percent of the temperature rise which resulted from increases in atmospheric $CO_2$ alone (Lacis, 1981). (See Figure 2-3.) Other investigators have reached similar conclusions (Ramanathan, 1980; MacDonald, 1982; and Chamberlain, 1982).

## POSSIBLE EFFECTS OF A WARMER EARTH

If climate models prove accurate, changes in world climate are likely to occur at an unprecedented rate. All human activities are likely to be in some way affected. Farming, transportation, coastal habitation, and the provision of water supplies are the most obvious. Some nations are likely to benefit from changes in climate; others will suffer. The same dichotomy will generally be true for areas within countries.

However, even the areas that will benefit from changes in climate may experience difficulties during a transitional period. For example, if precipitation were to increase in the Colorado Basin, the Southwest would certainly benefit in the long run. But, these benefits could only be fully realized if water storage and control facilities were constructed to accommodate different monthly patterns of precipitation and runoff. The 1983 flooding and resulting economic losses in the Colorado Basin are a case in point.

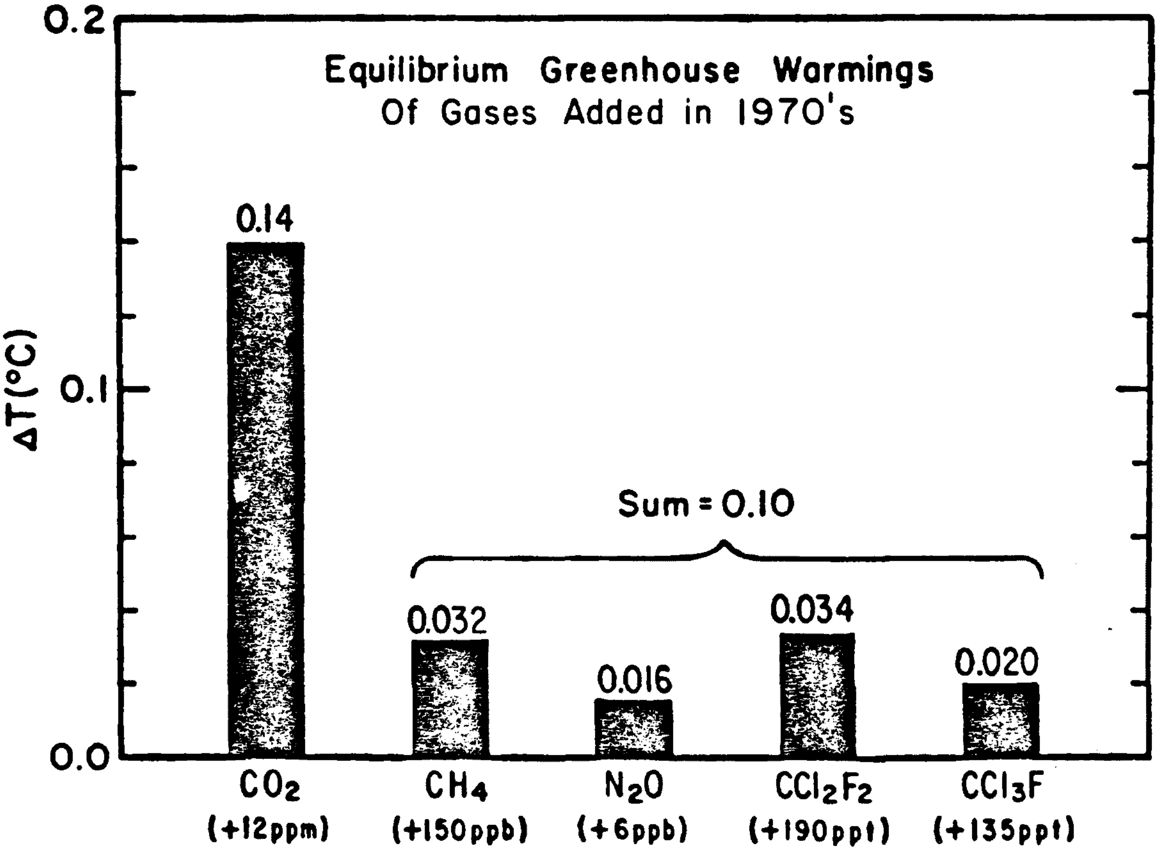
Estimates of what the world's climate will be like if $CO_2$-induced increases in global temperatures occur have been derived primarily from two sources: paleoclimatic evidence and general circulation models. Although both of these sources have their shortcomings, they provide useful insights into possible regional climatic changes accompanying different levels of a global warming.

## RECONSTRUCTING PAST CLIMATES

Paleoclimatic studies attempt to reconstruct historical climatic conditions using a variety of methods, including analysis of tree rings and ice core samples, and carbon dating techniques. By piecing together various clues, paleoclimatic analysis provides useful indications of past regional climatic conditions when global average temperature was warmer.

FIGURE 2-3

TEMPERATURE INCREASES FOR SEVERAL
GREENHOUSE GASES (1970-80)



Equilibrium greenhouse warmings for estimated 1970-1980 abundance increases of several trace gases, based on climate model with sensitivity ~3°C for doubled $CO_2$

SOURCE: Lacis, 1981

One important advantage of this approach is that interactions within the complex systems that determine climate can be examined as a whole. Unlike experiments using climate models, this approach includes all factors that influence climate.

It does have its drawbacks, however. Like most field experiments, it is impossible to control for individual variables. All we generally know about the time period being studied is that global temperature was warmer. Often we lack information required to fully understand the cause or causes of warmer climates in the past. Without this knowledge, we must assume that, whatever forces produced the climate, the effects are similar to those caused by increases in greenhouse gases. Also, the record is far from complete; estimates are missing for many regions at various points in time.

An additional problem in using paleoclimatic studies to predict future climate patterns arises because of past shifts in sea level, in the location and size of mountains, and in other geomorphological features that significantly influence regional climatic patterns.

Despite these drawbacks, paleoclimatic studies can be a useful analytic tool:

- to show that significant changes in local conditions (e.g., an ice-free Arctic) have accompanied relatively small shifts in past climates; and
- to identify relationships between global conditions and local phenomena, and to assist in filling in details concerning the possible range of impacts accompanying a global warming.

Within the range of possible $CO_2$-induced temperature changes reported by the NAS (3.0 ± 1.5°C), several geologic periods have been identified as possible climatic analogies. An extensive analysis of these periods has been conducted by Herman Flohn as part of his work for the International Institute for Applied Systems Analysis.

Flohn examined the early Middle Ages, about 1,000 years ago, as an example of a time when global temperatures exceeded current temperatures by approximately 1°C. Using paleoclimatic techniques, Flohn found that the treeline during this period had advanced considerably farther north in Europe and Canada, that Vikings had settled on southern Greenland, and that frequent droughts affected Europe.

If the average global temperature increases by 2.5°C, Flohn suggests regional climatic conditions might be similar to those experienced during the last interglacial period, 120,000 years ago. During this period, the oceans were 5-7 meters higher than today's. As a result, the sea substantially inundated the shorelines of Europe and western Siberia, and Scandinavia became an island.

Finally, Flohn examined the time just before the current glacial-interglacial period, approximately 10 million years ago, when the global temperature was 4°C warmer. During this period, evidence suggests that the Arctic was ice-free, while the eastern Antarctic continent still remained covered by glaciers. The resulting imbalance between an ice-free Arctic and an ice-bound Antarctic dramatically affected regional climatic patterns. It caused the arid areas of the Southern Hemisphere to expand toward the equator, and it extended the arid belt in the Northern Hemisphere. In general, Flohn predicts that a 4°C warming would shift the earth's climatic zones northward by 400-800 kilometers.

## MODELING FUTURE CLIMATES

Although the results of GCMs are far more accurate when discussed in terms of global averages, several broad conclusions about regional climatic changes can be drawn from recent experiments.

First, because of melting ice, increased water vapor, and the resulting change in the earth's albedo, far more dramatic temperature changes will occur at the poles than at the equator. For example, where average global temperatures are estimated to increase by 3°C, the projected change at the poles is 10°-12°C, and less than 3°C at the equator. Since the temperature differential between the equator and the poles is a primary driving force behind regional weather patterns, a change of this magnitude could dramatically alter current weather conditions.

A second conclusion based on GCM experiments involves shifts in precipitation patterns. While it is not clear exactly which areas will become dryer or wetter, significant departures from current patterns are projected. Overall, it appears likely that both evaporation and precipitation will increase worldwide (Smagorinsky, 1982). Preliminary results from region specific climate modeling suggests that time patterns of precipitation and evaporation may be far different as well (NASA, 1983). Major changes in monthly precipitation, runoff, and soil moisture would hold profound implications for agriculture and water resources planning.

## DETECTING A FUTURE GREENHOUSE WARMING

The greenhouse theory, with GCM experiments and paleoclimatic studies in support of it, offers convincing evidence for the likelihood and potential impact of changes in climate induced by $CO_2$ and other greenhouse gases. However, despite the useful information produced by experiments and field studies, much uncertainty remains.

Given the complexity of the climatic system, detecting a change in global climate and attributing it to increases in atmospheric greenhouse gases is difficult. Yet, because of the potentially high costs and large-scale disruptions involved in responding to the threat of climatic change, policymakers seek a clear signal that increases in $CO_2$ and other gases are directly responsible for warmer temperatures. Simply detecting a future warming trend will not be enough. It must be convincingly attributed to the greenhouse effect.

As a prelude to this future task, recent efforts have been aimed at explaining the historic variability in climate and at isolating that portion that might be attributed to rising levels of greenhouse gases. These efforts have focused on identifying the effects on temperature of various factors, including increases in greenhouse gases, the frequency of volcanic eruptions, and changes in solar radiance.

Hansen and his associates used a one-dimensional model to isolate the effects of $CO_2$ -- compared with those of other factors -- on global warming experienced since 1880 (Hansen, 1981). As Figure 2-4 indicates, estimates of atmospheric temperature due to $CO_2$ alone do not match observed temperatures very well. With the addition of the changes in volcanic activity and solar radiance during this period, the fit improves substantially. Hansen's study suggests that since the 1880s, $CO_2$ increases are responsible for a 0.4°C increase in temperature.*

This analysis is one of the first attempts at developing a better understanding of the variations in historical temperatures. Only by isolating $CO_2$-induced changes from other factors affecting temperature will scientists be able to develop a conclusive case in support of global warming due to $CO_2$ and other greenhouse gases.

## SUMMARY

This chapter highlighted evidence both of the potential magnitude of a greenhouse warming and of the critical importance of resolving existing uncertainties. There is no doubt that

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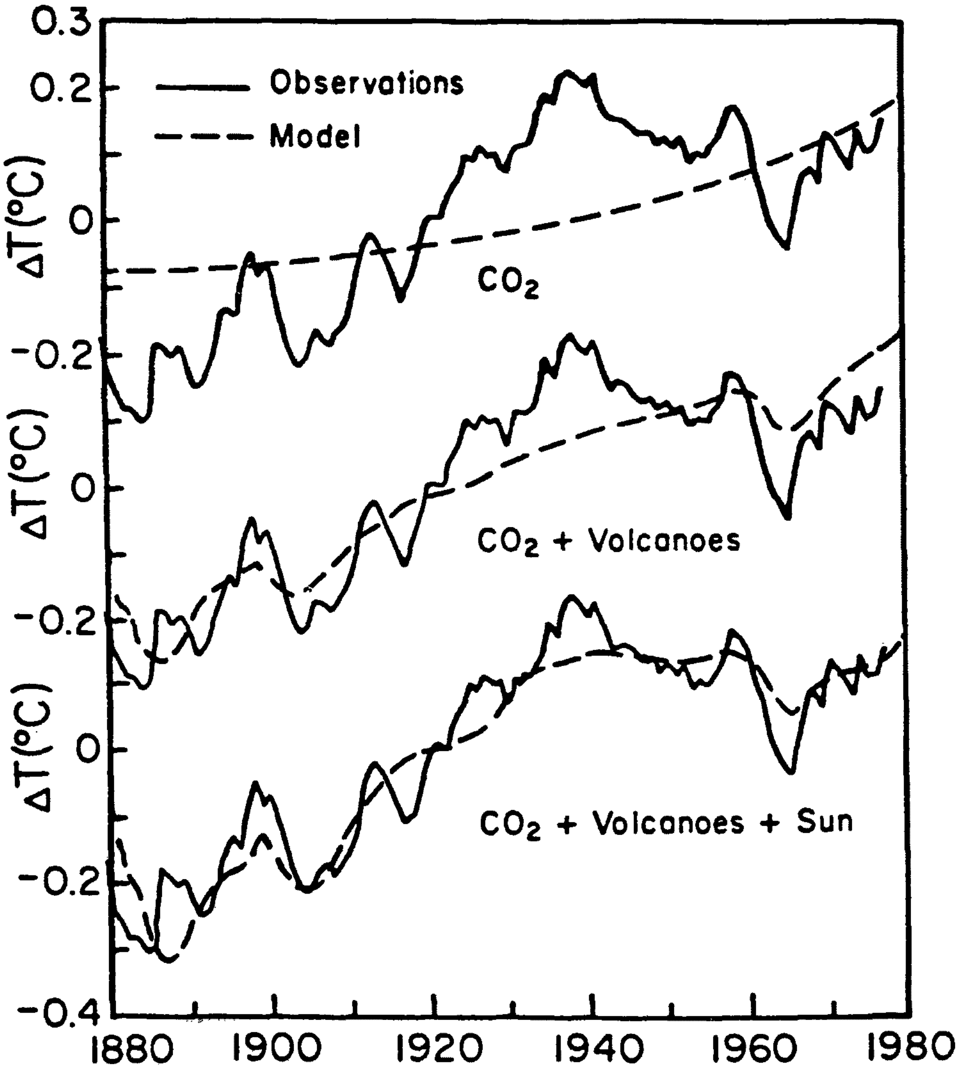
* A comparable method has been used with similar results by Gilliland (1982) and Budkyo, et al. (1969).

FIGURE 2-4

MODELED VERSUS OBSERVED TEMPERATURE TRENDS



Global temperature trend computed with a climate model with sensitivity 2.8°C for doubled CO$_2$ and an exchange rate $\kappa$ = 1.2 cm$^2$ s$^{-1}$ between a 100-m mixed layer ocean and the thermocline.

Source: Hansen (1981).

atmospheric $CO_2$ levels have increased and will continue to rise as long as the world remains dependent on fossil fuels. Models that estimate the climatic effects of this change in atmosphere, along with increases in other greenhouse gases, are by no means exact, but provide strong evidence of the likelihood of unprecedented rates of temperature increases during the next 120 years. Based on the strength of what we now understand about the greenhouse effect, and the social and economic implications of such climatic change, extensive research efforts aimed at addressing the remaining unknowns and at evaluating response options appear to be warranted.

# CHAPTER 3

# METHODOLOGY FOR PROJECTING FUTURE ENERGY AND $CO_2$ SCENARIOS

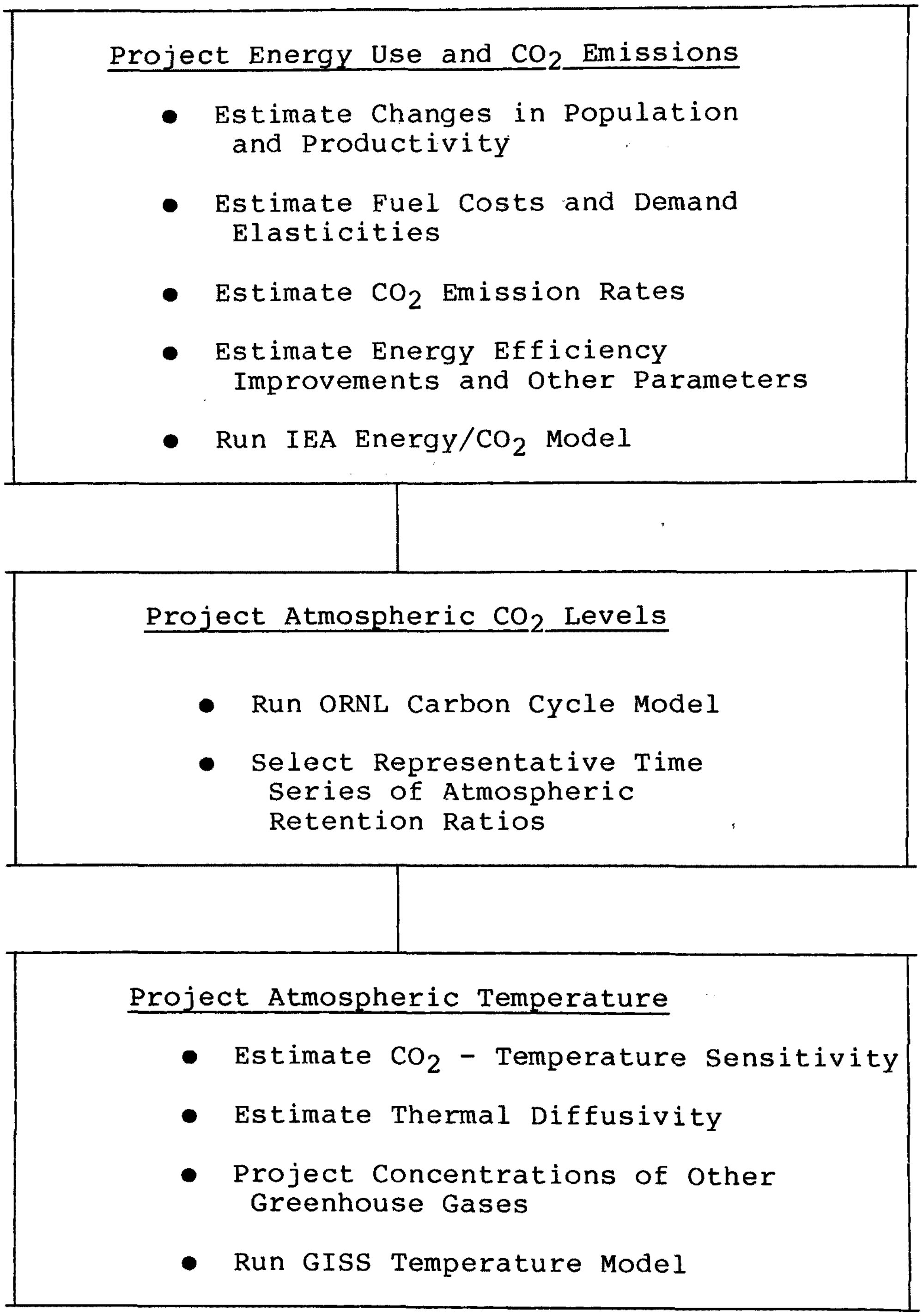
Increases in $CO_2$ will depend on both the total amount of energy demanded and the mix of fuels employed to satisfy energy demands. The importance of fuel mixes is reflected by differences in the amount of $CO_2$ emitted by alternative fuel types, from a high of 47.6 terragrams of carbon/EJ (1.02 million tons/quadrillion Btus) for shale oil to zero net emissions for biomass, solar, and nuclear fuels. Thus, two basic energy strategies for limiting or slowing the rise of $CO_2$ present themselves--reduce the total demand for energy, and shift the fuel mix toward fuels with low $CO_2$ emission coefficients.

To evaluate the effectiveness of energy-based policies in slowing or limiting the rise in atmospheric $CO_2$, we developed a methodology for projecting patterns of energy use, estimating future $CO_2$ emissions, and translating emissions into atmospheric $CO_2$ concentrations and temperature increases. This methodology relies heavily on a set of computerized models for manipulating data and simulating relationships. The primary components of the methodology and the key characteristics of the individual models are depicted in Figure 3-1.

This chapter describes each step in the method including the key features of each model. It emphasizes the assumptions and parameter values used to initialize model runs, since the

FIGURE 3-1

STUDY METHODOLOGY



**Project Energy Use and $CO_2$ Emissions**

- Estimate Changes in Population and Productivity
- Estimate Fuel Costs and Demand Elasticities
- Estimate $CO_2$ Emission Rates
- Estimate Energy Efficiency Improvements and Other Parameters
- Run IEA Energy/$CO_2$ Model

**Project Atmospheric $CO_2$ Levels**

- Run ORNL Carbon Cycle Model
- Select Representative Time Series of Atmospheric Retention Ratios

**Project Atmospheric Temperature**

- Estimate $CO_2$ - Temperature Sensitivity
- Estimate Thermal Diffusivity
- Project Concentrations of Other Greenhouse Gases
- Run GISS Temperature Model

confidence placed in our findings depends on the reasonableness of these assumptions and values. The sensitivities of model outputs to the most important assumptions are described in Chapter 4.

A general discussion of energy supplies and technologies is presented in Appendix A. It serves as background to the more specific treatment of energy supply modeling used in this chapter.

## PROJECTING ENERGY USE AND $CO_2$ EMISSIONS

The Institute for Energy Analysis (IEA) energy and $CO_2$ emission model (Edmonds and Reilly, 1983a) served as the basic vehicle for developing alternative energy and $CO_2$ emission scenarios.* The IEA model is attractive for this type of application for several reasons. First, it is global in scope and thus encompasses world energy markets and international trading in all principal fuels. Second, it is designed as a sketch model -- that is, as a representation of general structural relationships between fuel supplies and energy demands. This is highly desirable for a study of long-term energy supply and demand. Finally, the IEA model has been structured to facilitate the evaluation of energy policy options.

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* See Appendix B for a more detailed description of the IEA model.

Based on a series of sensitivity analyses conducted by both Edmonds and Reilly, and us, the model also appears to be highly robust. That is, it is not overly sensitive to any single parameter or assumption. This is due, at least in part, to the use of logit share equations and the resulting continuity of change in market fuel shares. In other words, the market responses to major changes in prices, supplies, and demand are modulated and lagged.

The IEA model divides the world into nine geopolitical regions (Figure 3-2). Population, economic growth, energy supply and demand, and all other key variables are specified for each of these regions. The model estimates prices for each fuel in each region sufficient to balance supply and demand at each future point in time (currently, 1975-2100 in 25-year intervals). Interregional trading in all fuels except electricity (for which no world market exists) is simulated as part of the market price solution process. The total quantity of $CO_2$ emitted is calculated from the worldwide consumption of the various fuels and the $CO_2$ emissions coefficients of each fuel. Figure 3-3 depicts the key inputs and outputs and the major computational pathways in the IEA model.

Although the basic structure of the IEA model was not modified for this study, many of the parameter values and assumptions were altered to specify new baseline energy and policy scenarios. To emphasize these changes, we will refer to our runs as IEA/EPA scenarios.

FIGURE 3-2

## GEOPOLITICAL REGIONS IN THE IEA MODEL

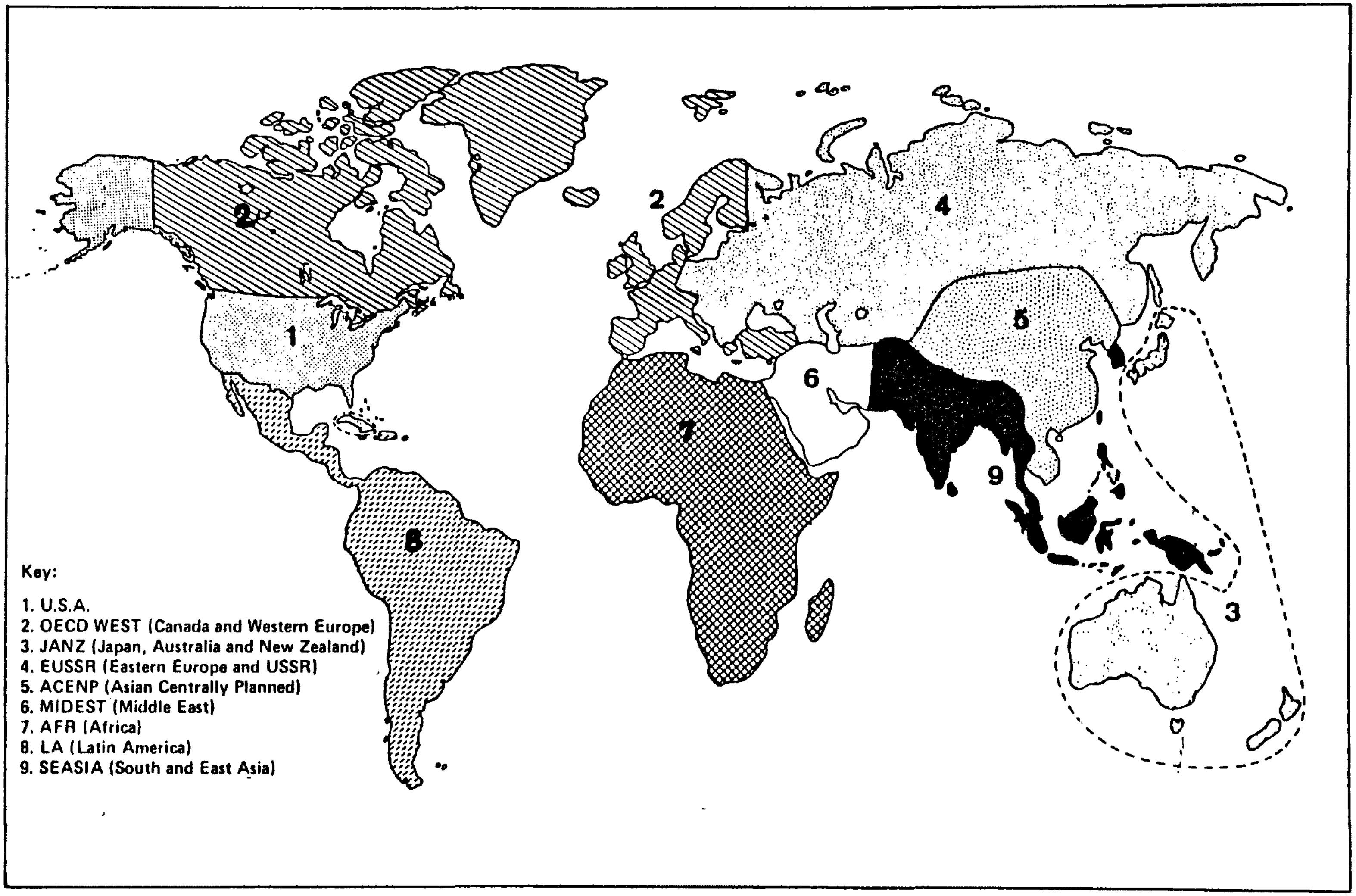
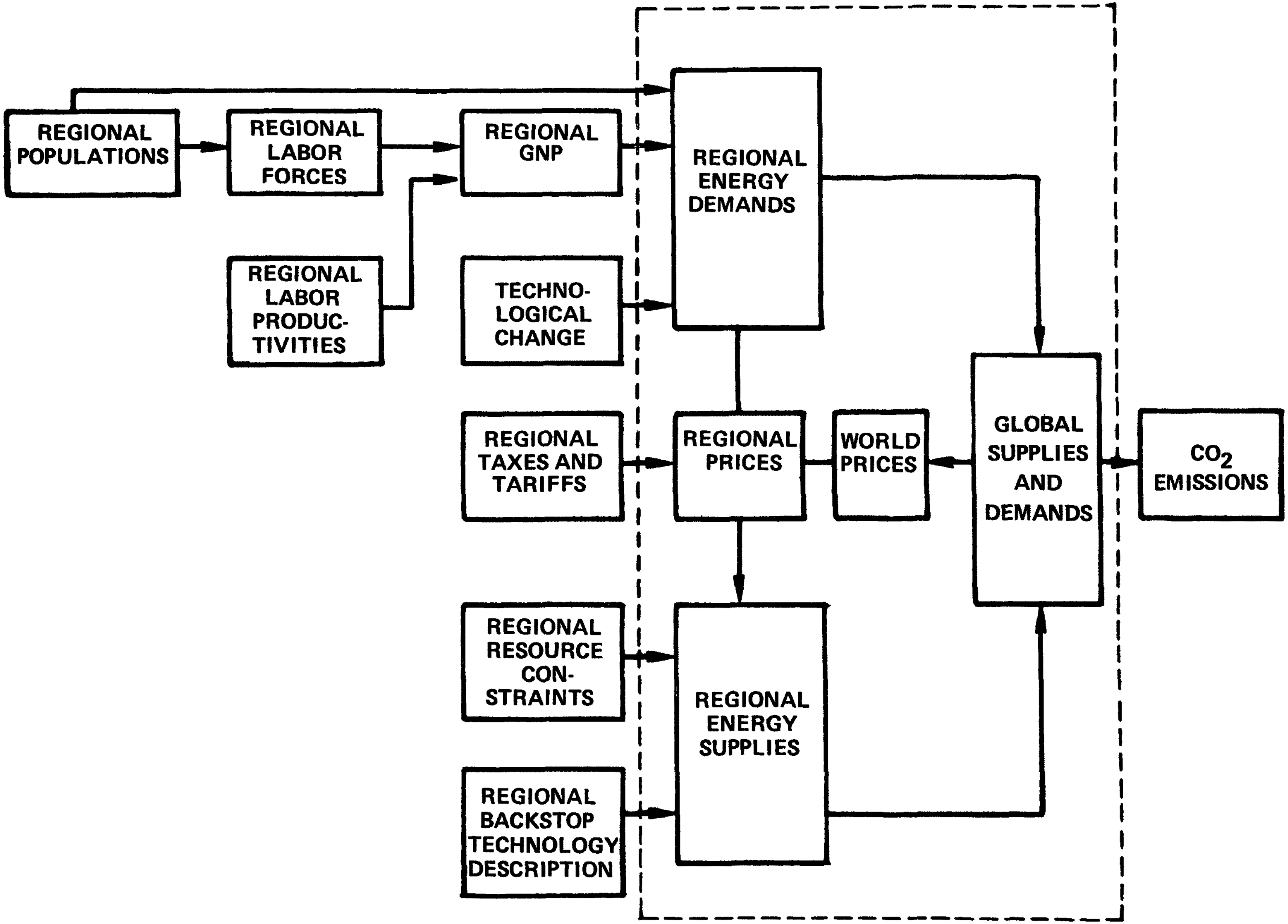


FIGURE 3-3

STRUCTURE OF THE IEA MODEL



## ENERGY DEMAND PARAMETERS

As shown in Figure 3-3, the major determinants of energy demand in each region are (1) population and labor force, (2) labor productivity, and (3) enhanced energy efficiency, on the positive side, and energy prices on the negative side. These determinants work together within the economy of each region to create the underlying demand for fuel liquids, gases, solids, and electricity.

Values for regional populations and gross national products (the product of labor forces and labor productivities) used in the IEA/EPA Mid-range Baseline scenario (see Chapter 4) are shown in Table 3-1. The values for 1975-2050 are based on a detailed study of each region and are taken without change from Edmonds and Reilly (1983b).* Values beyond 2050 extend the 1975-2050 trends, with worldwide population reaching a zero growth level by 2075. In terms of growth rates, worldwide population averages 1.0 percent per year between 1975 and 2050, and worldwide GNP averages 2.7 percent per year between 1975 and 2100.

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* The Edmonds and Reilly study combined an exhaustive review of the energy demand literature with specially commissioned investigations of population growth and productivity change in each of the nine regions. See Appendix B for additional documentation.

## TABLE 3-1

## BASELINE VALUES FOR POPULATION, GNP, AND TECHNOLOGICAL CHANGE

| Region | Population (billions) | | | | | | GNP (trillions of 1975 $) | | | | | | Enhanced Energy Efficiency[a] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1975 | 2000 | 2025 | 2050 | 2075 | 2100 | 1975 | 2000 | 2025 | 2050 | 2075 | 2100 | 1975 | 2000 | 2025 | 2050 | 2075 | 2100 |
| U.S. | .21 | .25 | .28 | .29 | .29 | .29 | 1.52 | 2.85 | 4.59 | 6.84 | 10.11 | 14.66 | 1.00 | 1.28 | 1.64 | 2.11 | 2.70 | 3.47 |
| Canada & W. Europe | .41 | .48 | .53 | .55 | .56 | .56 | 1.82 | 3.60 | 6.42 | 10.38 | 16.18 | 24.65 | | | | | | |
| Japan, Aust., & New Zealand | .13 | .15 | .16 | .17 | .17 | .17 | .59 | 1.59 | 3.21 | 5.38 | 8.41 | 12.82 | | | | | | |
| E. Europe & U.S.S.R. | .40 | .47 | .52 | .53 | .54 | .54 | .97 | 1.76 | 2.85 | 4.31 | 13.85 | 21.10 | 1.00 | 1.11 | 1.26 | 1.44 | 1.68 | 1.99 |
| Asian Centrally Planned | .91 | 1.25 | 1.50 | 1.61 | 1.65 | 1.65 | .32 | .85 | 1.75 | 3.31 | 13.47 | 28.20 | | | | | | |
| Mideast | .08 | .15 | .21 | .24 | .25 | .25 | .14 | .50 | 1.24 | 2.49 | 9.14 | 14.99 | | | | | | |
| Africa | .40 | .70 | .94 | 1.10 | 1.15 | 1.15 | .15 | .48 | 1.14 | 2.14 | 9.28 | 18.07 | | | | | | |
| Latin America | .31 | .54 | .72 | .82 | .85 | .85 | .32 | 1.09 | 2.84 | 5.16 | 17.89 | 29.35 | | | | | | |
| S.& E. Asia | 1.13 | 1.90 | 2.56 | 2.89 | 2.99 | 2.99 | .23 | .71 | 1.65 | 3.11 | 11.07 | 21.03 | | | | | | |

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[a] This is an index that reflects improvements in energy efficiency, in addition to those induced by energy price rises. In the Mid-range Baseline scenario, it applies to only the industrial sector in the OECD countries, and to the single aggregate sector elsewhere.

Accelerated increases in GNP in the current underdeveloped and developing regions reflect a high population growth rate earlier in the 21st century combined with higher labor productivity later in the century as the economies in these regions mature.* Viewed from a different perspective, initially high population growth rates in these regions are brought to zero through improvements in the standard of living as reflected in GNP values. This is consistent with the generally held view that birth rates are negatively correlated with per capita GNP.

With respect to the enhanced energy efficiency index, note that this parameter reflects improvements in energy efficiency beyond those induced by increases in energy prices. Our Mid-range Baseline scenario assumes such improvements occur only in the industrial sector where the rate of technological innovation historically has been higher than in the other economic sectors. The average rate of increase over the 125-year period is 1.0 percent per year in the OECD (first three regions in Figure 3-2) industrial sectors, and about 0.6 percent per year in the single aggregate sector elsewhere.

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* Average annual rates of increase over the 125-year period range from about 2.8 percent per year to over 3.0 percent for the less developed countries.

The effect of energy prices on demand is captured in the set of long-term (25-year) price elasticities of demand for each region.* For the OECD regions, the sectoral elasticities are: -0.90 for residential/commercial, -0.80 for industrial, and -0.70 for transportation. (The residential/commercial elasticity accounts for the increased use of passive and active solar energy in these sectors.) Since the other regions are not disaggregated by sectors, a single -0.8 elasticity is employed. Because prices vary individually for different fuels, interfuel elasticities are used to reflect the tendency for substitution among fuels. However, these elasticities vary with the market share of each fuel and thus over time as the mix of fuels changes in each region.

Total energy demand is driven by GNP both through the consumption of goods and services that require energy for production, and through the direct consumption of energy by consumers. These effects are summarized by income elasticities of demand, which are set for the OECD countries at 1.0 (with respect to per capita income) for the residential/commercial and transport sectors, and 1.0 (with respect to GNP) for the industrial sector. For the single-sector regions, the aggregate elasticity declines from 1.25 to 1.0 in Eastern Europe and the USSR, and from 1.4 to 1.0 elsewhere, over the period 1975-2050. Thereafter, it

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* A price elasticity of demand is the percent change in demand caused by a one percent change in the mean price.

remains at 1.0 everywhere. The growth in GNP is also affected by the energy price increases, but the effect is the opposite of income changes. The GNP-price elasticity is -0.10.

The demand for energy is further disaggregated into fuel types based on market shares of each fuel in 1975 and assumed changes in fuel share parameters over time. Market penetration of alternative fuel types also depends on the relative prices of these fuels, as reflected in a series of cross-price elasticities. The combination of market share parameters and fuel price differentials controls the rate at which new energy technologies emerge and old ones are supplanted. Thus, as noted previously, sudden changes over any one 25-year period are avoided.

## ENERGY SUPPLY PARAMETERS

Three generic energy supply categories are defined based on the physical availability of the resource:

| Resource-Constrained Conventional Sources | Resource-Constrained Renewable Sources | Unconstrained Sources |
|---|---|---|
| Conventional Oil<br>Conventional Gas | Hydro<br>Biomass (Solids and Synthetic Fuels) | Unconventional Oil<br>Unconventional Gas<br>Coal (Solids and Synthetic Fuels)<br>Solar Nuclear |

Definitions of each fuel type can be found in Appendix A.

The rates of production of conventional oil and gas are represented by simple resource depletion curves. This assumes that the rates of oil and gas extraction over the next few decades follow historical trends and are insensitive to changes in market prices. Although this assumption is not literally valid and leads to some distortion in estimated oil and gas prices, the inaccuracies are mitigated since conventional oil and gas will have become relatively minor sources of energy by the middle of the next century -- well within our time frame.

Hydropower for generating electricity is modeled in a fashion similar to unconventional oil and gas, with one exception. Rather than resource depletion, maximum resource utilization is simulated. Biomass is both resource-limited and price-sensitive. That is, maximum land areas for growing fuel crops have been estimated for each region, and these limits bound a land area-energy price supply curve. Upper limits on the amount of waste available for use as fuel are estimated as a function of GNP in each region.

All other fuels are assumed to be present in large enough quantities as to be inexhaustible within the time horizon of this study.* Production of these fuels is thus influenced only by their market price. However, a distinction is made between

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* For nuclear power, the development and use of breeder reactors is assumed. See Appendix A for further elaboration.

unconventional oil (primarily shale oil),* unconventional (deep) gas, and coal, on the one hand, and nuclear and solar on the other. The first group is assumed to follow both a long-run "normal" rate of growth (which occurs at constant real prices) and a shorter (25-year) supply schedule that adjusts the production level above or below the "normal" level corresponding to higher or lower than "normal" prices.

Both nuclear and solar-electric** power are considered true "backstop" fuels. That is, their costs of production remain constant (or decrease) for all time scales. Moreover, the demand for these fuels is derived from the total demand for electricity, and the costs of producing electricity from nuclear and solar power relative to competing fuels.

The demand for and market price of liquids and gases similarly influences the production of synthetic fuels from coal and biomass, although synfuels are modeled by a logit-share function, rather than by superimposition of long- and short-run supply schedules as above.

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* Unconventional oil includes both heavy oil and tar sands/shale oil (see Appendix A). However, although the IEA/EPA model runs include all types of unconventional oil in their resource estimates, production costs are based on shale oil costs.

** Solar for nonelectric uses is included in the IEA conservation category.

A key production parameter for all emerging energy sources is the minimum production cost, or breakthrough price. This is the lowest market price at which any production is feasible.* Breakthrough prices are shown in Table 3-2 for each emerging energy source in the IEA/EPA Mid-range Baseline scenario. Note that the price for each source, other than unconventional gas, declines over time (a smooth nonlinear curve connects 1975 and 2100), reflecting technological advances in extraction and processing technologies. Since unconventional gas is currently being produced in several parts of the world (and is thus not actually an "emerging" source), the associated technology can be considered mature and subject to a modest increase in real costs over time.

For purposes of comparison, breakthrough prices for the other principal fuel types are shown in Table 3-3. These cost estimates include pollution control and other nonenergy costs. They are based on the results of an energy technology comparison as reported in Reilly and associates (1981), with extrapolations to 2100 and with modifications based on more recent cost data.

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* For synfuels, the "breakthrough price" concept is not directly applicable. Production costs relative to market prices for liquids and gases are used to determine the relative amounts of liquid, gaseous, and solid fuels made from coal and biomass. A small amount of synfuel production may occur even when market prices are slightly below production costs.

## TABLE 3-2

## BREAKTHROUGH PRICES FOR EMERGING ENERGY SOURCES IN THE MID-RANGE BASELINE SCENARIO

| | Breakthrough Price (1980 $) | | |
|---|---|---|---|
| Fuel[a] | Beginning (1975) | Final (2100) | Production Initiated |
| Unconventional Oil (primarily shale) | 12.0 - 17.8[b] ($/GJ)<br>70 - 103 ($/boe) | 7.1 ($/GJ)<br>41 ($/boe) | 8.8 ($/GJ)<br>51 ($/boe) |
| Unconventional Gas | 5.2 ($/GJ)<br>0.005 ($/cf) | 6.4 ($/GJ)<br>0.006 ($/cf) | 5.5 ($/GJ)<br>0.006 ($/cf) |
| Synthetic Oil[c] | 100 ($/GJ)<br>580 ($/boe) | 6.7 ($/GJ)<br>39 ($/boe) | 7 ($/GJ)<br>41 ($/boe) |
| Synthetic Gas[c] | 100 ($/GJ)<br>0.10 ($/cf) | 5.0 ($/GJ)<br>0.005 ($/cf) | 5.5 ($/GJ)<br>0.006 ($/cf) |
| Centralized Solar-Electric | 153-570[b] ($/GJ)<br>2.32 - 8.63 ($/kWh) | 9-22[b] ($/GJ)<br>0.29-0.33 ($/kWh) | 20 ($/GJ)<br>0.30 ($/kWh) |

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[a] See Appendix A for definitions.

[b] Varies by region.

[c] Synthetic fuels are not, strictly speaking, modeled with breakthrough prices. Rather, the production costs are used together with other factors to estimate the fractions of raw material (coal and biomass) that are used to produce solid, liquid, and gaseous fuels. In addition, the costs of producing synfuels are higher for biomass than for coal.

## TABLE 3-3

## BREAKTHROUGH PRICES FOR TRADITIONAL ENERGY SOURCES IN THE MID-RANGE BASELINE SCENARIO

| Fuel | Breakthrough Price (1980 $) | |
|---|---|---|
| | Beginning (1975) | Final (2100) |
| Coal | 0.37 ($/GJ)<br>11 ($/mtce) | 0.49 ($/GJ)<br>15 ($/mtce) |
| Biomass | 0.57 ($/GJ)<br>17 ($/mtce) | 0.57 ($/GJ)<br>17 ($/mtce) |
| Nuclear | 9.6 - 36.4[a] ($/GJ)<br>0.15 - 0.55 ($/kWh) | 10.0 ($/GJ)<br>0.15 ($/kWh) |

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[a] Varies by region.

For two fuel sources (unconventional gas and coal) modeled by superimposing long-run and medium-run supply schedules, the reference price of the "normal" production level also increases over time. In other words, the long-run supply schedules slope upward. The time-rate of increase in reference price equals the rate of increase in breakthrough price. In a similar but opposite sense, the long-run "normal" supply curve for unconventional oil slopes downward, paralleling the decline in breakthrough price.

All IEA/EPA scenarios assume that significant commercialization of exotic energy sources will not be realized within the next 120 years. Thus, rapid development of fusion technology or new methods of generating hydrogen during the first half of the next century, for example, could make model projections of fossil fuel use unreliable by the end of the next century, even if all other assumptions were to hold. (See Appendix A for a discussion of exotic sources.)

## BALANCING SUPPLY AND DEMAND

Once supply and demand schedules have been estimated for each fuel type in each region, the model solves for market-clearing prices in each region. Starting points are the world prices for each fuel traded internationally, plus transport costs and tariffs, if any. Regional prices are then adjusted for each fuel (gases, liquids, solids, and electricity) until supplies and demands match within a predesignated increment.

## ESTIMATING $CO_2$ EMISSIONS

The total quantity of $CO_2$ emitted is calculated as the product of fuel used in each time period and $CO_2$ emitted per unit quantity of each fuel. The following $CO_2$ (carbon) emission coefficients are employed (Edmonds and Reilly, 1983b):

$CO_2$ Emissions (Terragrams of Carbon/EJ)

| Fuel | Preparation | Combustion | Total |
|---|---|---|---|
| Conventional Oil | -- | 19.7 | 19.7 |
| Unconventional Oil (Shale Oil) | 27.9 | 19.7 | 47.6 |
| Gas | -- | 13.8 | 13.8 |
| Coal | -- | 23.9 | 23.9 |
| Synthetic Oil (from coal) | 18.9 | 19.7 | 38.6 |
| Synthetic Gas (from coal) | 26.9 | 13.8 | 40.7 |

All other fuels are assumed to contribute no $CO_2$ to the atmosphere. In the case of synthetic fuels from biomass, this implies that biomass is used to generate the energy needed for liquifaction and gasification.

Using these coefficients, estimates of global $CO_2$ emissions are generated for each 25-year period. Estimates at 5-year intervals are then prepared for the next analytical step by interpolation using a curve-fitting procedure. The starting date for estimating atmospheric $CO_2$ is 1980.

## PROJECTING ATMOSPHERIC $CO_2$ LEVELS

A global carbon cycle model developed at Oak Ridge National Laboratory (ORNL) (Emmanuel, et al., 1981) was employed to estimate the fate of $CO_2$ emitted into the atmosphere and, ultimately, the airborne fraction (retention ratio).* The ORNL model simulates stocks of carbon in three major compartments: the atmosphere, the ocean (surface and deep layers), and the biosphere (ground vegetation, trees, and soil). Changes in the quantities of carbon in these reservoirs are affected primarily by (1) $CO_2$ emissions, (2) land clearing and reforestation, and (3) temperature changes. The last factor implies a major feedback loop, since increasing atmospheric $CO_2$ levels will raise atmospheric and ocean temperatures which, in turn, will increase the flow of carbon from the ocean to the atmosphere. Moreover, the flows of carbon among other compartments are also affected by temperature.

Since temperature is a key variable in estimating the fate of emitted $CO_2$, a special effort was made to represent the temperature effects of rising $CO_2$ in the atmosphere as realistically as possible. This involved coupling the ORNL and Goddard Institute for Space Studies (GISS) models, since $CO_2$-temperature relationships are represented in a more sophisticated (and presumably more accurate) fashion in the GISS model than in the ORNL model. Details of the coupling procedures are described in Appendix E.

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* See Appendix C for a more detailed description of the ORNL model.

To simplify the analysis, we assumed no net change in forest cover over the 120-year period of interest. This is not unreasonable, given the offsetting trends in land clearing and reforestation currently observed in different parts of the world.

Using the coupled ORNL-GISS models we made several runs for a variety of energy use/$CO_2$ emission scenarios. These generated a large set of 10-year average retention ratios, from which we selected four representative series. These correspond to very low, low, medium, and high $CO_2$ emission scenarios, as indicated in Figure 3-4. High rates of growth in $CO_2$ emissions imply a gradual saturation of natural carbon sinks and thus an increase in atmospheric retention of $CO_2$ over time, while low emission rates suggest a constant or even slightly falling retention ratio.

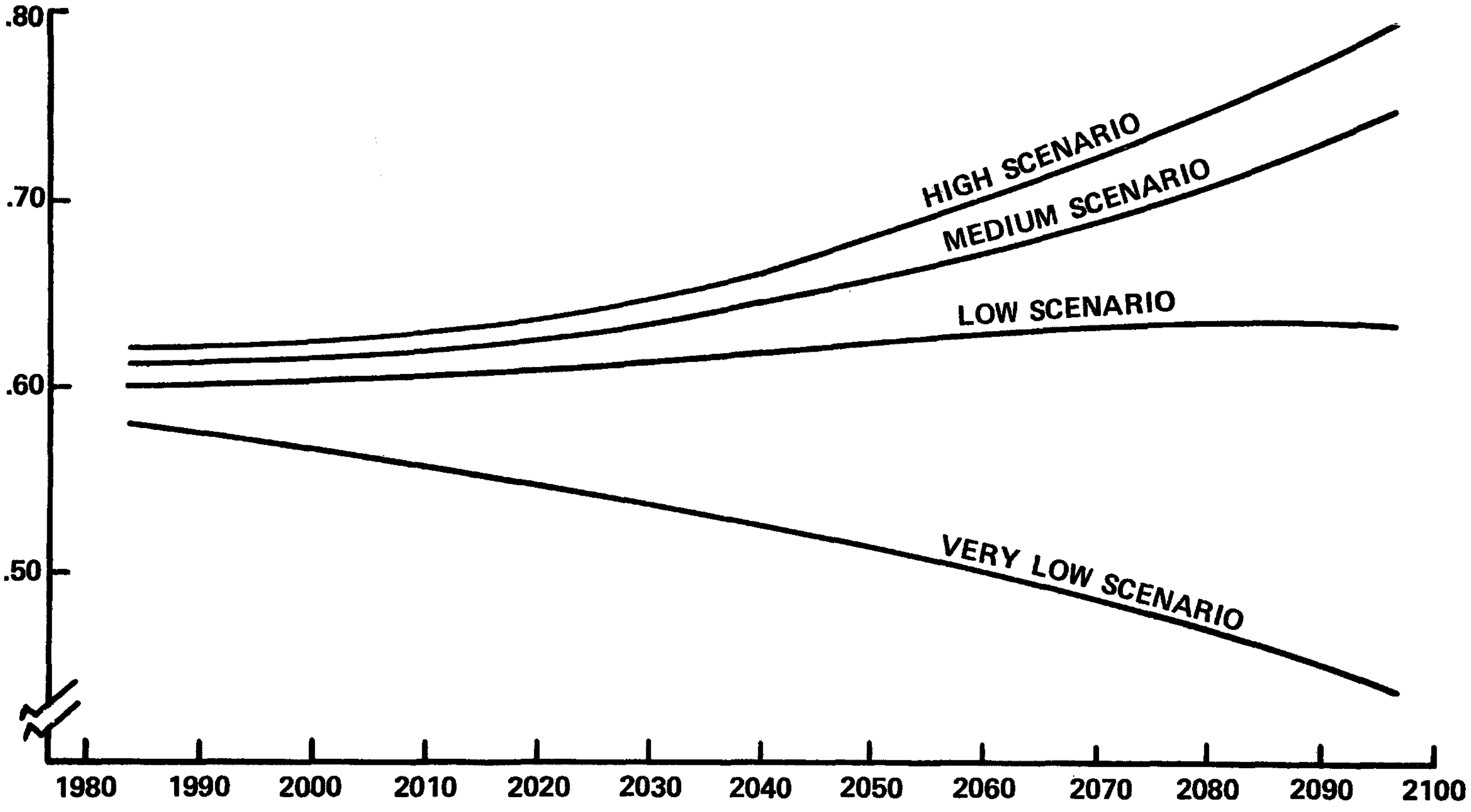
Note also that the retention ratios calculated by the ORNL model are somewhat higher than those estimated from empirical data on historical fuel use, land use changes, and measured increases in $CO_2$ concentrations. However, substantial uncertainty accompanies the interpretation of past empirical estimates, and higher future retention ratios are consistent with current scientific understanding of the carbon cycle (see Chapter 2).

The $CO_2$ emission categories in Figure 3-4 cover a wide range of scenarios. The designation of only four separate categories may appear to introduce substantial error, since the retention ratios assigned to these categories differ considerably, especially in the later years. In addition, the rates of growth in emissions

# FIGURE 3 - 4

## FINAL ATMOSPHERIC $CO_2$ RETENTION RATIOS FOR FOUR TYPES OF $CO_2$ EMISSION SCENARIOS

(ADDITIONAL TONS OF ATMOSPHERIC $CO_2$/TONS OF $CO_2$ EMITTED)



DEFINITIONS: VERY LOW SCENARIO = DECLINING ANNUAL EMISSIONS
LOW SCENARIO = 1.0 – 1.49% ANNUAL GROWTH IN EMISSIONS
MEDIUM SCENARIO = 1.5 – 1.79% ANNUAL GROWTH IN EMISSIONS
HIGH SCENARIO = GREATER THAN 1.79% ANNUAL GROWTH IN EMISSIONS

NOTE: NO SCENARIOS WERE INVESTIGATED WITH GROWTH RATES BETWEEN ZERO AND 1.0% PER YEAR.

used in defining the emission scenarios in Figure 3-4 are average annual rates over the 120-year time span of this study. These average rates obviously mask significant trends in annual rates within this time span, which may imply changes in retention ratios. However, the end product of these investigations -- changes in atmospheric temperature -- is much less sensitive to variations in retention ratio than is atmospheric $CO_2$. A comparison of (1) estimated temperature levels derived from atmospheric $CO_2$ concentrations computed by the ORNL model with (2) temperature levels associated with $CO_2$ concentrations calculated from the representative retention ratios revealed no significant differences.

Using representative series of retention ratios derived from the ORNL models output accomplishes two goals. First, it incorporates, in an approximate fashion, the flows of carbon and changes in carbon reservoirs in the global carbon cycle as estimated by the ORNL model. Second, it avoids the necessity of running the costly ORNL model for each new scenario. Instead, the appropriate retention ratio series is selected and atmospheric levels of $CO_2$ computed directly by the GISS model.

## PROJECTING ATMOSPHERIC TEMPERATURE LEVELS

Once atmospheric levels of $CO_2$ have been estimated for future time periods, these levels are translated into changes in atmospheric temperature using a simplified heat flux model of the earth-atmosphere system. This is the GISS model -- a simplification of a one-dimensional radiative/convective (RC) atmospheric temperature model developed at GISS (Hansen, et al., 1981; and Lacis, et al., 1981).*

In essence, the GISS model computes changes in the flux of heat from atmosphere to land and ocean, which results from $CO_2$'s capacity to absorb infrared radiation from the earth. As discussed in Chapter 2, some of this energy is reradiated toward the earth's surface, thus raising the temperature of the earth and the atmosphere at the surface and rebalancing total energy received and emitted by the earth-atmosphere system. The rate at which this occurs for a given rise in $CO_2$ depends on the degree to which the additional heat is dissipated in the ocean and on several feedback mechanisms, the most important of which is the increase in water vapor with rising temperature.

The GISS model represents both the heat flux from the atmosphere to the surface (well-mixed) layer of the ocean, and from this layer into 63 lower layers (the thermocline) of the ocean. A simple "box diffusion" scheme is employed to represent the diffusion and transport of heat in the ocean. Since this process is a relatively slow, several years may be required for the earth-atmosphere system to reach thermal equilibrium for a given

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* See Appendix D for a more detailed description of the GISS model.

increase in $CO_2$.* Thus, atmospheric temperature rises always lag $CO_2$ rises. For large rates of growth in annual $CO_2$ emissions, this time lag may be as much as a few decades.

The effects of rising temperature on atmospheric water vapor and on cloud cover and height are treated explicity in the GISS model. These feedback mechanisms also delay the attainment of thermal equilibrium, although the timing effect is short compared with that of heat dissipation in the ocean.

The GISS model incorporates various factors that influence atmospheric temperature, in addition to $CO_2$. These include the level of other greenhouse gases (specifically, nitrous oxide, methane, and chlorofluorocarbons), the change in atmospheric optical depth** due to volcanic activity, and variations in solar luminosity. Values for those parameters are based on extrapolations of past trends or on average measured levels. However, since data on historical trends and current levels for these parameters are sketchy at best, the assignment of future values must be considered highly speculative. The temperature sensitivity (the net change in temperature at equilibrium from a doubling of pre-industrial $CO_2$) and the rate of heat diffusion in the ocean are the final two key parameters.

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* Of course, the atmosphere never attains equilibrium if the concentrations of greenhouse gases change continually.

** Optical depth is a dimensionless parameter that measures the opacity of the atmosphere.

Values assigned to all parameters are shown in Table 3-4. References and brief explanations for these values are also included in Table 3-4 and are described in more detail in Appendix D.

Since most of the effects of $CO_2$ will be manifest in terms both of rises in atmospheric temperature and of the consequences of these rises, much of the discussion in Chapter 4 will focus on temperature trends. It is useful to keep in mind, however, that tracing changes in fuel use through to the impact on atmospheric temperature requires many assumptions about behavioral responses to changing technologies and costs, energy use, and production, and about physical and biological relationships involving $CO_2$.

## TABLE 3-4

## PARAMETER VALUES FOR THE GISS MODEL

| Parameter | Value | Comments | Reference |
|---|---|---|---|
| Atmospheric Level of $CH_4$ | ● Constant 1.6 ppm for all years<br>● 1.6 ppm through 1980, increased by 2.0% per year thereafter | Estimates of growth for 1970-80 range from 0.5 to 3.0% per year. | Lacis, et al., 1981<br>Rasmussen and Khalil, 1981 |
| Atmospheric Level of $N_2O$ | ● Constant 0.300 ppm for all years<br>● 0.300 ppm through 1980, increased by 0.2% per year thereafter | Estimates of growth for 1975-80 range from 0.1 to 0.5% per year. | Lacis, et al., 1981<br>Weiss, 1981 |
| Atmospheric Level of $CCl_2F_2$ | ● Constant 0.306 ppb for all years starting in 1980 [a]<br>● 0.306 ppb in 1980, increased in 10-year decreasing increments to 1.50 ppb in 2100 | Growth estimates are based on measured levels between 1970 and 1980, and assume a decrease in emissions over the 120 year time period | Lacis, et al., 1981. |
| Atmospheric Level of $CCl_3F$ | ● Constant 0.176 ppb for all years starting in 1980 [a]<br>● 0.176 ppb in 1980, increased in decreasing 10-year increments to 0.642 ppb in 2100 | | |
| Volcanic Activity | ● Constant level of activity: increase in optical depth of a constant 0.007 every year from 1980-2100 | This is the average measured value over the last 100 years | Lamb, 1970<br>Hansen, et al., 1981 |
| Change in Solar Luminosity | ● Zero | No net change is projected for the next 120 years | Hoyt, 1979<br>Hansen, et al., 1981 |
| Temperature Sensitivity | ● 1.5°C<br>● 3.0°C<br>● 4.5°C | Spans the estimated 50% confidence interval for $T_e$ | Charney, 1979 |
| Diffusivity | ● 1.18 $cm^2/sec$ | This is within the accepted range of diffusivity values for a "box diffusion" model and consistent with a 3.0°C temperature sensitivity value in the GISS model | Broecker et al, 1980<br>Hansen, et al., 1981 |

Abbreviations: $CH_4$ = methane, $N_2O$ = nitrous oxide, $CCl_2F_2$ and $CCl_3F$ = chlorofluorocarbons, ppm = parts per million, ppb = parts per billion

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[a] Emissions of chlorofluorocarbons were initiated in the 1940s but did not accumulate to significant atmospheric levels until the 1960s and 70s. Assuming zero levels before 1980 does not distort estimates of atmospheric temperature appreciably.

## CHAPTER 4

## THE EFFECTIVENESS OF ENERGY POLICIES FOR CONTROLLING $CO_2$

To explore the possible effects of future energy scenarios on atmospheric $CO_2$ and temperature, a large number of analyses were undertaken using the models described in Chapter 3. Each separate run focused on one or more key assumptions or examined the effect of specific policies designed to slow the rate of $CO_2$ rise. The results of these analyses are described and interpreted in this chapter.

For clarity in discussing the results, the energy scenarios are divided into two groups -- baseline projections and policy assessments. The baseline projections depict alternative future patterns of energy use and resulting atmospheric $CO_2$/temperature levels in the absence of any overt public effort to lower $CO_2$ emissions. These IEA/EPA projections include a reference baseline (Mid-range), four lower $CO_2$ baselines (High Renewable, High Nuclear, High Electric, and Low Demand), and one higher $CO_2$ baseline (High Fossil). Policy assessments do just the opposite -- they evaluate the effectiveness of policies intended to slow or limit the rate of $CO_2$ rise and atmospheric warming as measured in terms of differences from the reference (Mid-range) baseline projection. Policy options investigated include taxes on $CO_2$ emissions and various bans on specific types of fossil fuels.

Although the distinction between baseline projections and policy assessments is sometimes arbitrary (e.g., a low cost renewable energy baseline could be the result of government subsidies for renewable energy use), using a range of energy scenarios independent of any policy considerations is useful in clarifying the uncertainty involved in projecting future energy use, and thus in providing a context for judging the effectiveness of policies.

## BASELINE SCENARIOS

The starting point in developing baseline scenarios is a projection of future fuel use patterns which represents a composite of "best guesses" about the state of the world through the next century. This case is named the Mid-range Baseline scenario. Predicting the future is not the goal here. Rather, the Mid-range Baseline serves simply as a reference point for asking "what if" questions. The answers to these questions shed light on, first, the overall degree of uncertainty in estimating atmospheric effects produced by future fuel-use patterns, and second, the relative importance of specific assumptions concerning energy behavior and atmospheric responses.

### MID-RANGE BASELINE

#### Energy Supply and Demand

Assumptions regarding growth in population and labor productivity, technological change (enhanced energy efficiency), energy use behavior, and fuel production costs used to specify the

Mid-Range Baseline scenario were listed in Chapter 3. Figure 4-1 charts the estimated change in several fuel use characteristics from 1975 to 2100. Point estimates at 25-year intervals are shown, with straight lines connecting the points for display purposes.

Note first the relatively modest rise in final* energy use through 2050 (about 1.2 percent per year for final energy use) and the steep rise thereafter (about 2.1 percent per year). This is due to the substantial increase in GNP after 2050 in all currently underdeveloped and developing regions (see Table 3-1). Lower GNP growth rates in the less developed and developing regions were used to test the sensitivity of energy-use estimates to GNP growth. By lowering the average annual rate of GNP growth (2050-2100) in all less developed and developing regions from about 3.8 percent to 2.8 percent, final energy use in 2100 dropped by 17 percent to roughly 1100 EJ.

The energy use curves also reflect a large amount of energy conservation, that is, energy saved through solar applications in the residential and commercial sectors plus reduced demand due to increases in the price of energy. In fact, the estimated amount of final energy conserved is so large that it exceeds the amount used after 2050. This conservation is also reflected

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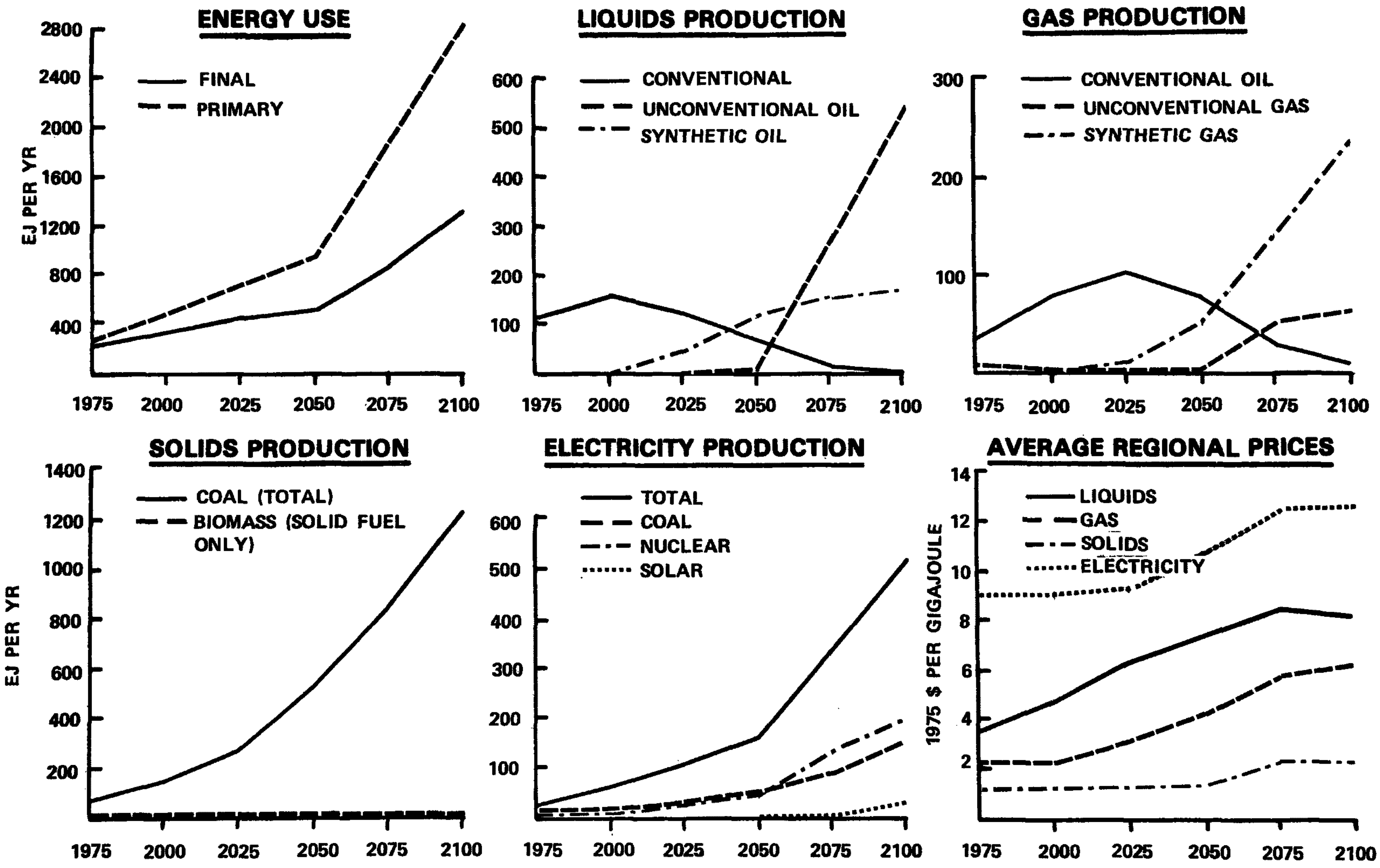
* Final energy use refers to the energy value of the fuels actually used. That is, energy lost in fuel preparation is not included. Total energy use is referred to as "primary energy".

## FIGURE 4-1

## MID-RANGE BASELINE SCENARIO: ENERGY USE CHARACTERISTICS [a]



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[a] PRODUCTION OF ELECTRICITY, UNCONVENTIONAL FUEL, AND SYNTHETIC FUEL IS SPECIFIED IN UNITS OF FINAL ENERGY. PRODUCTION OF OTHER FUELS IS IN UNITS OF PRIMARY ENERGY.

in declining energy/GNP ratios from about 43 GJ/$ in 1973 to about 16 GJ/$ in 2100, a decline of over 60 percent. Thus, the energy effects of increasing GNP are offset to some extent by efficiency improvements.

These energy-use estimates can be placed in perspective by comparing them with estimates made by other investigators. The International Institute for Applied Systems Analysis has projected primary energy use worldwide of between 705 and 1,123 EJ in 2030 (Anderer, et al., 1981). A much lower energy-use future is envisioned by Lovins--165 EJ in 2030 (Lovins, et al., 1981). Our projection of about 710 EJ in 2025 thus falls in the middle of this range of projections.

The fuel production charts in Figure 4-1 reveal that increasing energy demand is satisfied largely by coal, and after 2025, by both unconventional and synthetic sources of oil and gas. Use of electricity also increases sharply after 2050. Conventional sources of oil decline rapidly after 2000 while conventional sources of gas peak in 2025 with a steady decline thereafter. Interestingly, synthetic gas is estimated to be much more price-competitive than unconventional gas throughout the next century, while synthetic oil is first more (before 2075) and then less competitive than unconvention oil (largely shale oil). The crossover in production curves for synthetic versus unconventional oil reflects the fact that, despite technological improvements, synfuel costs are tied to the steadily increasing cost of raw materials (almost exclusively coal), while costs for unconventional oil reflect only the decreases from maturation of the technology. Coal shows unfaltering strength throughout the entire period both as a solid fuel and as the raw material for synthetic oils and gases. Biomass and solar electric remain minor fuel types. Biomass is undercut economically by coal, and solar is underpriced by both nuclear and coal.

Fuel-price patterns reveal differences in both production costs and demands among fuel types.* Higher prices for electricity and liquids are sustained by the fact that, for some end uses, no other fuel can substitute. For example, some industries such as aluminum smelting are heavily invested in electrolytic technologies, and transportation vehicles continue to be operated by liquid fuels due to the high energy content per unit weight and transportability of liquids. The rising prices of all fuels over time reflect the depletion of less costly sources relative to demand. Since, of all the unconstrained fuels, coal remains plentiful and is characterized by the initially lowest and least rapidly rising long-term cost function, its rate of price increase is the smallest.

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* The fuel prices shown in Figure 4-1 are average regional prices unweighted by fuel use.

## $CO_2$ and Atmospheric Responses

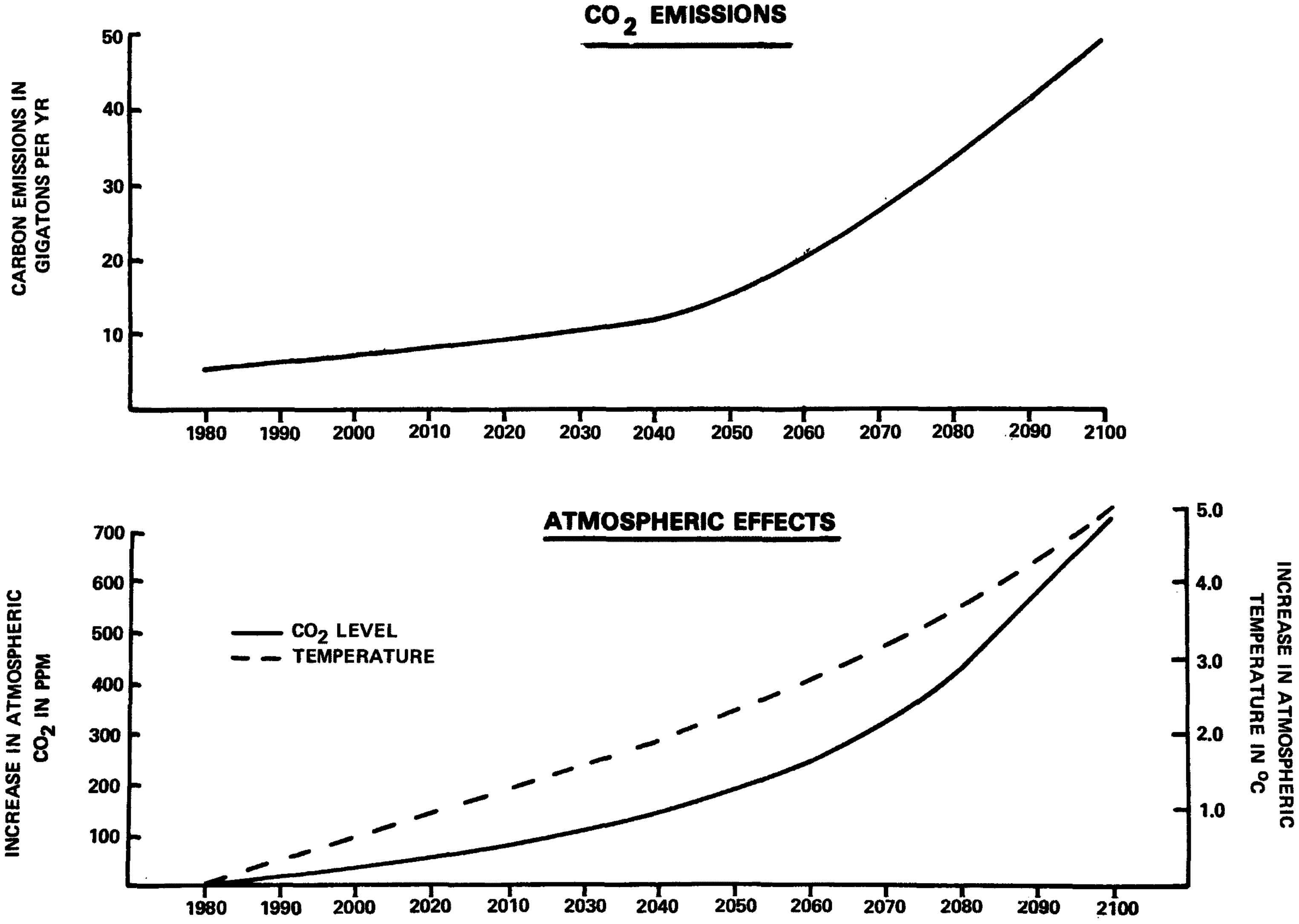
The changing pattern of fuel use estimated for the IEA/EPA Mid-range Baseline scenario will produce a specific trend in $CO_2$ emissions over time. These emissions in turn will raise the level of atmospheric $CO_2$ and temperature, the extent of the estimated increase being dependent on assumptions about how the earth-atmosphere system responds to additional $CO_2$ emissions.

Figure 4-2 shows the time course of $CO_2$ emissions, $CO_2$ concentrations, and atmospheric temperature at the surface of the earth for the Mid-range Baseline scenario from 1980-2100. Atmospheric $CO_2$ and temperature values were estimated using the following GISS model parameters: greenhouse gases other than $CO_2$ were assumed to increase moderately over time, the equilibrium temperature for a doubling of $CO_2$ ($T_e$) was set at 3.0°C, and the other parameters were set at their nominal values (those identified in Table 3-4).

All three model outputs increase steadily in Figure 4-2 through 2040, with $CO_2$ concentrations doubling from pre-industrial levels around 2060.

# FIGURE 4-2

## $CO_2$ MODELING RESULTS FOR THE MID-RANGE BASELINE SCENARIOS



$CO_2$ EMISSIONS

ATMOSPHERIC EFFECTS

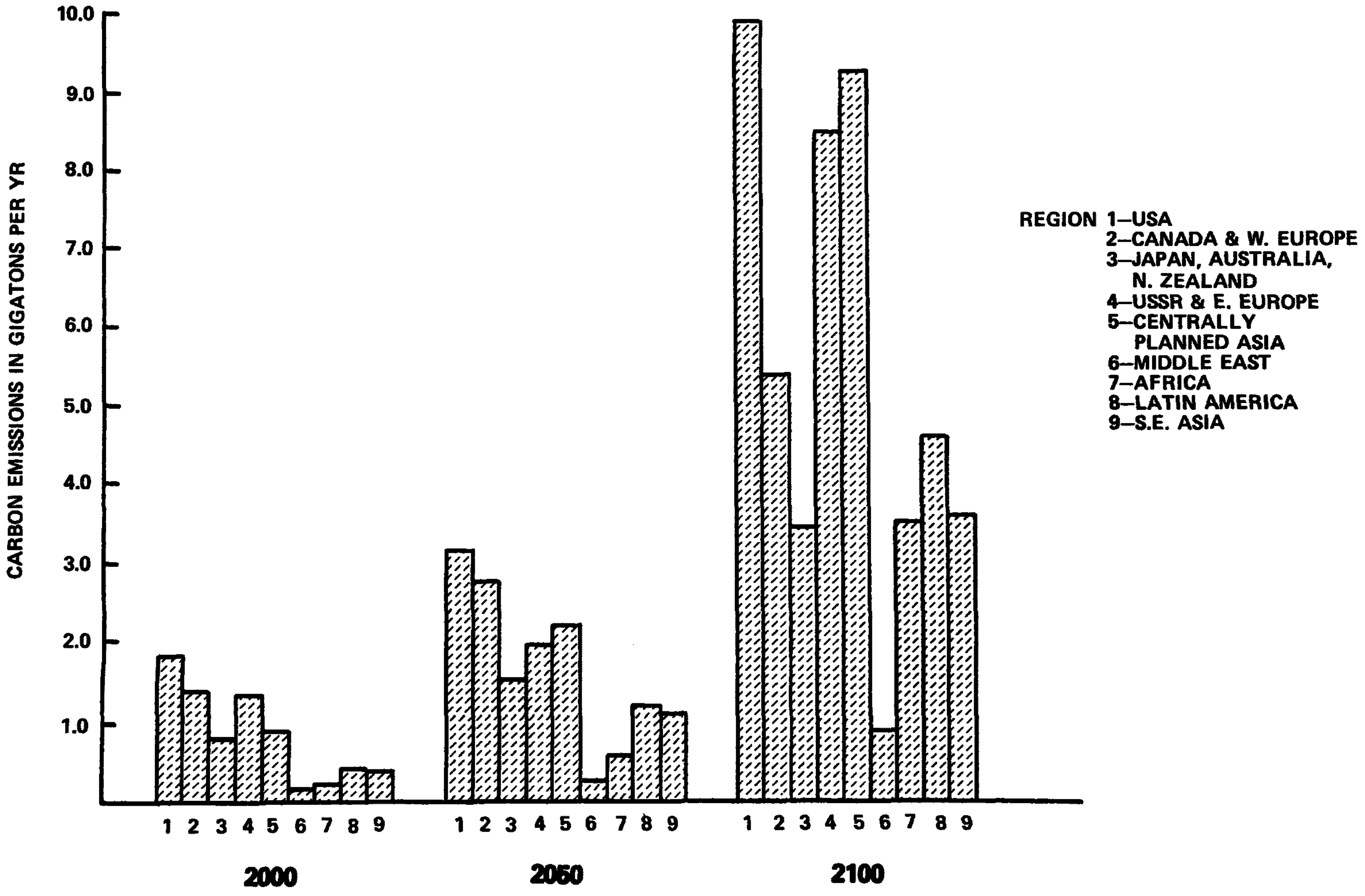
After this date, the rate of increase in $CO_2$ emissions accelerates dramatically. This is due largely to (1) the assumed maturation of the world's economies after 2050 and the resulting increase in GNPs, and (2) the accelerated use of synthetic fuels after 2025 and unconventional oil (especially shale oil) after 2050. These factors combine to produce an average annual rate of increase in $CO_2$ emissions of about 2.4 percent from 2050-2100. (However, this is still lower than the rate of increase from 1950-1980, roughly 4.1 percent per year [Clark, 1982]).

To further illustrate patterns and time trends in projected $CO_2$ emissions, the IEA model estimates for each of the nine regions and for three time periods are shown in Figure 4-3. In 2000, $CO_2$ emissions are dominated by the developed regions (Regions 1-4 in Figure 4-3). Together they account for almost 73 percent of global emissions. However, the growing importance of the other 5 regions is readily apparent. By 2100, the proportion of global $CO_2$ emissions accounted for by the three developed regions has fallen to just under 55 percent. This fraction would be even lower except for the large quantities of coal and shale oil located in the developed regions (especially the U.S., Canada, Europe, and the U.S.S.R.) and the resulting large quantities of $CO_2$ generated in producing usable fuels from these resources.

To demonstrate the sensitivity of the atmospheric temperature results to the primary GISS modeling parameters, the Mid-range Baseline scenario was modeled for three values of $T_e$

# FIGURE 4-3

## GEOGRAPHIC DISTRIBUTION OF $CO_2$ EMISSIONS FOR THE MID-RANGE BASELINE SCENARIO



(1.5°C, 3.0°C, and 4.5°C), both with and without growth in atmospheric levels of other greenhous gases. This range in $T_e$ encompasses the NAS confidence interval (3.0 ± 1.5°C), while the range in growth rates of other greenhouse gases, from 0 (i.e., constant levels of trace gases) to those extrapolated from historical rates (see Table 3-4), may or may not be a good approximation of the variability in future levels of trace gases. A uniformly higher growth rate for all trace gases (2.0 percent per year) was also used together with the highest value of $T_e$ (4.5°C) to establish an upper bound for the rate of temperature increase. The results are shown in Figure 4-4.

Uncertainty in the $T_e$ and trace gas parameters produces substantial variability in the rate of temperature increase. Measured in terms of the year in which a temperature rise of 2°C is experienced, the overall variability is about 80 years (from roughly 2015 to 2095 for the extreme cases). Looking just at the curves for a moderate growth rate in greenhouse gas levels (middle curves in Figure 4-4), varying the assumed temperature sensitivity of the atmosphere (temperature equilibrium) between $T_e$ = 4.5°C and 1.5°C is seen to change the estimated 2°C year from 2030 to 2070. Likewise, assuming that other greenhouse gases remain at their current levels (and that $T_e$ = 1.5°C) delays the 2°C date roughly 25 years, from about 2070 to 2095. On the other hand, assuming a very high growth rate of greenhouse gases other than $CO_2$ (and that $T_e$ = 4.5°C) advances the 2°C date by another 15 years, from 2030 to 2015.

# FIGURE 4-4

# SENSITIVITY OF MID-RANGE BASELINE TEMPERATURE ESTIMATES

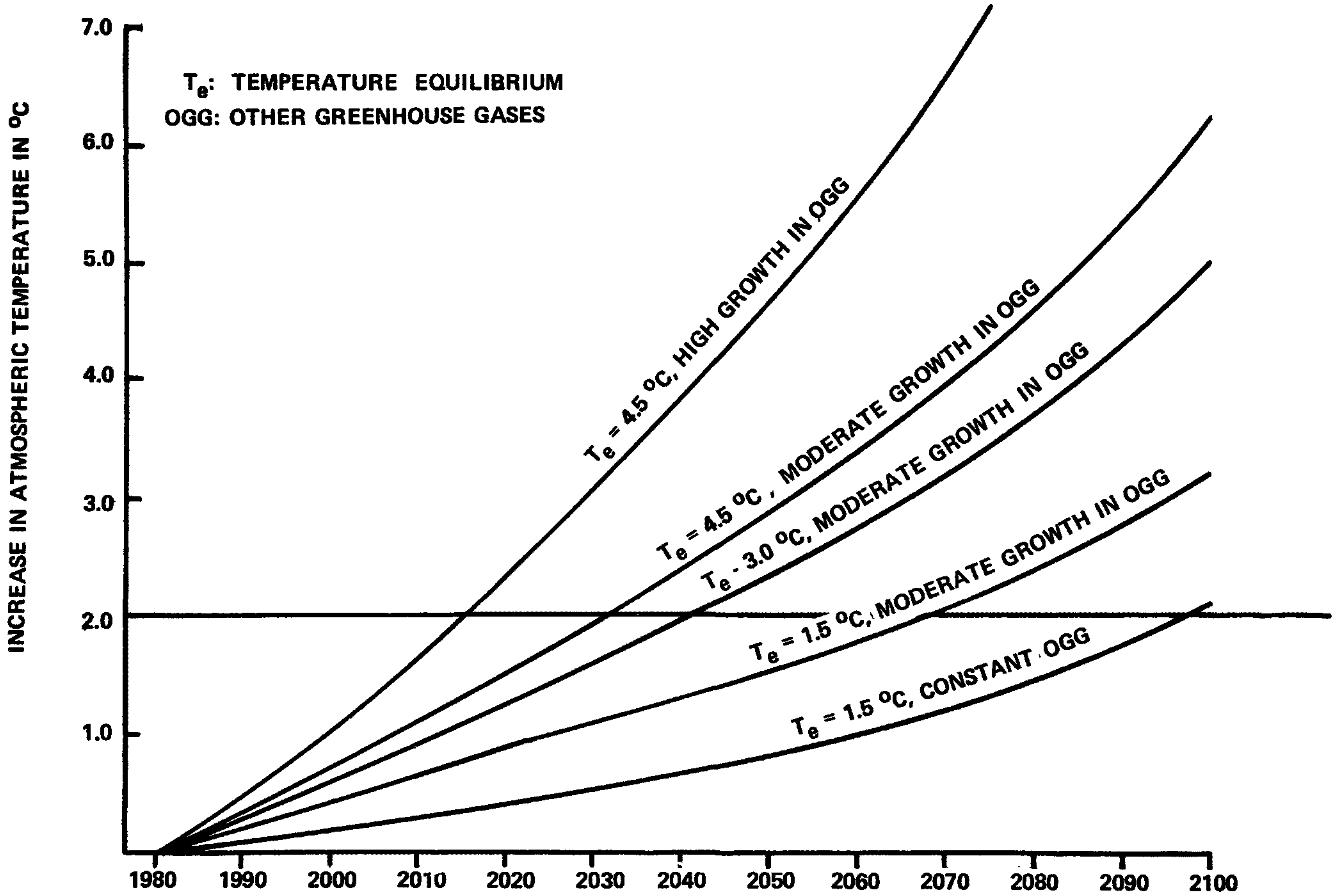


Figure 4-4 reveals considerable nonlinearity in the way uncertaintities in temperature sensitivity and the rate of growth of other greenhouse gases combine to change the estimated date of a 2°C rise in temperature. This is due in part to the angle with which the 2°C line intersects the curves. Moreover, the realism of the range in parameter values remains in doubt, at least for the greenhouse gas growth rates. Nevertheless, this type of sensitivity analysis provides a means for gauging the relative importance of these two parameters. Based on the curves in Figure 4-4, uncertainty in temperature sensitivity appears to introduce about 35-40 years of variability in the estimate of when a 2°C temperature rise will be observed, while uncertainty in the growth of other greenhouse gases introduces roughly 40-45 years of variability.

The size of these changes in the rate of temperature increase appear to be highly significant in the context of time needed by public and private decisionmakers to develop and implement response strategies. Although a simple set of "more likely" assumptions ($T_e$ = 3.0°C and moderately increasing levels of other greenhouse gases) is employed for investigating baseline and policy scenarios, the uncertainty which accompanies these assumptions must be kept in mind when interpreting the significance of the analytical results.

## OTHER BASELINE SCENARIOS

As the name implies, the Mid-range Baseline scenario is believed to be representative of likely future conditions. However, other scenarios may be equally probable given the incomplete nature of the data base on which these projections are based and the inherent risks in projecting events in the distant future. To gauge the variability in atmospheric responses from changes in baseline energy conditions, several alternative baseline scenarios were investigated.

### Energy Supply and Demand

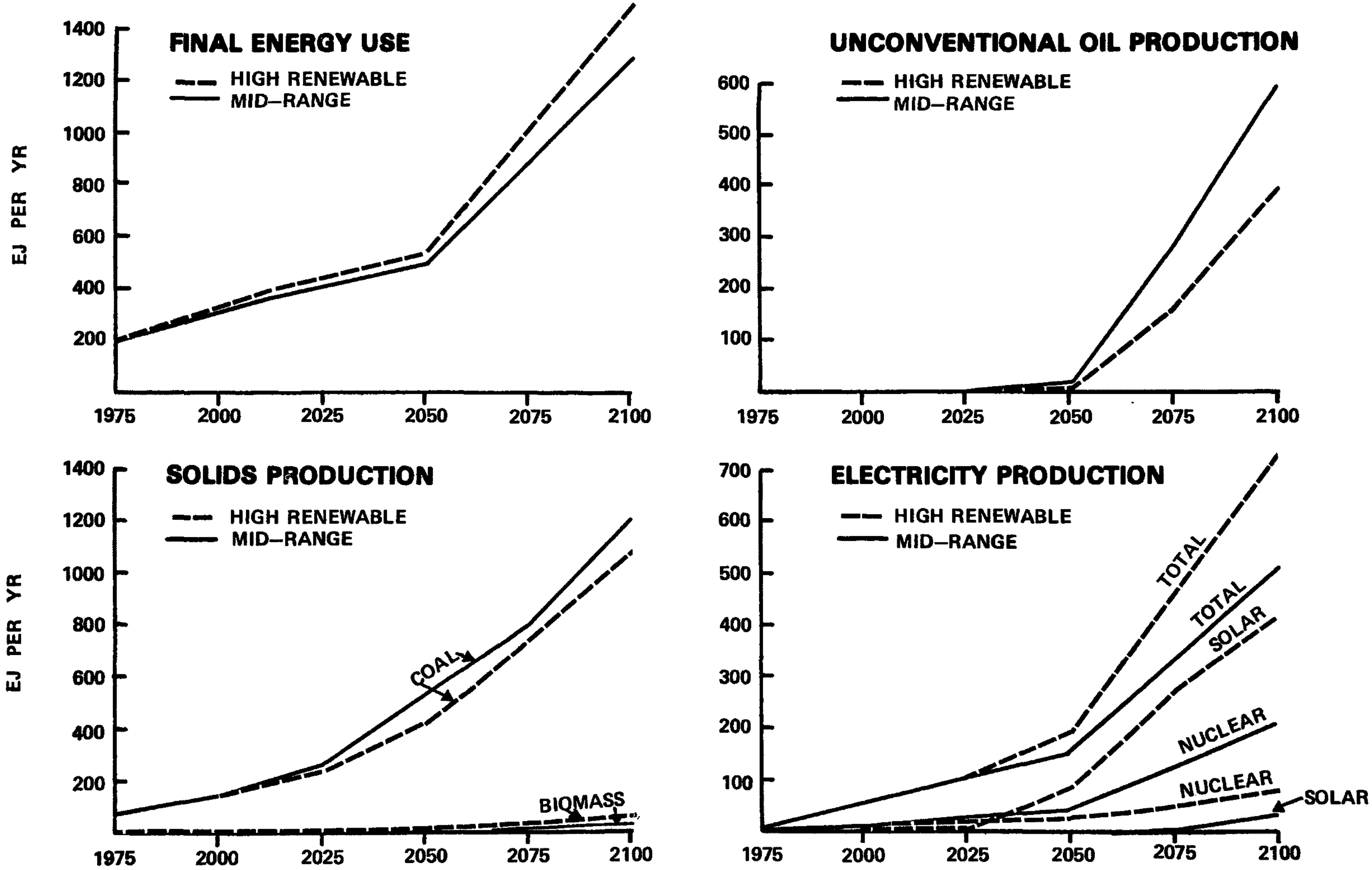
The first alternative is a scenario with reduced $CO_2$ emissions that features (1) lower production costs and therefore higher use of renewable fuels, and (2) increased use of passive solar building designs in the residential and commercial sectors of the OECD regions. This is called the High Renewable scenario. First, the cost (assumed constant over time) of producing biomass from wastes and from energy farms is reduced by half at every step of the supply schedule. Second, the rate of decline in costs of producing solar-powered electricity is accelerated and the final costs reduced by between 68 and 77 percent, depending on the region. Finally, use of passive solar energy is expanded by increasing the "enhanced energy efficiency" parameter at a 0.2 percent average annual rate.

Figure 4-5 compares trends in selected fuel-use characteristics between the High Renewable and Mid-range scenarios. First, energy use is higher. The reduction in solar electric and biomass production costs lower energy prices, thus stimulating energy demand. For example, the average regional price of electricity is one third less by 2100 in the High Renewable scenario. As a result, electricity production is up appreciably, as shown, especially solar-powered production. From a $CO_2$ emissions perspective, however, the positive effect of increased use of solar electricity is eroded since nuclear rather than coal is primarily replaced as the generation fuel. (That is, solar replaces nuclear as the marginal cost fuel.) As will be shown later, the reduction in $CO_2$ emissions compared with the Mid-range Baseline is substantial but not dramatic (about 20 percent reduction between 2050 and 2100). Figure 4-5 also reveals that the use of biomass as a solid fuel is increased only slightly by the 50 percent reduction in production costs since coal is still less expensive and can meet demand for solids in most regions.

A lower $CO_2$-producing baseline which relies increasingly on nuclear fuel was also investigated. Increased use of nuclear power is simulated by (1) reducing the final (in 2100) production costs of nuclear by half (and thus production costs in earlier years by somewhat less than half), and (2) increasing the parameters which control (along with relative cost) the fuel shares for electrity generation. The latter change implies fewer indirect

FIGURE 4-5

HIGH RENEWABLE vs MID-RANGE SCENARIOS: FUEL USE CHARACTERISTICS[a/]



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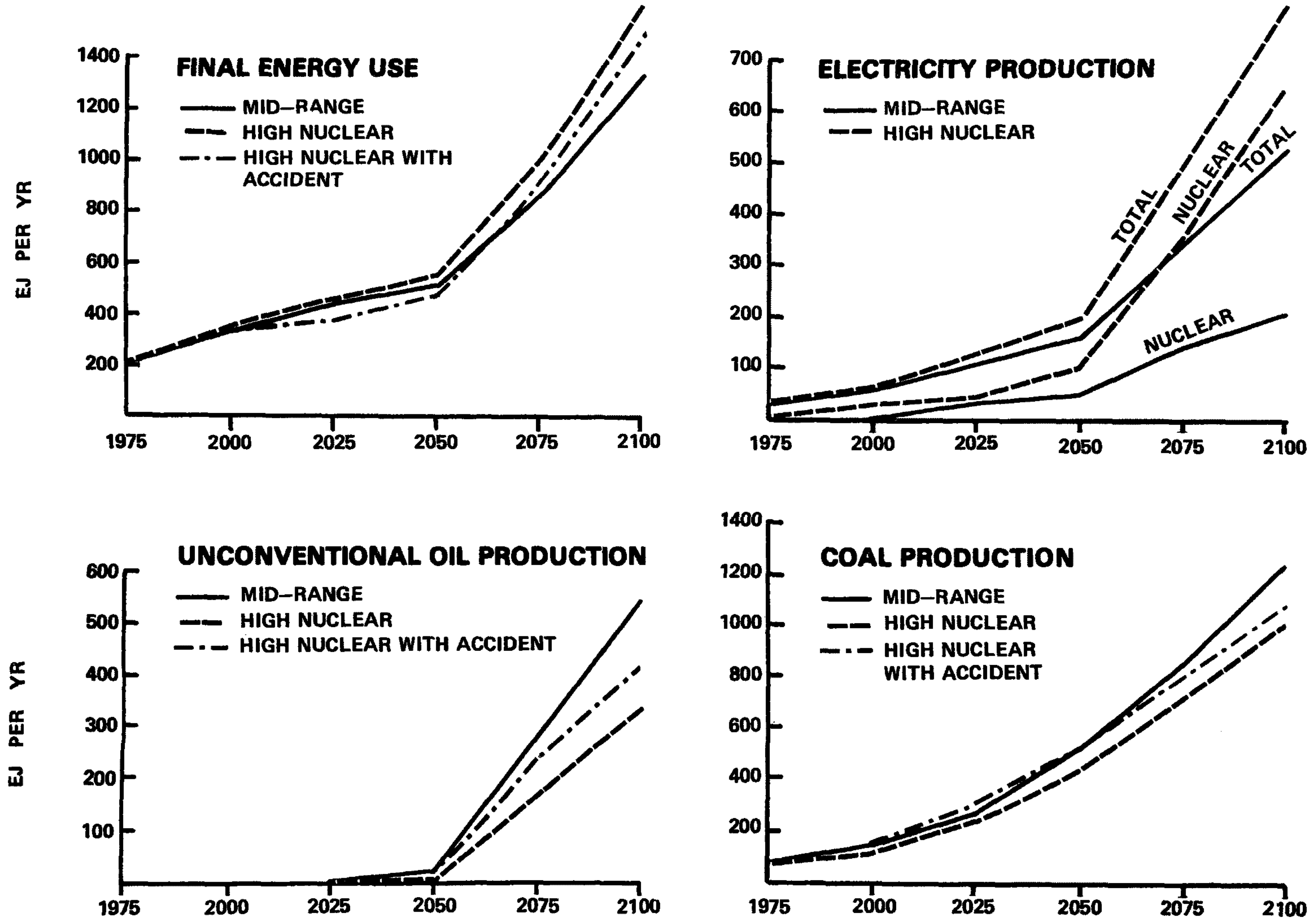
[a/] PRODUCTION OF SOLIDS IS SPECIFIED IN UNITS OF PRIMARY ENERGY. PRODUCTION OF OTHER FUELS IS IN UNITS OF FINAL ENERGY.

cost restrictions on the construction of nuclear facilities such as reductions in the time to obtain construction permits. In addition, a temporary reduction in generating capacity and a longer term slow-down in the rate of nuclear power plant construction as a result of a nuclear accident sometime between 2000 and 2025 is superimposed on this baseline. The accident scenario is intended to simulate the consequences of an intermittent acceleration of nuclear power use. These scenarios are called High Nuclear and High Nuclear with Accident Baselines.

Figure 4-6 shows the major fuel use features of these scenarios. Lowering production costs and easing the restrictions on nuclear power is a powerful stimulant to the use of electricity. And as use of electricity expands, given this set of cost assumptions, production of coal and unconventional oil declines. However, as costs decrease, total energy demand grows as well, up to 20 percent by 2100. The impact on $CO_2$ emissions is a reduction from the Mid-range Baseline but an increase above the High Renewable Baseline. The effect of the simulated nuclear accident is to cause a temporary reduction in energy demand, but the rate of growth of nuclear power in the long-run is not affected. The realism of the High Nuclear with Accident scenario remains in question since the IEA model does not explicitly consider disruptions to supply factors which likely would occur if a moratorium on new plants was declared for an extended period of time. The effect on $CO_2$ of a moratorium is to bring total emissions closer to the Mid-range Baseline.

## FIGURE 4-6

## HIGH NUCLEAR VS. MID-RANGE SCENARIOS: ENERGY USE CHARACTERISTICS [a]



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[a] PRODUCTION OF COAL IS SPECIFIED IN UNITS OF PRIMARY DEMAND. PRODUCTION OF OTHER FUELS IS IN UNITS OF FINAL ENERGY.

A third lower $CO_2$-producing scenario is one in which electrification is encouraged coupled with low solar and nuclear costs. This is called the High Electric Baseline and features (1) increased market penetration of electricity in each economic sector in the OECD regions, and (2) the same production cost functions for solar and nuclear as in the High Renewable and High Nuclear Baseline scenarios. Higher market penetration would be accomplished, for example, by greater use of heat pumps, electric boilers, and electric cars, all encouraged by factors other than the relative annualized costs of electricity and competing fuels.*

This scenario produces substantially higher electricity demand but only slightly higher total energy use, than the Mid-range Baseline, as shown in Figure 4-7. Only a small increase in total demand occurs despite a decrease in the average regional price of electricity in 2100 of 40 percent, compared to the Mid-range scenario. Although this price difference is substantial, the price of electricity is still higher here than other fuels available in the Mid-range scenario. Since many consumers are assumed to be using electrical equipment in this secenario irrespective of its price relative to other fuels, they would be paying more for the same level of energy use estimated in the Mid-range Baseline (since electricity costs more), thus their level of demand decreases.

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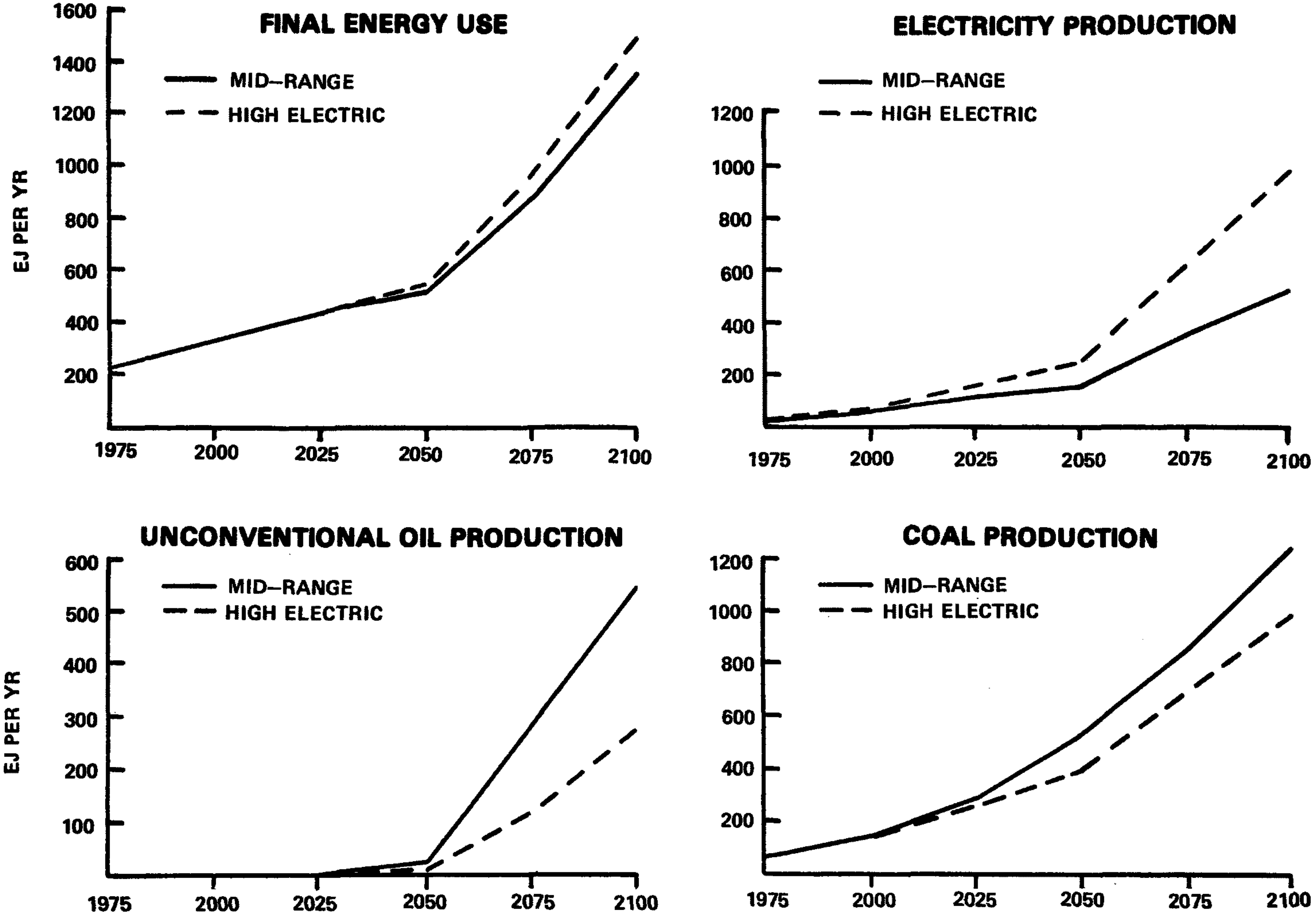
* These factors could be lower initial costs, greater reliability, or better ease of operation associated with electrical equipment.

## FIGURE 4-7

## HIGH ELECTRIC VS. MID-RANGE SCENARIOS: ENERGY USE CHARACTERISTICS [a/]



[a/] PRODUCTION OF COAL IS SPECIFIED IN UNITS OF PRIMARY ENERGY. PRODUCTION OF OTHER FUELS IS IN UNITS OF FINAL ENERGY.

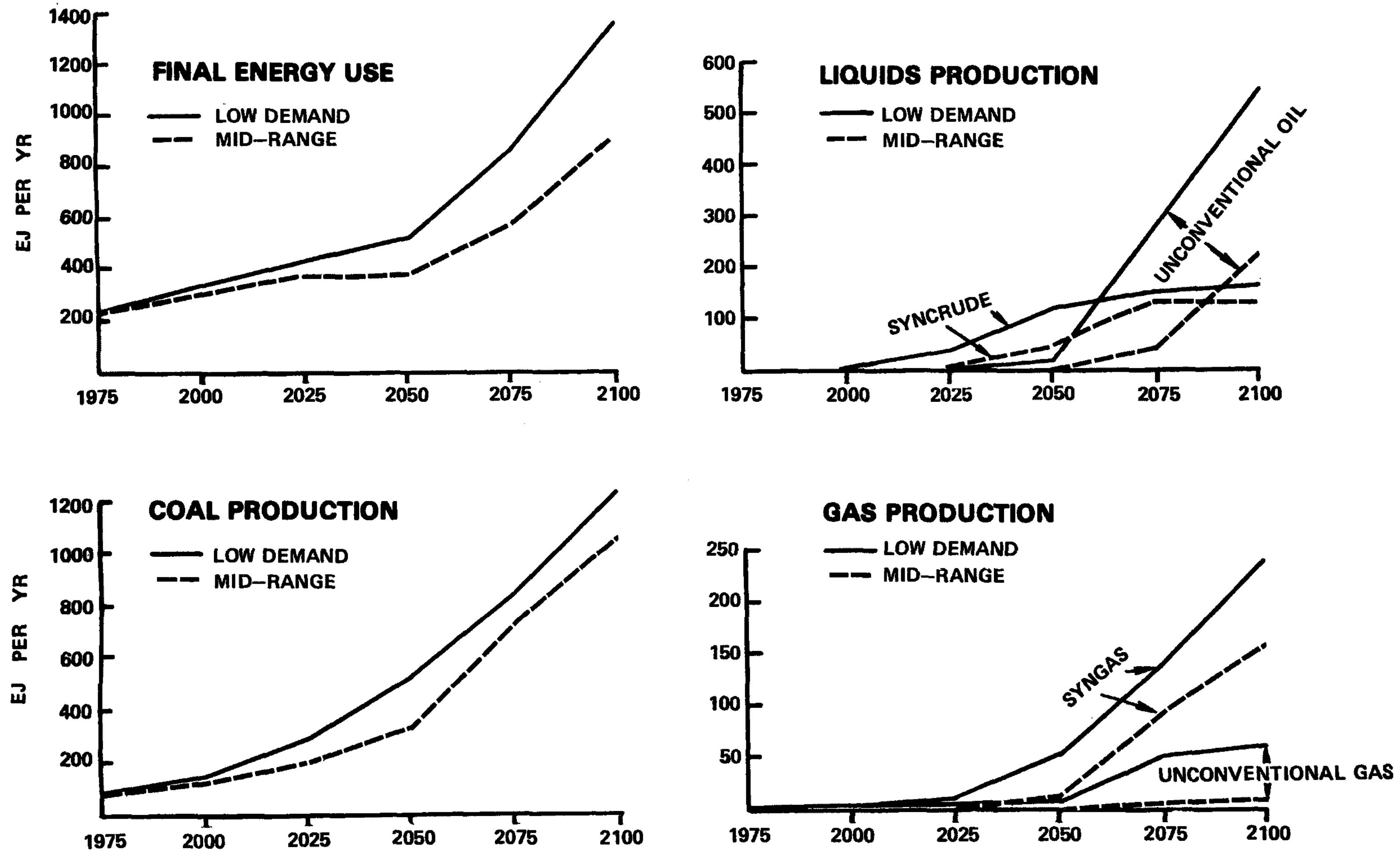
Figure 4-7 also shows a substantial reduction in the use of coal and unconventional oil. Synthetic oil, however, remains at about the same level as in the Mid-range Baseline. All of these effects work together to produce a substantial reduction in $CO_2$ emissions -- 33% by 2100.

The final low $CO_2$ baseline features high fossil fuel costs and enhanced conservation. These factors work together to lower overall energy demand; thus, this senario is called the Low Demand scenario. The breakthrough and long-run reference prices for coal, unconventional oil, and unconventional gas are each increased by 50 percent. (In effect, this raises the long-run supply curves for these fuels without changing the slope of the curves.) The nonenergy costs of producing synfuels are also increased by 50 percent. Conservation is enhanced by introducing an arithmetic increase in the "enhanced energy efficiency" parameter of 1.0 percent per year for OECD cuntries (residential and commercial sector), and moderately increasing the rate of increase for the aggregate sector in other regions. (To illustrate the changes from the Mid-range Baseline, the parameter index for 2100 is increased from 1.0 to 2.25 in the OECD sectors, and from 1.99 to 2.25 elsewhere.)

These changes produce significant reductions in estimated energy demand, as illustrated in Figure 4-8. Compared with the Mid-range baseline, final energy demand falls about 24 percent in 2050 and over 32 percent in 2100. Reductions in primary

# FIGURE 4-8

## LOW DEMAND VS. MID-RANGE SCENARIOS: ENERGY USE CHARACTERISTICS a/



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a/ PRODUCTION OF COAL IS SPECIFIED IN UNITS OF PRIMARY ENERGY. PRODUCTION OF OTHER FUELS IS IN UNITS OF FINAL ENERGY.

energy use are somewhat higher in 2050 (about 30 percent) but somewhat lower lower in 2100 (about 26 percent). As discussed in the next section, the reduction in $CO_2$ emissions are of a comparable magnitude.

One higher $CO_2$-producing baseline was explored. Since the costs of all fossil fuels but conventional oil and gas are reduced, it is called the High Fossil scenario. Final costs of production (i.e., those in 2100) are reduced by 50 percent for unconventional (shale) oil, unconventional gas, and coal. The costs of converting coal and biomass to synfuels are also reduced by half, but non-energy costs of synfuel production are unchanged.

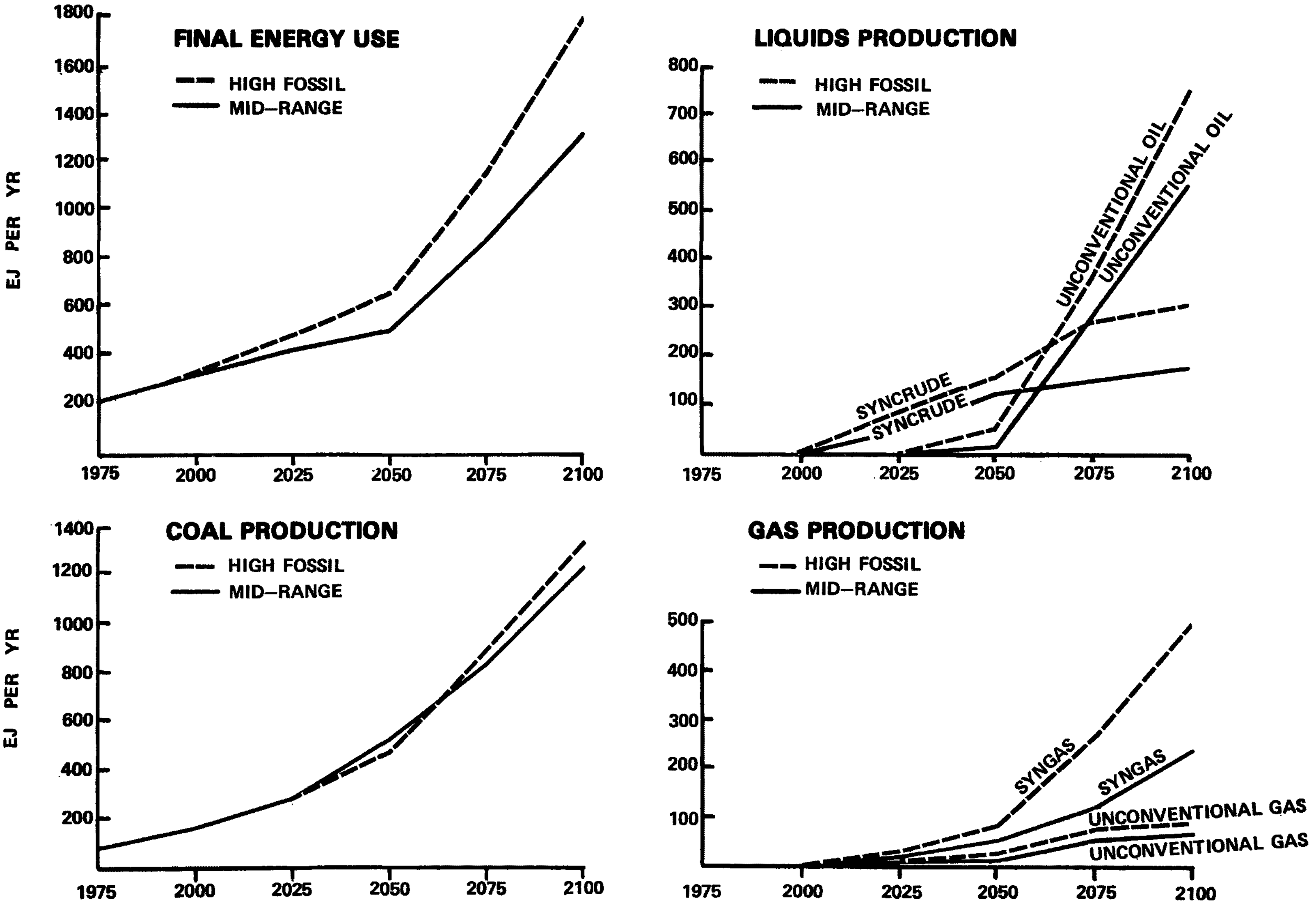
Figure 4-9 summarizes the resulting fuel use patterns compared with those of the Mid-range scenario. As shown, the increase in total demand (resulting from lower prices after 2000) is satisfied largely by increased production of (1) synthetic oil and gas from coal and (2) unconventional oil. Use of these high $CO_2$-emitting fuels raises total emissions by about 20% in 2100.

### $CO_2$ and Atmospheric Responses

The GISS modeling results for the baseline scenarios are illustrated in Figure 4-10. The variation in $CO_2$ emissions and especially in atmospheric temperature change appears small. Using the "time to increase by 2°C" measure, the differences among the various baseline scenarios are negligible -- less than 5 years. In other words, the temperature curves are essentially idential through 2040. Even the difference in estimated temper-

## FIGURE 4-9

## HIGH FOSSIL VS. MID-RANGE SCENARIOS: ENERGY USE CHARACTERISTICS [a]



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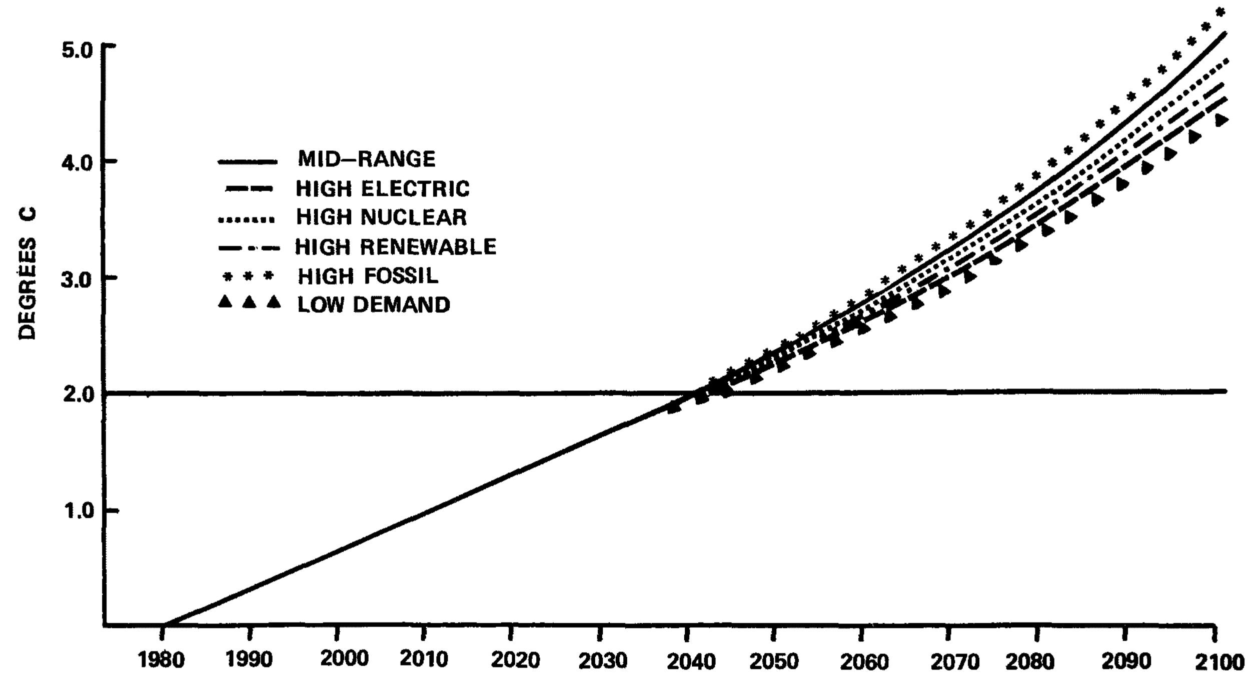
[a] PRODUCTION OF COAL IS SPECIFIED IN UNITS OF PRIMARY ENERGY. PRODUCTION OF OTHER FUELS IS IN UNITS OF FINAL ENERGY.

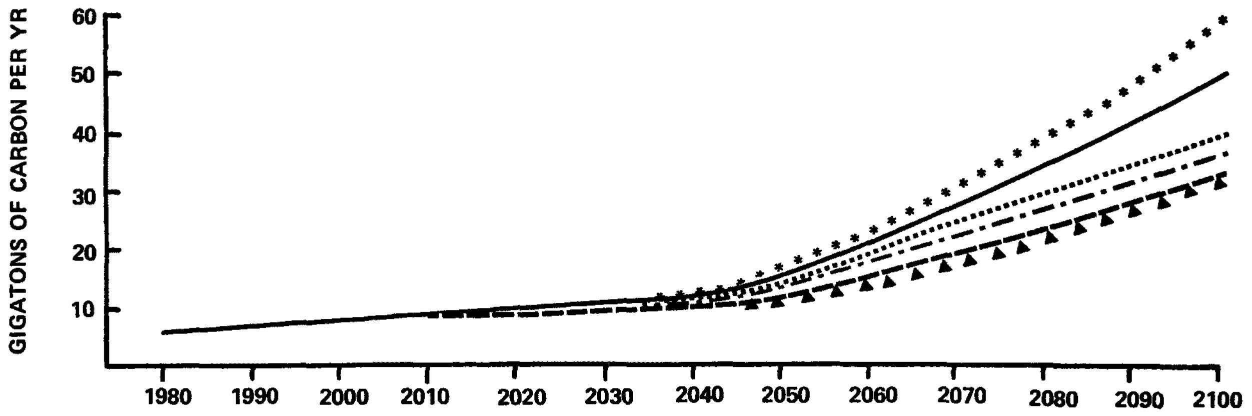
## FIGURE 4-10

## $CO_2$ MODELING RESULTS FOR ALTERNATIVE BASELINE SCENARIOS

INCREASE IN ATMOSPHERIC TEMPERATURE



$CO_2$ EMISSIONS



atures in 2100 varies by only about 0.7°C or less than 15 percent of the projected Mid-range temperature. Clearly, conclusions about the effectiveness of policy options which are reached in this study will not be substantially affected by the choice of baseline scenario.

## OTHER BASELINE SENSITIVITY TESTS

In addition to specifying alternative energy use baselines, the sensitivity of the principal model outputs to selected inputs was tested separately. As noted earlier in this chapter, lower GNP growth rates were tested (2.8 versus 3.8 percent per year) for the less developed and developing regions for the period 2050-2100. Another test involved lowering income (or GNP) elasticities of energy demand. Initial values of 1.0-1.4 in the Mid-range Baseline were reduced uniformly to 0.85 for all regions and all time periods.

Although changing each of these input variables reduced energy demand by as much as 22 percent in 2100, the effects on $CO_2$ emissions and concentrations and especially on atmospheric temperature were substantially muted. Lowering GNP growth rates after 2050 obviously did not affect the projected year of a 2°C rise (2040 in the Mid-range Baseline), and reduced the estimated temperature rise in 2100 by only 0.2°C (less than five percent). Decreasing the income elasticity of demand likewise had no perceptable effect on the 2°C year, and lowered the rise in 2100 by less than 0.5°C.

We conclude from these results that moderate changes to GNP growth rates (post-2050) and to income elasticity of energy demand values will not significantly alter the findings and conclusions of our study.

## POLICY OPTIONS

Policies selected for assessment are designed explicitly to reduce emissions of $CO_2$ either indirectly by depressing aggregate energy demand, or directly by shifting fuel-use patterns toward fuels with low net emissions of $CO_2$. Most policy options examined possess some elements of each strategy.

### TAXES ON $CO_2$ EMISSIONS

The first set of policy options are based on taxing fuel use proportionately to the fuel's net $CO_2$ emissions per unit of energy. Three variations were examined: (1) a tax only in the United States, (2) taxes in all OECD countries, and (3) taxes in all countries. Tax schedules were specified to double the cost of the highest $CO_2$ emitting fuel (unconventional oil):

| Fuel Type | Tax (percent) |
|---|---|
| Conventional Oil | 41% |
| Conventional Gas | 29 |
| Unconventional (Shale) Oil | 100 |
| Unconventional Gas | 29 |
| Synthetic Oil | 81 |
| Synthetic Gas | 86 |
| Coal | 52 |
| All Others (solar, biomass, hydro) | 0 |

Taxes of up to 300 percent were also investigated.

Taxes were initiated in 2000 and were applied at both the points of end use and production such that the combination was sufficient to achieve the total percent taxation indicated above.* In addition, fuel export bans were placed on the United States (U.S. Tax scenario) and on all OECD countries (OECD Tax scenario) to prevent the export of fuels from taxed to untaxed regions, which would otherwise have undercut the global effectiveness of the policy.

Energy Supply and Demand

Changes in total energy demand and in the use of selected fuel types are illustrated in Figure 4-11 for each of the three $CO_2$ tax scenarios. First, an overall dampening of worldwide energy demand is apparent in direct relation to increases in fuel prices as a result of the taxes. Second, a shift away from high $CO_2$-emitting fuels is projected with one exception -- synthetic oil. Production of syncrude is depressed relative to the Mid-range Baseline early in the next century, but exceeds the baseline levels by 2075 for all tax scenarios. Apparently the demand for liquid fuels remains high (especially in the transportation sector), and syncrude is selected over unconventional oil to satisfy this demand. (Recall that the tax on syncrude is 81

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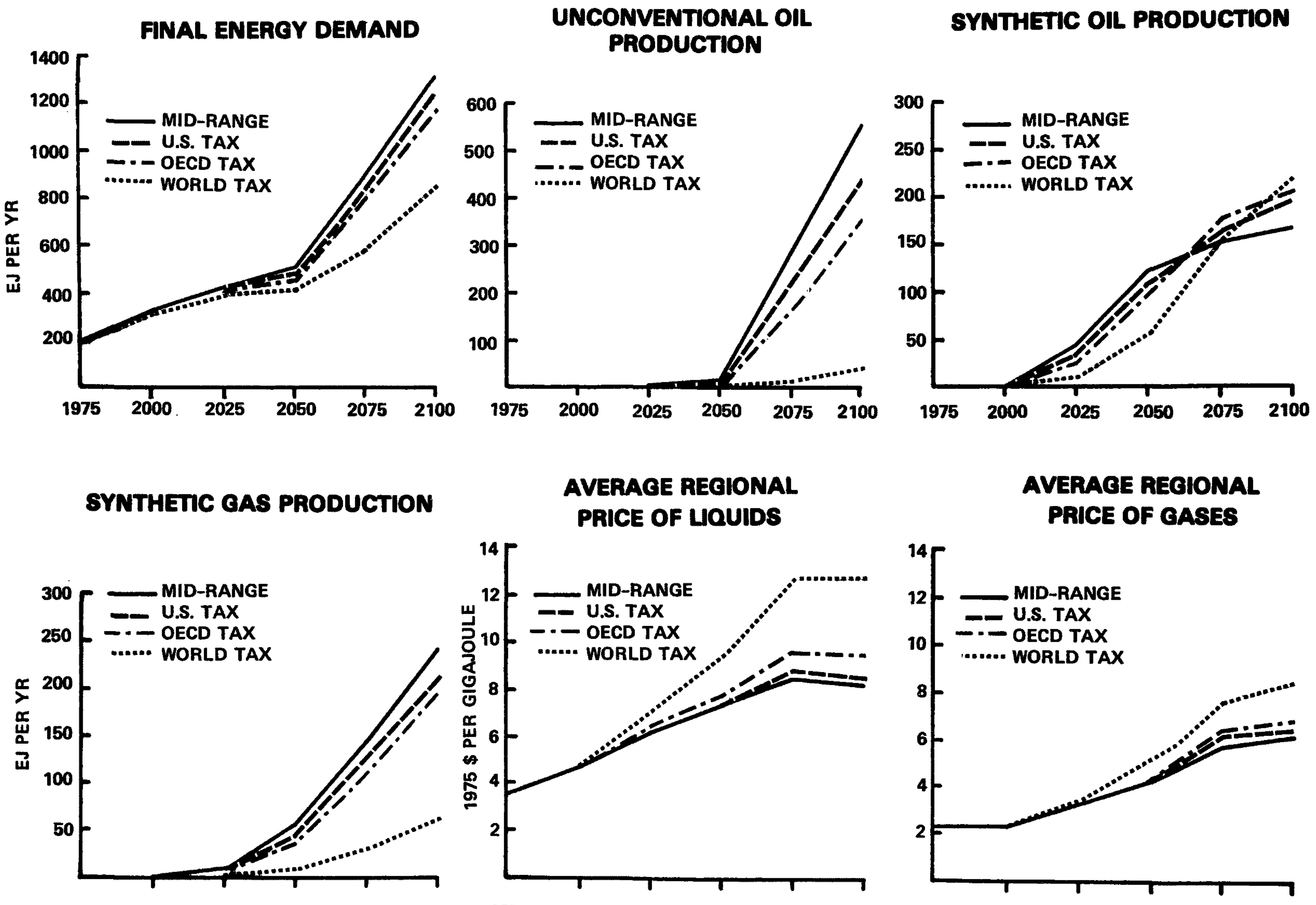
* Due to the structure of the IEA model, negative taxes (subsidies) had to be applied to biomass production to offset the end use taxes on biomass and biomass-derived synfuels.

# FIGURE 4-11

# CO$_2$ TAX POLICIES VS. MID-RANGE BASELINE SCENARIOS: ENERGY USE CHARACTERISTICS [a/]



FINAL ENERGY DEMAND

UNCONVENTIONAL OIL PRODUCTION

SYNTHETIC OIL PRODUCTION

SYNTHETIC GAS PRODUCTION

AVERAGE REGIONAL PRICE OF LIQUIDS

AVERAGE REGIONAL PRICE OF GASES

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[a/] PRODUCTION OF ALL FUELS IS SPECIFIED IN UNITS OF FINAL ENERGY.

percent while the tax on unconventional (shale) oil is 100 percent.) Note also that much of the effect achieved by taxing $CO_2$ emissions occurs after the middle of the next century when large-scale production of unconventional oil and synthetic fuels is underway.

Figure 4-11 also reveals that the World Tax scenario is much more effective in shifting energy demand and fuel-use patterns than the other two scenarios. This is a direct reflection of energy use levels in the U.S. and all OECD countries compared with total worldwide levels. For example, in 2050 under the Mid-range Baseline assumptions, the United States is projected to account for 21 percent and all OECD countries 51 percent of the world's energy consumption. By 2100, these levels are projected to fall to 14 and 34 percent, respectively.

Interestingly, none of the tax scenarios affects the use of coal appreciably. The demand for solid fuels remains strong and the level of $CO_2$ taxes investigated does not provide sufficient cost advantage for biomass to capture a substantial share of this market.

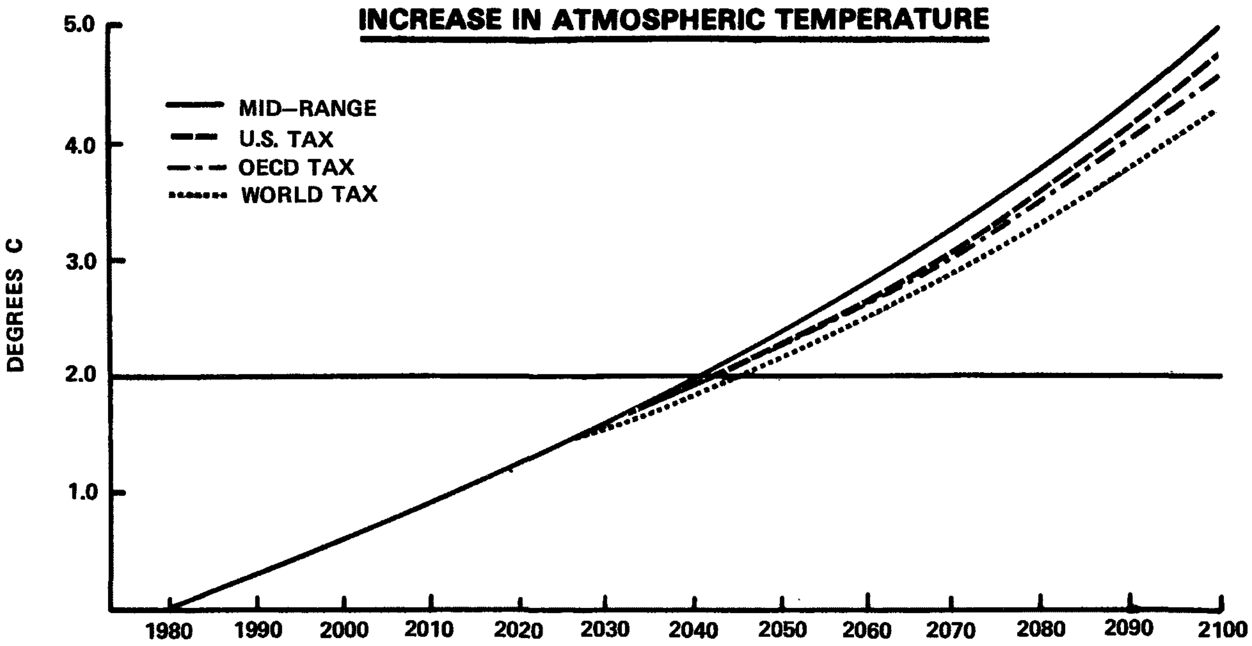
Tripling the level of taxation on all fossil fuels worldwide (i.e., 300 percent on unconventional oil and proportional increases for the others) enhances each of the fuel use trends shown in Figure 4-11. Projected energy demand in 2050 is just over 300 EJ (60 percent of the Mid-range level), synfuel production is delayed until after 2050, and even coal production is depressed (by over 50 percent relative to the Mid-range level). Changes by 2100 are even more dramatic. However, the penalty paid for improved effectiveness in reducing $CO_2$ emissions is a substantial rise in average regional energy prices: approximately 60 percent for liquids, 40 percent for gas, and 20 percent for solids compared with the Mid-range Baseline price schedules in 2050.

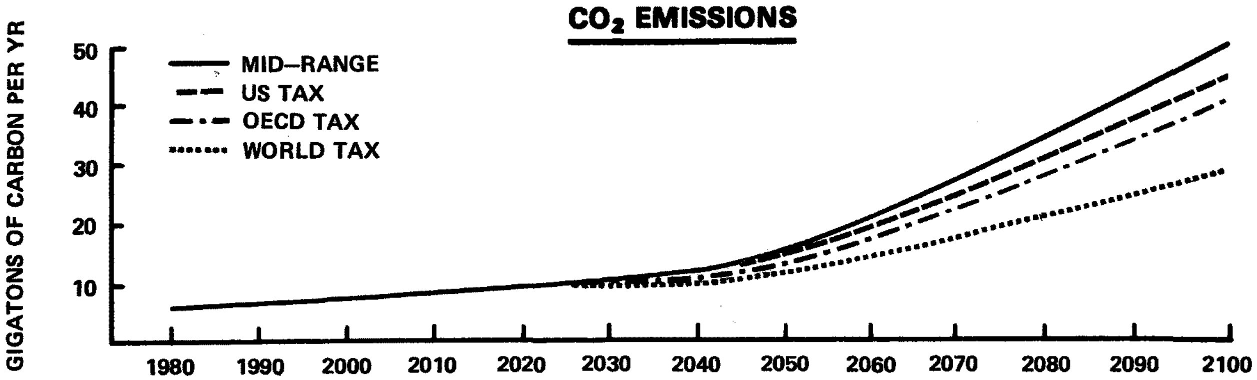
### $CO_2$ and Atmospheric Responses

The resulting $CO_2$ emissions and atmospheric temperature trends are shown in Figure 4-12. As suspected from the fuel-use effects, only the World Tax scenario achieves a significant reduction in $CO_2$ emissions and, even here, only toward the end of the next century. (Emissions are reduced from 5-18 percent in 2050 and from 10-42 percent in 2100.) In terms of changes in atmospheric temperature, the differences between the tax scenarios and the Mid-range Baseline are even less dramatic. Only the World Tax scenario appears to affect the timing of a 2°C increase in temperature and only on the order of a few years. Even tripling taxes worldwide delays a 2°C rise by just over 5 years. Temperature differences are more pronounced in 2100, but even this far into the future, the maximum estimated reduction is only about 0.7°C. Tripling taxes is more effective but not overwhelmingly so (a lowering of temperature in 2100 by perhaps 1.3°C).

# FIGURE 4-12

# $CO_2$ MODELING RESULTS FOR TAX POLICIES AND MID-RANGE BASELINE SCENARIOS





## FUEL BANS

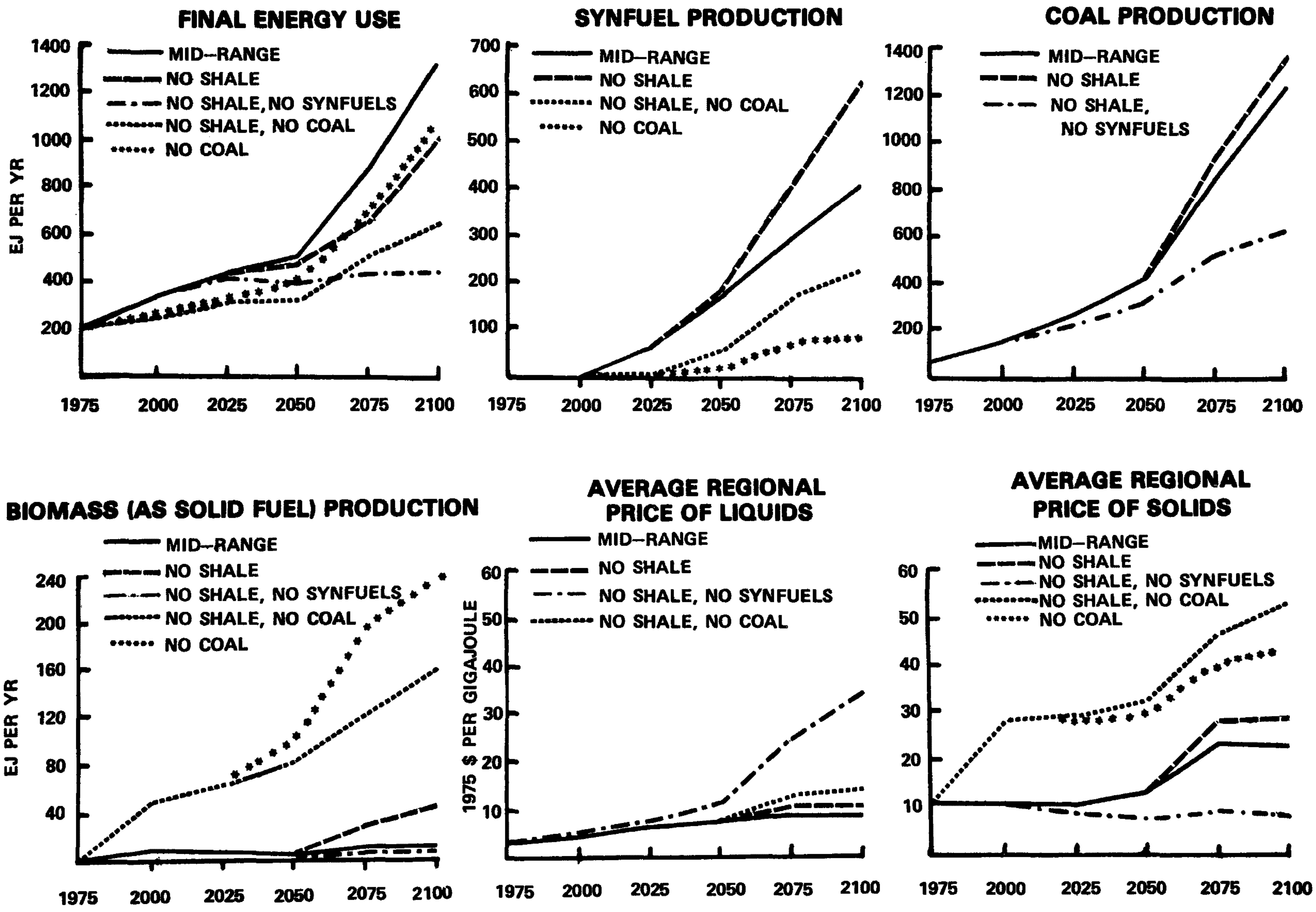
A more direct approach to slowing the rate of $CO_2$ growth is to prohibit all uses of selected high $CO_2$-emitting fuels. Four separate combinations of fuel bans were investigated: (1) coal alone, (2) unconventional (shale) oil alone, (3) shale oil and synthetic fuels, and (4) shale oil and coal. The ban on coal is phased-in between 1980 and 2000. To obtain the maximum effect from these policies, worldwide cooperation among governments is assumed.

### Energy Supply and Demand

Figure 4-13 shows the energy patterns produced by the four fuel ban scenarios. Due to prohibitions on the indicated fuels, energy prices in general are bid upwards by consumers attempting to satisfy their demands. Price increases for liquid fuels are especially dramatic (over a 300 percent increase) for the scenario banning shale oil and synthetic fuels. Solid fuel prices are increased the greatest for the two scenarios banning coal (80-120 percent increase). (Gas prices also rise relative to the Mid-range Baseline but in a somewhat muted fashion). The ultimate effects are substantial decreases in total energy demand compared with the reference baseline, from 20 to almost 80 percent in 2100. The two scenarios banning coal achieve these reductions earlier than the other scenarios.

**FIGURE 4-13**

**FUEL BANS VS. MID-RANGE BASELINE SCENARIOS: ENERGY USE CHARACTERISTICS [a/]**



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[a/] PRODUCTION OF COAL AND BIOMASS IS SPECIFIED IN UNITS OF PRIMARY ENERGY. PRODUCTION OF SYNFUELS IS IN UNITS OF FINAL ENERGY.

Production patterns for individual fuel types provide additional insights. Synfuels are allowed under three scenarios. When shale oil is banned, synthetic oil production grows to meet demands for liquid fuels. However, when coal is also banned, synfuel production is limited by the availability (and price) of biomass. Thus, synfuel levels drop relative to the Mid-range Baseline. Similarly, the production of coal is affected by the demand for coal-derived synthetic oil and gas; when synfuels are banned, coal production drops below the Mid-range Baseline levels. (This is also reflected in the constant or slightly decreasing price of solid fuels.)

Biomass and coal are direct competitors both as solid fuels and as raw materials for synfuels. Whenever coal is unconstrained, it has a substantial competitive edge in almost all regions. However, when coal is banned, the full potential of biomass to satisfy demands for liquids, gases, and solids worldwide can be assessed. Figure 4-13 reveals that, in the "No Shale, No Coal" scenario, biomass accounts for about 225 EJ of synthetic liquid and gas production and about 160 EJ of solid fuel production in 2100. Together, this represents almost 60 percent of total energy demand projected for this scenario.* The penalty for relying

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* The worldwide potential of energy farms to produce biomass for energy has been estimated at between 237 and 3374 EJ, depending on the types of crops planted and the agricultural practices employed. Urban waste may add another 100 EJ potential by 2100 (Reilly, et al., 1981). These estimates are considerably higher than the biomass resource estimates in Appendix A (Table A-2). However, the latter assume no dramatic change in the availability of coal, and thus implicitly incorporate considerations of current economic feasibility. The resource availability estimates used in the IEA/EPA scenarios are intended to reflect extreme circumstances.

on biomass is reflected in the higher price of solid fuels -- approximately $5.25/EJ in 2100 compared to the reference price of $2.25.

## $CO_2$ and Atmospheric Responses

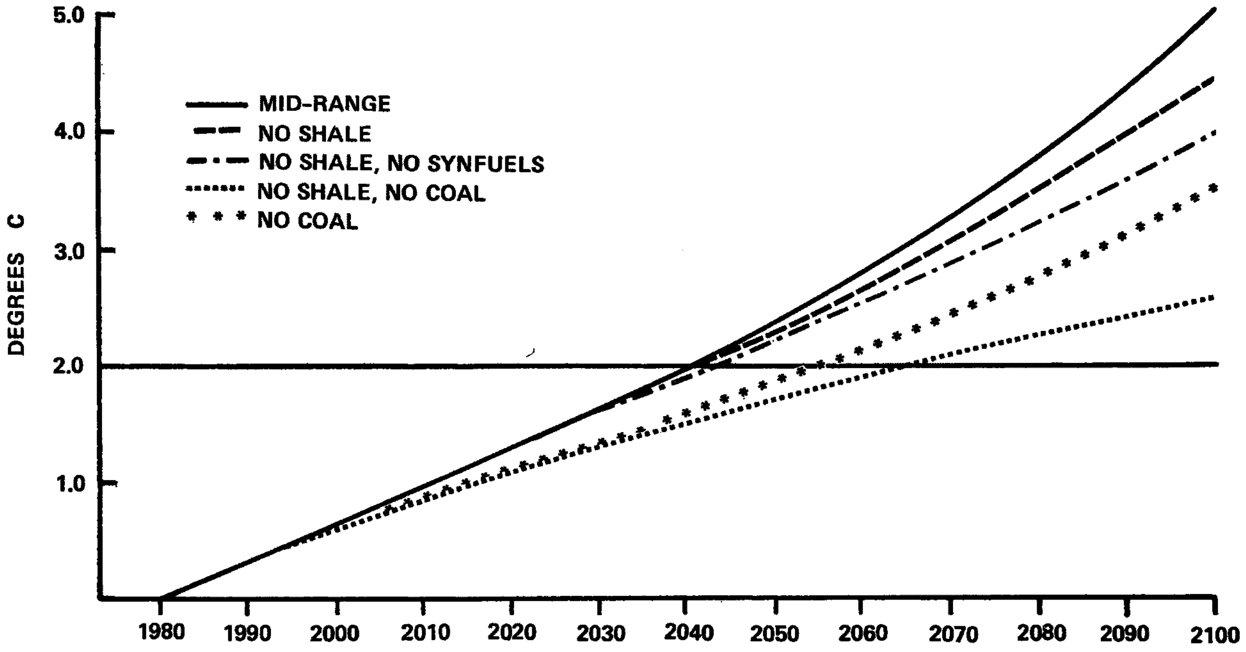
The time course of $CO_2$ emissions and atmospheric temperature for the fuel ban scenarios are shown in Figure 4-14. The changes in energy demand and fuel use discussed above translate into significant decreases in $CO_2$ emissions. The most stringent prohibition scenario (coal and shale oil bans) achieves absolute reductions in $CO_2$ emissions over time; emissions in 2100 are slightly more than 1000 gigatons of carbon worldwide compared to about 4700 in 1975. Moreover, reductions begin very early in the 120-year time period due to the ban on coal phased-in between 1980 and 2000. The "No Shale, No Synfuels" scenario is less effective in terms of total emissions avoided, but does achieve reductions beginning about 2020 and totaling about two-thirds of the projected 2100 emissions in the Mid-range Baseline. Banning just shale is less effective although it still achieves almost a 60 percent reduction in $CO_2$ emissions in 2100 compared with the baseline emissions. Finally, much of the effectiveness of a "coal only" ban is eroded after 2040 when shale oil comes on-line.

To further illustrate the effect of fuel bans on reducing $CO_2$ emissions, Figure 4-15 shows changes in emissions over time for two scenarios in each of the nine geographic regions. In the

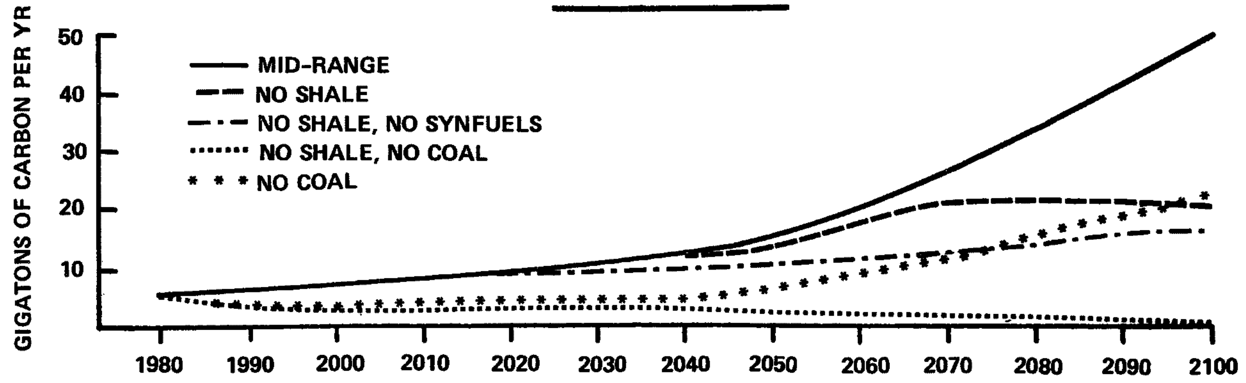
**FIGURE 4-14**

**CO$_2$ MODELING RESULTS FOR FUEL BANS AND MID-RANGE BASELINE SCENARIOS**

**INCREASE IN ATMOSPHERIC TEMPERATURE**

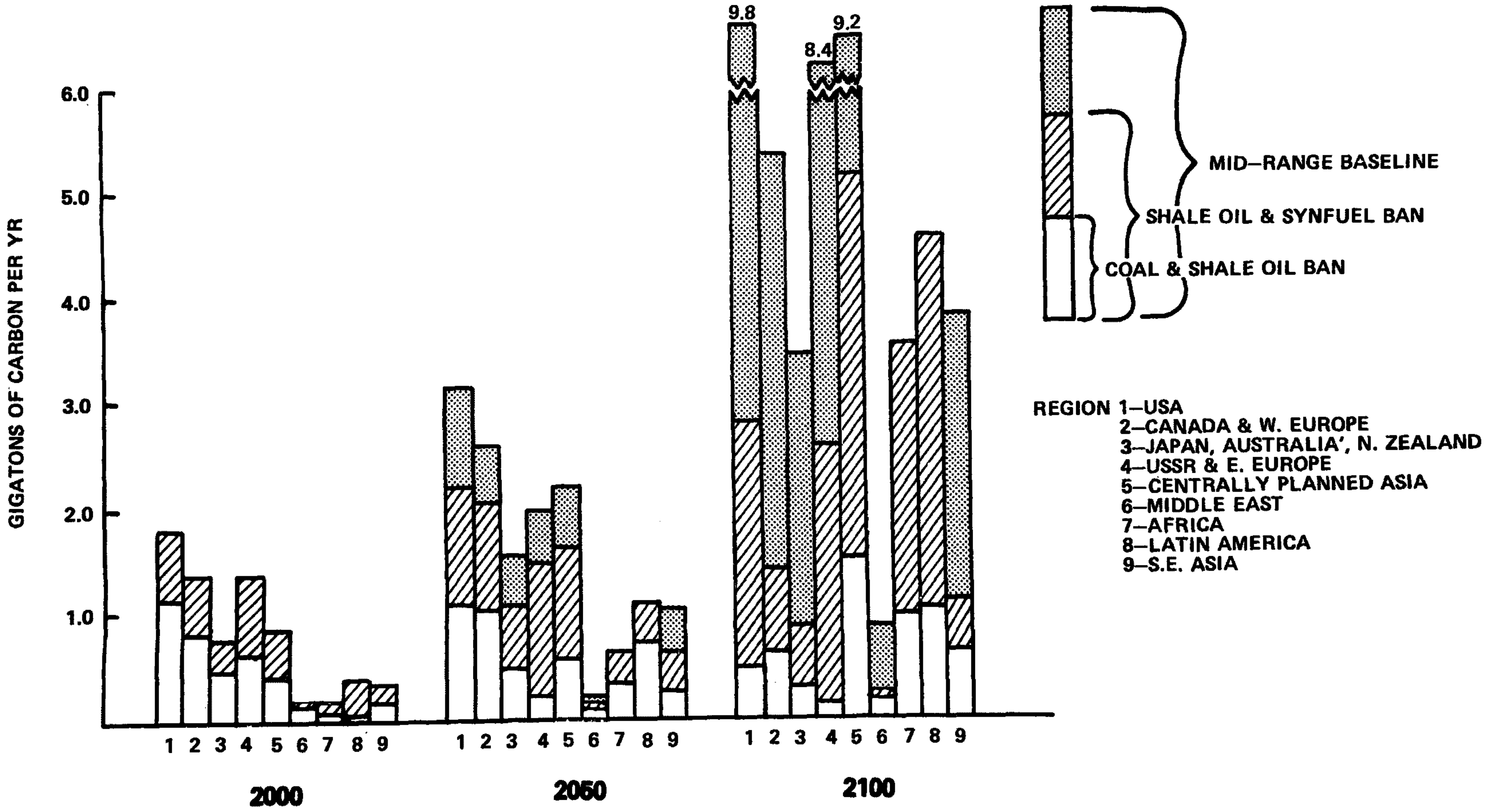


**CO$_2$ EMISSIONS**



## FIGURE 4-15

## GEOGRAPHIC DISTRIBUTION OF $CO_2$ EMISSIONS FOR SELECTED FUEL BANS AND THE MID-RANGE BASELINE SCENARIOS



earliest year (2000) when only a ban on coal reduces emissions, the effects of the ban fall on regions roughly in proportion to their emissions of $CO_2$ in the Mid-range Baseline scenario. Exceptions to this rule are Region 6 (the Middle East), which has very little coal, and Region 8 (Latin America), which has a large biomass potential and is given credit for exporting biomass-derived fuels. By 2050, the effect of a coal ban becomes more uneven, as the coal-rich regions -- Region 1 (U.S.) and Region 4 (U.S.S.R. and Eastern Europe) -- show proportionately the largest drop in projected emissions. By 2100, these two regions have reduced emissions by about 95 and 98 percent respectively, relative to the Mid-range Baseline projections. (Africa and Latin America both show zero net emissions due to the IEA model's accounting scheme for exported biomass energy.)

The pattern of impacts from a ban on shale oil and synfuels is similar -- those regions with large deposits of shale oil or coal are affected the most. Thus, by 2100, Region 1 (U.S.), Region 2 (Canada and Western Europe), and Region 4 (U.S.S.R and Eastern Europe) are forced to reduce emissions by the greatest percentage. In the opposite sense, regions with large capacities for biomass production are also disadvantaged by the ban on synfuels and thus show higher emission levels than those in the coal ban scenario.

Looking at the atmospheric effect of reductions in $CO_2$ emissions associated with fuel bans (Figure 4-14), only the scenarios which ban coal affect the timing of a 2°C rise in atmospheric temperature. For these, however, the size of the effect is significant -- the estimated 2°C year is delayed from roughly 2040 in the baseline to approximately 2055 in the coal ban scenario, and to 2065 under coal and shale oil bans. The scenario featuring a ban on shale and synfuels appears to delay the 2°C date by no more than 5 years, while a ban on shale alone is totally ineffective by this measure.* All prohibition scenarios achieve substantial reductions in temperature rise by 2100, with the most stringent scenario achieving almost a 50 percent reduction.

Based on these results, a clear distinction between medium-term and long-term strategies emerges. The scenarios in which coal is banned show significant medium-term effects (delay in a 2°C rise) since the ban affects fuel use and $CO_2$ emissions in the early years (by 2000 and thereafter). Bans on synthetic

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* In other words, although banning shale alone is not effective in delaying a 2°C rise, banning shale in addition to coal appears to add about 10 years to the "coal only" delay (2055 to 2065). These results at first appear contradictory but can be reconciled; a prohibition on coal encourages an earlier emergence of shale oil (about 100 EJ of unconventional oil are produced in 2050 in the "coal only" scenario compared with only 10 EJ in the Mid-range Baseline), presumably because the lack of coal-derived synthetic oil makes shale oil more cost-competitive.

fuels and unconventional oil only become effective when these fuels would otherwise come on-line. Thus, policies incorporating synfuel and shale oil bans reduce long-run temperature increases, but not the timing of a 2°C rise.

It is also useful to note that a simultaneous ban on coal and synfuels would be duplicative; no additional reduction in either $CO_2$ emissions or atmospheric temperature is achieved by prohibiting synfuels once coal is banned. Moreover, allowing the production of synthetic liquids and gases while prohibiting coal will provide for a biomass-based synfuel industry, thus partially satisfying the demand for liquid fuels in a manner that depresses $CO_2$ emissions.

## SUMMARY

Of the various energy policies designed to slow the rate of atmospheric warming over the next century that were examined in this analysis, only two have been demonstrated to effectively delay the timing of 2°C rise in temperature. Both include a ban on the use of coal which becomes fully effective in 2000. This ban (1) reduces demand for solid fuels by raising their price, and (2) stimulates the use of biomass as a coal substitute. Both effects reduce the aggregate amount of $CO_2$ emitted between now and the middle of the next century. When a ban on coal is combined with a ban on shale oil, the projected 2°C warming may be delayed by perhaps 25 years.

Banning shale and synthetic fuels alone will produce a slowing of temperature rise in the second half of the next century. If coal is also banned, prohibitions on synthetic fuel production are not necessary since all synfuels would be derived from biomass. The effectiveness of fuel bans in lowering the projected temperature in 2100 is significant for all prohibition policies studied, and greatest for policies which ban both coal and shale oil.

The imposition of fuel taxes applied in proportion to $CO_2$ emission characteristics of individual fuels appears to be much less effective than outright fuel bans. Taxes of several hundred percent in magnitude would be needed to substantially depress demand. Even then, the distinction among different type of fuels in terms of $CO_2$ emission characteristics is not nearly as sharp as placing bans on selected fuels. Thus, fuel taxes do not appear to be effective medium-term policy options, and would be effective in the long-run only if taxes were very high.

Regardless of which general policy approach is under consideration, any hope of success requires cooperation among at least the major energy consuming and producing nations. Over time, almost all nations will fall into this category. Without worldwide cooperation, international fuel trading and unconstrained use of fuels in non-cooperating countries would impede the effectiveness of any policy.

These findings must be placed in the context of uncertainties surrounding the relationships between (1) emissions and atmospheric concentrations of $CO_2$ (that is, the nature of the carbon cycle), and (2) atmospheric temperature and $CO_2$ concentrations (that is, the actual temperature equilibrium for doubled $CO_2$). The latter appears to be the more important, and introduces substantial variability in projections of temperature rise. This variability is on the order of 35-40 years in the estimate of when a 2°C warming will occur. Of at least equal significance are uncertainties regarding future levels of other greenhouse gases and their effect on atmospheric temperature. These uncertainties may account for another 40-45 years in the variability of the estimated 2°C warming date.

# CHAPTER 5

## THE ECONOMIC AND POLITICAL FEASIBILITY OF ENERGY POLICIES

The analysis in Chapter 4 clearly shows that only policies that ban coal, or coal and shale oil, would significantly delay a warming of 2°C or more. Furthermore, a ban on coal and shale oil would be effective in reducing the temperature rise in 2100. This chapter examines whether these policies are also economically and politically feasible.

The economic implications of banning coal and shale oil are likely to be significant. Prohibitions on using these fuels would necessitate a fundamental change in fuel use and would most likely affect all sectors of the world economy. It would dampen economic growth by causing a shift to more expensive fuel substitutes. The asset value of existing coal and shale oil resources would decline, as might the value of facilities supporting the production, transportation, and use of fossil fuels due to premature retirement. On the other hand, the value of alternative fuels would be enhanced by coal and shale oil bans.

The economic impact of these policies would affect different countries in very different ways. Impacts would be largest in developed economies heavily dependent on fossil fuels or in countries with large coal and shale oil deposits. Higher energy prices could also severely constrain the economic growth of developing and less developed countries. Such economic hardships could be mitigated by anticipating and planning for changes in energy supplies.

This chapter examines each of these issues. In particular, it looks at our current and likely future commitment to coal and shale oil, and the economic consequences of banning their use. Ideally, this analysis would be based on a detailed model of the world economy capable of translating changes in the energy sector into changes in inflation, economic growth, income levels, and other relevant economic indicators. Unfortunately, no current model provides the desired level of detail and specificity. Given this limitation, we have focused on specific aspects of likely economic impacts and have tried to illustrate the magnitude of potential effects through a series of examples.

## EFFECTS OF POLICIES ON COAL RESOURCES

A nation's natural resources can constitute a significant percentage of its wealth. An obvious example is the gold and diamonds of South Africa. Similarly, oil and gas resources have created enormous wealth for Mideast nations. Vast coal deposits in several nations are considerably valuable now, and could be even more valuable in the years to come.

### GLOBAL DISTRIBUTION OF COAL

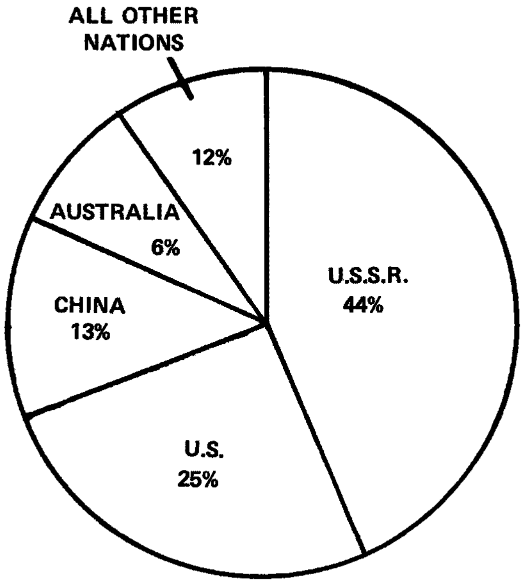
Most of the world's known coal resources are found in the Northern Hemisphere. The Southern Hemisphere contains fewer large sedimentary basins where coal typically forms, and has not been as extensively explored because of limited regional demand. However, many developing countries may increase their rate of exploration in anticipation of increased industrial activity and in pursuit of greater energy independence. Hence, estimates of total coal resources are very likely to increase in the future.

Figure 5-1 provides a summary of coal resources throughout the world. Coal resources total approximately 10 trillion metric tons of coal equivalent (mtce) worldwide, based on a compilation of estimates from various international organizations. As shown, the Soviet Union ranks first, with 44 percent of total resources, and the United States, China, and Australia are the next three leading nations. The top three countries alone contain 83 percent of the world's total coal resources.

Figure 5-2 contains estimates of "economically recoverable" coal resources, that is, of coal reserves. The world's recoverable reserves are estimated to be 688 billion tons -- only 6.9 percent of known resources. Yet, at 1980 production levels, this recoverable coal still represents about 258 years of supply. The United States has the largest amount of reserves, followed closely by the U.S.S.R. and China. Combined, these three countries have some two-thirds of the world's recoverable coal reserves.

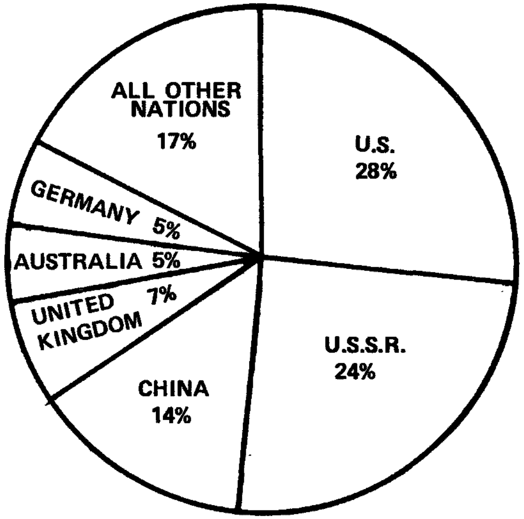
These data on coal resources and reserves have important implications for $CO_2$ mitigation strategies. The economic burden of any international agreement to limit the use of coal will fall

## FIGURE 5-1
## COAL RESOURCES



TOTAL: 10,000 BILLION MTCE

## FIGURE 5-2
## RECOVERABLE COAL RESERVES



TOTAL: 688 BILLION MTCE

SOURCE: UNITED NATIONS, 1981, 1979 YEARBOOK OF WORLD ENERGY STATISTICS, AND FEDERAL INSTITUTE FOR GEOSCIENCE AND NATURAL RESOURCES, 1980, SURVEY OF ENERGY RESOURCES, AS REPORTED IN GROSSLING, 1981, WORLD COAL RESOURCES.

primarily on three nations -- the U.S.S.R., China, and the United States. Moreover, the exclusion of any one of these nations would permit the use of enough coal to erode the effectiveness of any $CO_2$ control policy based on banning its use.

## CHANGES IN VALUE OF COAL RESERVES

Any substantial shift away from coal would have a dramatic effect on the value of these resources. A ban (or even a tax) on coal would reduce the demand for these resources and therefore depress their asset values. Countries and people owning deposits of the affected fossil fuels would lose the revenues these resources would otherwise earn. In addition, the value of the infrastructure used to produce, transport, and use these fuels would also decline if these facilities are prematurely retired.

To some extent, the loss in value of these resources would be offset by the enhanced worth of substitute fuels and technologies. Whether the alternatives are solar, nuclear, biomass, or some combination thereof, the value of these technologies should increase in direct proportion to their increased demand. Although it is clear which nations would lose from prohibitions against certain fossil fuels, it is less clear which ones would gain. Who the winners and losers are will play an important role in determining the feasibility of international $CO_2$ policies.

Estimating the magnitude of the loss in asset value is straightforward in concept, but difficult in practice. The difficulty arises in estimating the value of the coal deposits with and without a coal ban. This value should be based on the future stream of production levels, forecasted production costs, and future prices. It would vary based on expectations of how long the ban would be imposed, the location of each deposit, and a host of other factors.

An approximation of lost asset value can be obtained by comparing production levels and prices of coal in the two relevant scenarios -- the Mid-range Baseline and either one of the coal ban scenarios -- and ignoring the other relevant variables. This provides an estimate of lost revenue, a portion of which reflects profits from coal, and thus is a measure of the loss in asset value. Using a real discount rate of 5 percent, the lost revenues are estimated to be approximately $2.8 trillion (in 1980 dollars). Using a real discount rate of 10 percent drops this estimate to just over $700 billion.* In either case, however, the lost value would be enormous. Moreover, this loss is understated because it does not include the decline in value of the coal resources that would have been used after 2100 in the absence of a ban.

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* Many economists argue that the appropriate discount rate for long-run resources (or future investments) should be close to zero to fairly reflect the interests of future generations.

## CHANGES IN FUEL PRICES

Another indication of the impact of a ban on coal is the magnitude of the changes in energy prices resulting from these policies. For example, in the year 2050, the projected price of solids (coal or biomass) would increase from about $1.40/GJ in the Mid-range scenario to about $3.10/GJ (just biomass) if a ban on coal were adopted. If oil shale is also banned, the price of liquid fuels in the Mid-range Baseline similarly would be bid upwards, almost doubling by 2100.

Higher prices for energy encourage increased efficiency and therefore reduce overall demand. However, higher prices also require that the production and use of energy absorb a greater portion of total wealth. As a result, less capital is available for other economic activities.

## CAPITAL INVESTMENTS IN COAL

In addition to the loss in value of coal resources, other aspects of the coal "market chain" may also be affected. The market chain provides a useful conceptual framework for identifying and analyzing capital investments directly linked to the use of that resource. The typical coal market chain consists of three components:

- extraction -- removing the fossil fuel from the earth either through a surface or deep mine;
- transportation/preparation -- moving the fossil fuel from its resource location to a consuming market and preparing it for consumption, including coal washing; and

- conversion -- using the prepared fossil fuel directly as a heat source or indirectly to generate electricity.

A comprehensive analysis of the costs involved in banning coal would require extensive knowledge of local conditions in each country. It is thus considerably beyond the scope of this study. Instead, this section looks at two specific market chains and a study of aggregate future coal investments to illustrate the magnitude of capital invested in extracting, moving, preparing, and converting coal. These chains involve moving coal from the western United States for use in (1) a power plant in Japan and (2) a power plant in the southwestern United States.

Table 5-1 summarizes the approximate investment necessary to establish a coal chain between a western United States mine and a Japanese 800-megawatt power plant. The total capital invested in the chain is about $1.2 billion (in 1980 dollars), with nearly 75 percent of this total associated with the power plant. Hence, for each short ton of coal traded annually between the United States and Japan related to this particular chain, approximately $471 of capital will have been invested.

The capital investment required for a domestic U.S. coal chain is almost as much as the above example (Table 5-2). Interestingly, even with the use of a capital-intensive slurry pipeline to move western coal to a West South Central market, the estimated share of total capital represented by the power plant is over 80 percent.

## TABLE 5-1

## APPROXIMATE CAPITAL INVESTMENT FOR INTERNATIONAL COAL CHAIN: WESTERN UNITED STATES TO JAPANESE POWER PLANT (MILLIONS OF 1980 DOLLARS)

| | Mine | Trains[a] | Seaport[a] | Ships[a] | Power Plant |
|---|---|---|---|---|---|
| Facility Required: | 25% capacity of a 10-million ton/yr. mine | 3.9 unit trains | 25% capacity of a seaport | 4.9 ships | One 800-MW power plant |
| Useful Life: | 20 years or more | 15 years or more | 30 years or more | 15 years | 45 years or more |
| Initial Capital Investment: | $33 | $42 | $39 | $195 | $877 |

Total Coal Shipped = 2.52 Million Short Tons/year
Total Initial Capital Investment = $1,186 Million
Capital Investment Per Ton-Year = $471

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[a] Facility required and capital investment are ICF interpretations of data reported in Coal - Bridge to the Future, Report of the World Coal Study, WOCOL, 1980, Figure 8-2, page 205.

Source: ICF Assessment, 1983

## TABLE 5-2

## APPROXIMATE CAPITAL INVESTMENT FOR DOMESTIC COAL CHAIN: WESTERN UNITED STATES TO WEST SOUTH CENTRAL POWER PLANT

(millions of 1980 Dollars)

| | Mine | Slurry Pipeline [a] | Power Plant |
|---|---|---|---|
| Facility Required: | 25% Capacity of 10-million ton/year mine | 10% Capacity of 24.75-million ton/year 1,400-mile pipeline | One 800-MW power plant |
| Useful Life: | 20 years or more | About 30 years | 45 years or more |
| Initial Capital Investment: | $33 | $135 | $877 |

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Total Coal Shipped = 2.52 million Short Tons/Year
Total Initial Capital Investment = $1,045
Capital Investment Per Ton-Year = $415

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[a] Slurry pipeline capital costs per ton are the low assumption from ICF report to U.S. Department of Energy entitled The Potential Energy and Economic Impacts of Coal Slurry Pipelines, January 1980, Table C-7, page C-48 (estimates for pipeline from Wyoming to Arkansas/Oklahoma/Louisiana).

Source: ICF Assessment, 1983

These two examples suggest that the dominant component of any future capital invested in the use of coal will be the power plants used in generating electricity. Moreover, coal-fired power plants cannot easily be converted to nonfossil fuels (e.g., nuclear) and, once built, they have a relatively long life. Some of the new coal-fired plants now under construction and scheduled for operation by 1990 may still be operating in 2050. Thus, to minimize the economic impact, any policy banning the use of coal would have to be applied prospectively to the construction of new facilities.

The extent to which capital is invested in coal market chains will depend on future demand for coal. The World Coal Study (WOCOL) provides the most comprehensive, although arguably optimistic, analysis of both demand and investment. This study concluded that approximately 740 GW of new capacity would be built in OECD countries from 1977 to 2000, with the United States responsible for over half of that increase (see Table 5-3).

Using WOCOL's prediction of the level of future OECD economies, the likely capital committed to coal market chains can be put in perspective (Table 5-4). This table takes into account the costs of mining, transporting, and burning coal at power plants. It does not include industrial use of coal. Nonetheless, over one trillion dollars or approximately 2.3 percent of the projected total OECD economy -- would be committed to the

## Table 5-3

## WOCOL FORECASTED NET ADDITIONS OF COAL-FIRED POWER PLANTS IN OECD COUNTRIES: 1977-2000

| | Cumulative Coal-Fired Capacity Additions | |
|---|---|---|
| OECD Countries | Capacity (GW) | Capital Investment (billions of 1980 Dollars) |
| Australia | 49 | 61 |
| Canada | 49 | 61 |
| Denmark | 10 | 12 |
| Finland | 4 | 4 |
| France | 20 | 25 |
| Germany, F.R. | 27 | 34 |
| Italy | 21 | 26 |
| Japan | 48 | 61 |
| Netherlands | 16 | 20 |
| Sweden | 12 | 15 |
| United Kingdom | 10 | 12 |
| United States | 423 | 533 |
| Other Western Europe | 53 | 67 |
| OECD TOTAL | 740 | 931 |

Source: Coal-Bridge to the Future, Report of the World Coal Study (WOCOL), Ballinger, Cambridge, 1980, Table 8-3, page 215.

## Table 5-4

## WOCOL FORECASTED CUMULATIVE COAL CHAIN INVESTMENTS FOR WOCOL COUNTRIES IN OECD:[a/] 1977-2000

| | Cumulative Capital (billions of 1980 Dollars) |
|---|---|
| TOTAL ECONOMY | 47,923 |
| COAL CHAIN COMPONENTS | |
| Supply Facilities | |
| Mines | 133 |
| Inland Transport | 58 |
| Ports | 18 |
| Ships | 45 |
| Consumption Facilities | |
| Electric Power Plants | 866 |
| Total | 1,120 |
| COAL CHAIN AS PERCENT OF TOTAL ECONOMY | 2.3% |

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[a/] Consists of the following countries: Australia, Canada, Denmark, Finland, France, Federal Republic of Germany, Italy, Japan, Netherlands, Sweden, United Kingdom, United States.

Source: Coal-Bridge to the Future, Report of the World Coal Study (WOCOL), Ballinger, Cambridge, 1980, Table 8-1, Table 8-3, pages 212-215.

coal market chain during this time period. This example further illustrates the size of the potential economic dislocation if a ban on the use of coal is adopted by the turn of the century.

## EFFECTS OF BANS ON SHALE OIL AND SYNFUELS

The examples used until now have focused on coal because the results in Chapter 4 indicate that, if we are to significantly delay a 2°C rise in temperature, a ban on coal by the year 2000 is the only effective means of accomplishing that end. Longer run temperature concerns extend beyond coal to include prohibitions on shale oil and synfuels as an alternative to coal.

Coal liquifaction would, of course, be prohibited by a ban on the use of coal. Similarly, a future ban on shale oil would affect very few existing facilities. The purpose of examining their production costs is to illustrate the quantity of required capital and the expected useful life of these facilities in the absence of future bans on coal and shale oil. If prohibitions are instituted soon, the primary loss would be the research and development costs invested in these industries to date. Moreover, if the industries do reach commercialization, future efforts at limiting use of their products would prove more difficult to implement and may involve premature retirement of the associated infrastructure.

Although costs for producing shale oil remain somewhat speculative, the initial capital costs for a facility producing 50 thousand barrels of oil per day are likely to be about $2.85

billion (1980 dollars). At an assumed heat content of 5.8 million Btu per boe and 19.91 million Btu per metric ton of coal, the cost of this shale oil facility is about $537 per annual mtce output (ICF, 1983).

Using the same assumptions, the capital investment in a coal liquifaction plant would be over $967 per annual mtce output or a total of $5.6 billion (1980 dollars) for a 50 thousand barrel per day facility (ICF, 1983). Each facility has an expected useful life of thirty years.

Producing energy from shale and coal involves far more complex technologies than those now used in producing oil or gas. As a result, the start-up time of these projects is considerably longer, the capital involved is far greater, and, generally, the expected life is longer. These factors would severely limit society's flexibility and increase its costs should future policies limit the use of coal liquifaction and shale oil production after these industries have become commercialized.

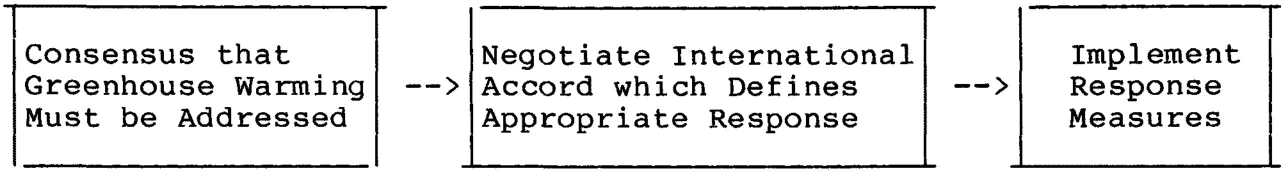
## OTHER IMPEDIMENTS TO POLICY IMPLEMENTATION

The long life cycles of energy projects complicate the problem of developing an effective response to the threat of rising $CO_2$. Whether that response involves adaptation or prevention, the earlier a concerted strategy is implemented, the lower the risks and costs of dealing with the $CO_2$ problem. Yet the selection of a particular response can occur only after several time-consuming preliminary steps have been taken:

scientists and other researchers must provide substantial and convincing evidence of the likely occurence and effects of the greenhouse warming; an international agreement must be reached specifying a consensus response to the problem; and this response must be implemented (see Figure 5-3). Until these steps are completed, few, if any, significant actions are likely to be taken by nations concerned with rising $CO_2$ levels.

Figure 5-3

PROCESS LEADING TO ACTION



Chapter 2 of this report discussed efforts to isolate, from the record of general climatic trends, any warming directly attributable to greenhouse gases. Some researchers anticipate that, by the beginning of the next decade, they will have successfully demonstrated the magnitude of the relationship between warming and the concentration of greenhouse gases. Initial recognition by individual researchers, however, falls far short of an international scientific consensus.

Efforts at reaching a consensus among political leaders to act on the $CO_2$ problem may prove even more difficult. A number of international organizations including the World Meterological

Society, the International Institute of Applied Systems Analysis, and the United Nations Environment Program, have been actively researching the problem, and have convened several conferences during the past decade. Despite these activities, the prospects for any future international accord remains uncertain. In general, environmental issues have not readily produced an international consensus. Acid rain and stratospheric ozone depletion are two recent examples where transboundary pollutants were involved, and where no international consensus on appropriate responses was forthcoming. In these cases, as is true with $CO_2$, countries are able to point to lingering uncertainties in the scientific evidence as the basis for inaction or delay.

Economic considerations may also play a role in the failure to reach a consensus. In the case of both acid rain and ozone depletion, some countries would be required to incur greater costs than others. As the analysis of fossil fuel resources presented earlier in this chapter clearly illustrates, this will almost certainly be true should there be a future ban on coal or shale oil.

The problem of inequitable distribution of costs and benefits is even more acute for $CO_2$-induced climate change, since the consequences from such changes will differ dramatically from country to country. In fact, some areas of the world are likely to experience more desirable temperatures and increased rainfall, and therefore would benefit from rising $CO_2$. Ironically, as general circulation models improve, more information on regional climate effects may further complicate the issue by better identifying the winners and losers throughout the world.

Carbon dioxide may also become a cause of conflict between developed and developing nations. Developed nations are currently most dependent on fossil fuels and generally possess the largest resource base. They have the most to lose by accepting a policy which limits the use of these resources. In contrast, developing nations are most in need of inexpensive energy supplies to provide food and to improve their standard of living. According to the IEA/EPA model projections used in this study, a large percent of the future increase in $CO_2$ emissions will be the result of population and economic growth in developing nations. In terms of equity, however, their contribution should probably be balanced against past increases which overwhelmingly were the product of industrialization in the developed nations. One international conference has already proposed that developed countries limit their $CO_2$ emissions to allow for greater fossil fuel consumption by developing nations, while still limiting overall emissions (Bach, 1980).

Given these competing interests, the future of any international accord remains, at best, a distant prospect. Unfortunately, the findings and conclusions of this study indicate clearly that only an international response will be effective in delaying significant temperature change.

## SUMMARY

The above illustrations fall far short of a complete economic and political feasibility analysis. They do, however, provide considerable support for the conclusion that policies banning the use of coal are unlikely to be adopted. The magnitude of the economic disruptions and need for a consensus among the United States, China, Russia and the developing nations are major hurdles to the adoption of a worldwide coal ban. A ban on shale oil or on synfuels per se may be more tractable since large scale production of these fuels has not yet begun. But, even here, international cooperation is far from assured.

# CHAPTER 6

# NONENERGY OPTIONS FOR CONTROLLING $CO_2$ EMISSIONS

Although most discussions of ways to reduce a greenhouse warming focus on manipulating fuel use, researchers have proposed several dramatically different approaches. These include controlling $CO_2$ emissions at the source, sequestering $CO_2$ from the atmosphere, and reducing the amount of solar radiation received at the earth's surface. Each of these alternatives is reviewed in this chapter. Technical and economic feasibility, and potential effectiveness are assessed.

## OPTIONS FOR CONTROLLING $CO_2$ EMISSIONS

Capturing $CO_2$ from smokestacks would be a more direct means of limiting its buildup in the atmosphere than switching to alternative energy sources. Many countries have successfully used emission controls to limit the adverse effects of a variety of pollutants from industrial processes. Firms are frequently required to install control equipment or alter production processes to reduce emissions below quantities that will harm the public's health or welfare.

A plan to control $CO_2$ emissions would appear attractive for several reasons. First, if the $CO_2$ problem could be remedied through emission controls, there would no longer be any need to consider potentially disruptive changes in fuel-use patterns.

Alternatively, controlling $CO_2$ emissions could be an easier means of accommodation than making the required social and economic adaptations to a warming climate. Second, requiring those sources emitting carbon dioxide to bear the burden of controlling their emissions represents an equitable solution to the problem. Third, an emission control approach would satisfy those who favor a technologic "fix" to environmental problems. Finally, the potential to quickly install controls on many sources of $CO_2$ would allow us to become more certain about the severity of the $CO_2$ problem before taking action.

Applying pollution controls (scrubbers) on major stationary sources to limit $CO_2$ emissions was first proposed by C. Marchetti in an article in Climate Change in 1977. Once $CO_2$ was captured, Marchetti proposed to inject it deep into the ocean where it would be carried to lower layers by natural currents. Entrapped $CO_2$ would thus be removed from the atmosphere for centuries.

Brookhaven National Laboratory (Albanese, 1980) examined several alternatives for controlling and disposing of carbon dioxide from coal-fired power plants. These plants, however, account for only approximately 30% of current fossil fuel emissions in this countury and even less worldwide.

The only feasible control option used a chemical solvent -- monoethanolamine (MEA) -- to absorb $CO_2$ from smokestack emissions. Albanese also compared three methods for disposing of captured $CO_2$: conversion into a gas, liquid, or solid blocks, each of which would be deposited into deep layers of the oceans.

As shown in Table 6-1, the capital costs of an MEA control system installed at a new 200-MW power plant were estimated to be \$46-\$216 million (1980 \$) for 50 percent removal efficiency and \$68-\$290 million for 90 percent efficiency, depending on the method of $CO_2$ disposal. These costs include the removal and recovery systems (which capture $CO_2$), and the significantly more expensive facilities required to transport and dispose of the captured $CO_2$.

They do not, however, include the costs of supplying energy to operate the scrubbing and disposal systems. As Table 6-1 indicates, the effective capacity of the power plant would drop by up to one-third for 50 percent $CO_2$ control and by up to roughly four-fifths for 90 percent control. This reduction in capacity reflects the energy penalty of the $CO_2$ scrubbing and disposal system.

Overall, the least expensive option for both 50 percent and 90 percent flue gas removal efficiency is gaseous disposal. (See "Electricity Generation Costs" in Table 6-1.) Even for this method of disposal, however, the cost increase is high enough to seriously question the economic feasibility of controlling $CO_2$ using today's technologies. These increases would almost double electricity costs for 50 percent removal and would increase costs by a factor of four to achieve 90 percent efficiency.

As high as these costs are, they underestimate the real costs for several reasons. As noted earlier, utilities contribute only 30 percent of $CO_2$ emissions in the United States and an even

## TABLE 6-1

### Costs of Generating Electricity With and Without $CO_2$ Control for Initial Power Plant Capacity of 200-MW(e) (1980 dollars)

| | $SO_2$ removal with no $CO_2$ control | $SO_2$ removed + 50% $CO_2$ control | | | $SO_2$ removed + 90% $CO_2$ control | | |
|---|---|---|---|---|---|---|---|
| | | Gaseous disposal | Liquid disposal | Solid disposal | Gaseous disposal | Liquid disposal | Solid disposal |
| Net capacity, (1) MW(e) | 200 | 161 | 159 | 134 | 86 | 83 | 37 |
| Capital investment (million $) | | | | | | | |
| (a) Power plant (2) | 160 | 160 | 160 | 160 | 160 | 160 | 160 |
| (b) $CO_2$ control system(3) | -- | 152 | 216 | 46 | 194 | 290 | 68 |
| Total | 160 | 312 | 376 | 206 | 354 | 450 | 228 |
| Energy penalty for operating $CO_2$ Controls MW(e) | -- | 39 | 41 | 66 | 114 | 117 | 163 |
| Total operating costs (4) (million $) | | | | | | | |
| (a) Coal @ $30/ton | 18.9 | 18.9 | 18.9 | 18.9 | 18.9 | 18.9 | 18.9 |
| (b) O&M | 4.8 | 5.8 | 5.8 | 7.2 | 5.8 | 5.8 | 7.2 |
| (c) Barging costs (5,6) | -- | -- | -- | 5.0 | -- | -- | 5.0 |
| (d) Capital charges @ 15% of capital investment | 24.0 | 46.8 | 56.4 | 30.9 | 53.1 | 67.5 | 34.2 |
| Total | 47.7 | 71.5 | 81.1 | 62.0 | 77.8 | 92.2 | 65.3 |
| Electricity generation costs, Mills/kWh (revenue requirements) | 30 | 56 | 64 | 58 | 113 | 139 | 221 |

(1) Electrical energy to drive the $CO_2$ control system is assumed to be obtained from the electrical output of the power plant. Therefore: $e_{net} = e_{gross}(200\ MWe) - e_{control}$.

(2) Total capital investment @ $800/kW(e), including sulfur removal equipment.

(3) Total capital investment @ 1.2 times fixed capital investment.

(4) Based on 8,000 hours of operation per year.

(5) Dry-ice barging costs @ $15,000 per day. Costs for transporting dry ice from power plant to barge are not included.

(6) Barging costs are based on a 100-mile barging distance (500-meter disposal depth). For a 200-mile distance (3000-meter disposal depth), barging costs are estimated at $9 million per year.

SOURCE: Albanese, Environmental Control Technology pg. 44.

smaller percentage worldwide. Thus, the effectiveness of such an approach is dubious. Moreover, the above analysis applies only to control costs at new power plants located near large bodies of water. Costs would be considerably higher to control $CO_2$ emissions at other types of power plants and at industrial sources. Thus, controlling $CO_2$ emissions appears to be marginally effective and prohibitively expensive.

## SEQUESTERING $CO_2$ USING TREES

If the costs of installing and operating $CO_2$ controls are prohibitive, one potentially attractive alternative is to reduce $CO_2$ after it has been emitted. By storing or sequestering the carbon through tree growth, an existing sink of $CO_2$ would be expanded.*

The first notion of using trees to reduce atmospheric $CO_2$ was developed in 1976 by the noted physicist Freeman Dyson. Dyson simply set forth the technical parameters of using trees to sequester $CO_2$, and concluded that "there seems to be no law of physics or of ecology that would prevent us from taking action to halt or reverse the growth of atmospheric $CO_2$..." (Dyson, 1976).

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* Some researchers have suggested that the trees should be cut and pickled in a manner that prevents their decomposition and the release of carbon to the atmosphere. Because of other problems that must be overcome first, we have not analyzed this aspect of the proposal.

More recent analyses used Dyson's concepts as a starting point, and examined in greater detail the feasibility of planting trees on the scale required to absorb sufficient quantities of $CO_2$ to limit or delay a global warming.

Sequestering $CO_2$ through forestation is attractive because it offers a decentralized solution to a global problem. Many countries could contribute to a forestation effort. This is in direct contrast to the energy options, which would fall most heavily on those few countries with most of the world's fossil fuel resources.

Tree planting is also attractive in its own right as a means of reversing past trends of deforestation. In many areas of the world, the growth of forests will help reestablish the nutrients in soil, prevent runoff, and stop the spread of deserts.

Despite the potential benefits of widespread forestation, none of the earlier proponents of this idea now believes that it is feasible (Greenberg, 1982). As illustrated below, the magnitude of the reforestation effort required appears to make this approach untenable.

## LAND REQUIREMENTS

Based on Dyson's original proposal, American sycamore seedlings would be planted on 6.7 million $km^2$ of land (Greenberg, 1982). Sycamore trees were selected because they grow well in temperate climates with a minimum of rainfall.

An enormous amount of land would be required to plant enough trees to absorb substantial quantities of $CO_2$. Sycamores would absorb an average 750 tons of carbon annually for each square kilometer until a steady state is reached when the forest matures (after about 50 years). Thus, a total of 37,500 tons of carbon would be sequestered for each square kilometer of sycamores. To offset 50 years of $CO_2$ emissions at the current annual rate (approximately 5 billion gigatons per year of carbon from fossil fuels), approximately 6.7 million $km^2$ of sycamores would have to be planted and maintained. The required acreage would be roughly equal to the land area of Europe.

Identifying available land of this magnitude that is also suitable for planting is a major problem. Thirty-eight percent of the world's total land is already covered with trees. An additional 9.5 percent is currently under cultivation and could only be used to grow trees if food production were sacrificed (MacDonald, 1982). Neither could be considered available for the purposes of planting trees to be used to sequester $CO_2$. Much of the remaining land consists of desert, rock, sand, and ice, and therefore would not be suitable for this endeavor.

## FERTILIZER REQUIREMENTS

The enormous quantity of fertilizer that would be needed to grow the sycamore plantations is a second critical barrier to a successful sequestering plan. It would call for an estimated 17 million tons of nitrogen, 5 million tons of phosphorus (as

$P_2O_5$), and 10 million tons of potassium (as potash, $K_2O$). This represents a very large percentage of the world's current fertilizer production: approximately 30 percent for nitrogen, 40 percent for potash, and 15 percent for phosphate (see Table 6-2).

TABLE 6-2

FERTILIZER REQUIREMENTS FOR GROWING AMERICAN SYCAMORE TREES, COMPARED WITH WORLD FERTILIZER PRODUCTION JULY 1979-JUNE 1980
(in millions of metric tons)

| Fertilizer | Quantity of Fertilizer Required | World Production | Requirements as of % of World Production |
|---|---|---|---|
| N | 17 | 59.8 | 28.4% |
| $K_2O$ | 10 | 25.7 | 38.9% |
| $P_2O_5$ | 5 | 32.3 | 15.5% |

Source: Minerals Yearbook, 1978-79.

Today's production figures do not clearly indicate the potential of the world's producers to raise output over time should future demand increase substantially. This analysis requires a closer examination of unused capacity and of the costs and availability of the inputs to produce each fertilizer.

Worldwide capacity to produce nitrogen fertilizer currently stands at about 80 million metric tons (about 20 million tons above current production). It is expected to increase to about 100 million tons by the end of the decade. Thus, there is enough currently unused capacity to satisfy the needs of a sycamore plantation, and planned capacity expansion in the industry suggests sufficient flexibility to respond to future increases in demand. However, it is not at all clear that future increases in capacity would be committed to growing sycamores. A significant percentage would probably be diverted to increasing agricultural productivity throughout the world.

World potash capacity also appears adequate to meet future demands. Known reserves in the U.S.S.R, Canada, and New Mexico would be sufficient to supply the $K_2O$ required for the sycamore plantation, if necessary. Moreover, Canada alone expects to nearly double its annual production between 1980 and 1990 from 11 million to 18 million tons (Harve, 1982), again demonstrating flexibility to meet increases in demand.

The situation is less encouraging for phosphate requirements. The United States and Morocco are the chief producers of phosphate rock. At current rates of consumption, reserves seem adequate only for the next 20 years. With a 15 percent increase in consumption resulting from the demands of the sycamore plantation, known reserves would be exhausted several years sooner. Unless new resources are located, scarcity could become a significant problem (Minerals Yearbook, 1978-79).

## COSTS OF SEQUESTERING

To further evaluate the viability of a $CO_2$ sequestering program, resource requirements for supporting the program should be translated into costs. Data on the costs of large-scale tree-planting programs are drawn from studies examining the feasibility of creating tree farms to produce biomass for energy consumption.

One such study examined in detail the potential for growing leucaenas on tree farms in Hawaii (Brewbaker, 1980). Although leucaenas could grow well only in tropical climates throughout the world, they are an attractive species for limiting increases in $CO_2$ because they consume carbon at a higher rate (11.8 dry weight tons of carbon per acre of wood) than American sycamores. These trees could sequester 2,827 tons carbon/km$^2$/year until the forests matured. To sequester the same 50 years of carbon emissions at the current annual rate, 1.77 million km$^2$ of land would have to be planted with leucaenas. This acreage is only 25 percent of that required for the American sycamore, but would have to be drawn from the more limited tropical areas of the globe.

Fertilizer requirements, shown with their percentage of world production, are illustrated in Table 6-3. Because the leucaena is a nitrogen-fixing legume, additional nitrogen fertilizer is not necessary. But, it requires more than twice as much as the sycamore of the fertilizer in the shortest supply -- phosphate.

To grow at the optimal rate, leucaenas need about 60 inches of rain a year. Hawaii gets about half that amount annually; the remainder would have to be made up by irrigation. Assuming all planted areas would have a climate similar to Hawaii, irrigation equipment to move the required 365,190 billion gallons of water a year would be required. Brewbaker estimated the cost of installing

### TABLE 6-3

### FERTILIZER REQUIREMENTS FOR GIANT LEUCAENA, COMPARED WITH U.S./CANADA AND WORLD PRODUCTION FERTILIZER PRODUCTION
July 1978 - June 1979
(in millions of metric tons)

| | Fertilizer Requirements for Leucaenas | World Production | Requirements as a % of World Production |
|---|---|---|---|
| $P_2O_5$ | 11.9 | 32.3 | 36.8 |
| $K_2O$ | 8.7 | 25.7 | 33.9 |
| $CaCO_3$ | 1.0 | - | - |
| Sulfur | 0.7 | - | - |

Source: Greenberg, 1982

a system to handle this amount of water to be $600/acre (1980 $) for equipment, and $78.40/acre/year for water and services. The total irrigation system for the entire plantation would require a capital investment of $262 billion and annual operating expenses of $34 billion.

The cost to purchase land is also substantial. On the Hawaiian Island of Molakai, land costs are very high and not representative of average global costs. They would run about $3,000/acre to buy or $100/acre to lease, which results in a one-time expense of $1,311 billion, or annual payments of $34 billion. Even if land prices were one-tenth these costs, or $300/acre (lease payments of $10/acre), the costs would be $131 billion to buy or $4 billion a year to lease. Preparing the land after purchase was estimated to cost another $55 per acre, or a total of $25 billion (Brewbaker, 1980).*

Based only on land and irrigation costs, a total initial cost of over $400 billion would be required. When added to the costs for pesticides, fertilizers, nursery facilities, storage and other requirements, a leucaena plantation would be exorbitantly expensive.

Availability of land, total costs, and energy requirements are not the only considerations in evaluating proposals to use trees to sequester carbon. Any undertaking of this magnitude will itself affect the world's climate. For example, by planting trees on what is now fallow land, we will significantly alter the earth's albedo (reflective characteristic) -- more of the sun's energy will be absorbed by the earth. Marchetti estimates a 20 percent reduction in reflectivity (1978), thus increasing the earth's temperature. The resulting temperature rise would be roughly equivalent to the amount of $CO_2$ emitted during a seven-year period at current $CO_2$ emission rates (Greenberg, 1982).

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* This figure agrees with the $50/acre land preparation costs estimated in a similar study (Fraser, et al., 1976).

In conclusion, rudimentary analysis of proposals found in the literature and extrapolations from energy tree-farm work show that sequestering atmospheric $CO_2$ by trees is an extremely expensive, essentially infeasible option for controlling $CO_2$.

## OFFSETTING THE GREENHOUSE WARMING

In contrast to actions that control or capture $CO_2$ emissions, an alternative proposal is directed at reducing the amount of solar radiation that penetrates the troposphere.* Under this proposal, large quantities of sulfur dioxide injected into the stratophere would reduce solar radiance about 2 percent by absorbing incoming visible sunlight. This reduction in incoming radiation would roughly neutralize the warming created by a $CO_2$ doubling.

Depositing the required 35 million tons/year of $SO_2$ in the stratosphere would require 750-800 daily airplane flights. Together with the costs of the sulfur dioxide, total costs would be roughly $21 billion/year (Broecker, 1983).

Costs aside, the practicality of such a scheme depends primarily on the associated environmental effects. Adding sizable quantities of $SO_2$ to the stratosphere may affect many chemical

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* This proposal was first suggested by Budyko (1974). A recent paper by Broecker (1983) provides a preliminary analysis of the costs and environmental implications of this approach to counteracting a greenhouse warming.

reactions in the stratosphere, including those that control the concentrations of ozone and $N_2O$.* Changes in these gases could significantly contribute to a warming. It could also increase acid rainfall in the troposphere. Much more analysis of each of these effects is required before the feasibility of this proposal can be judged.

## SUMMARY

Current proposals to slow a greenhouse warming by nonenergy means generally do not appear effective or feasible. At best, they require additional analyses before even tentative conclusions can be reached. Nonetheless, they retain their appeal if for no other reason than energy options appear to be economically and politically unacceptable.

Of the three proposals reviewed in this chapter, the sequestering may hold some promise, but only if new biological organisms can be developed. Such organisms would have to be capable of absorbing large quantities of $CO_2$ at low cost, and without adversely effecting fragile ecosystems. Until such time, however, sequestering cannot be viewed as a feasible solution.

Injecting $SO_2$ into the atmosphere is an intriging proposal, but raises questions about costs and adverse environmental effects. Much more research is needed.

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* Broecker projects a 2.5 fold increase in atmospheric $N_2O$, which is also a greenhouse gas.

# CHAPTER 7

## CONCLUSIONS

Based on the evidence marshalled to date, some warming of the lower atmosphere over the next century from increasing levels of $CO_2$ and other greenhouse gases seems inevitable. The only questions remaining are how large the temperature rise will be and how fast it will occur. These questions are critical. The consequences of a greenhouse warming and related societal responses will depend strongly on both the size and the speed of temperature rise.

### EFFECTIVENESS OF POLICIES AND SENSITIVITY OF RESULTS

The timing of a projected 2°C rise in temperature is the primary yardstick used to judge the effectiveness of alternative policies aimed at delaying a greenhouse warming. The magnitude of global warming in 2100 is a secondary measure. In addition to policy effectiveness, we extensively explored the sensitivity of temperature estimates to current scientific uncertainties.

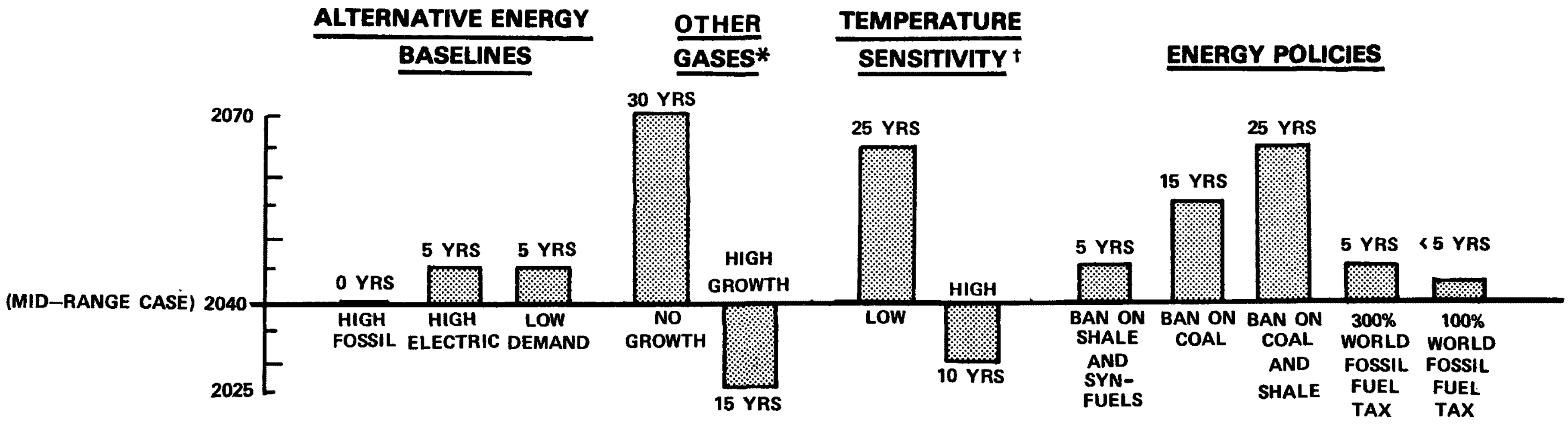
In the Mid-range Baseline, a 2°C warming is reached in 2040. Figure 7-1 compares this case with the results for alternative baseline, sensitivity, and policy scenarios. The main conclusions are:

- The future mix of fuel use has almost no effect on the date of a 2°C warming. Neither reductions in energy use (e.g., increased conservation) nor increases in the use of fossil fuels would appreciably change the timing of a 2°C rise.

## FIGURE 7-1

## CHANGES IN THE DATE OF A 2° C WARMING

(PROJECTED DATE IN MID-RANGE BASELINE: 2040)



*REFERS TO GREENHOUSE GASES OTHER THAN $CO_2$: NITROUS OXIDE, METHANE, AND CHLOROFLUOROCARBONS.

†REFERS TO THE TEMPERATURE RISE IN RESPONSE TO A GIVEN INCREASE IN GREENHOUSE GASES ONCE AN EQUILIBRIUM HAS BEEN REACHED.

- Of the energy policy options analyzed, a ban on coal instituted in 2000 would effectively delay a 2°C warming by 15 years. Bans on both coal and shale oil would result in a 25-year delay. Taxes on all fossil fuels, or bans on individual fuels other than coal produce only minor delays and are not considered effective. For example, a 300% U.S. tax on fossil fuels would have almost no effect on shifting the date of a 2°C warming; a worldwide tax at this level would only delay the warming by about 5 years. Similarly, a 100% tax applied worldwide would delay the date of a 2°C rise by less than 5 years.

- Different assumptions about other greenhouse gases and the actual temperature sensitivity of the atmosphere to increases in $CO_2$ are by far the most significant factors in projecting the timing of a 2°C rise. Assuming greenhouse gases (other than $CO_2$) remain at constant levels delays the projected date of a 2°C warming by 30 years. If these gases increase at a much higher rate than in the Mid-range Baseline, a 2°C warming might occur as soon as 2025. Using the probable range of values for the temperature sensitivity of the atmosphere (from 1.5°C to 4.5°C) delays the target date 25 years or advances it 10 years (respectively).

A similar comparison of results using the projected temperature in 2100 also proves insightful, although less confidence can be placed in these very long-term projections. The estimated temperature in the Mid-range Baseline is 5°C. Figure 7-2 summarizes results for other baselines, changed assumptions, and energy policy scenarios.

Several useful, albeit tentative, conclusions can be drawn:

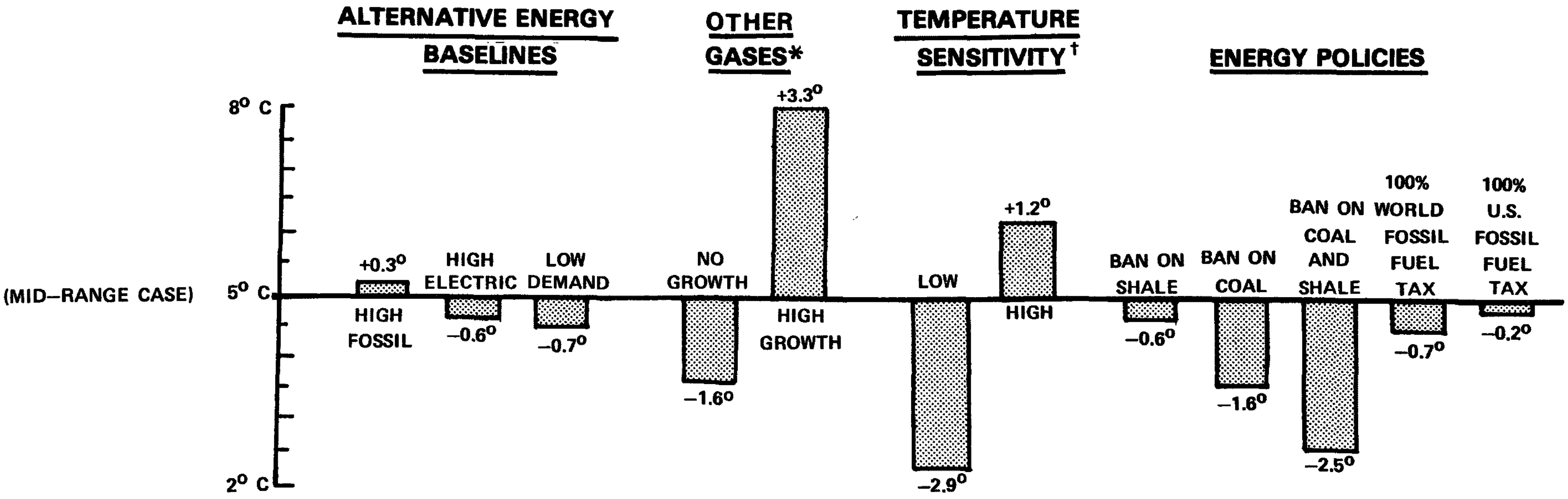
- Alternative assumptions about future energy patterns contribute negligibly to variations in projected temperature in 2100.

- Policy options that involve bans on fossil fuels could significantly reduce the warming by 2100. A ban on coal would reduce the temperature rise in 2100 from 5°C to 3.4°C; when coupled with a ban on shale oil, the total projected warming would be cut in half (to 2.5°C).

## FIGURE 7-2

## CHANGES IN TEMPERATURE PROJECTED FOR 2100

(PROJECTED MID-RANGE BASELINE TEMPERATURE: 5° C)



*REFERS TO GREENHOUSE GASES OTHER THAN $CO_2$; NITROUS OXIDE, METHANE, AND CHLOROFLUOROCARBONS.

†REFERS TO THE TEMPERATURE RISE IN RESPONSE TO A GIVEN INCREASE IN GREENHOUSE GASES ONCE AN EQUILIBRIUM HAS BEEN REACHED.

- Neither a U.S. nor a worldwide tax on fossil fuels (even a tax of 300%) would be as effective as selected fuel bans.
- Uncertainties regarding the growth in greenhouse gases other than $CO_2$ and the temperature sensitivity of the atmosphere are major sources of variability in projected temperature.

## FEASIBILITY OF POLICY OPTIONS

Though a ban on coal (or coal and shale oil) is the only policy that could significantly delay a 2°C warming, it appears to be economically and politically infeasible. This is due to (1) the substantial costs of these policies, (2) the unequal distribution of costs and benefits across nations, and (3) the need for worldwide cooperation to ensure their effectiveness.

We also found other efforts to reduce $CO_2$ levels to be infeasible, at least at present. Scrubbing $CO_2$ emissions has limited applicability -- it only applies to large power plants -- and is prohibitively expensive. Forestation, on the scale required to absorb significant amounts of $CO_2$, would cause severe competition for available land, fertilizer, and irrigation. Injecting $SO_2$ into the stratosphere to increase reflection of incoming solar energy appears somewhat more practical (although still expensive), but major uncertainties regarding environmental side effects remain to be investigated.

## MODELING ASSUMPTIONS

We made numerous assumptions and approximations, which moderate the strength of our conclusions. The most important assumptions are:

- Worldwide population is assumed to reach zero growth levels by 2075.
- The projections of future fuel-use patterns assume that no exotic energy technologies (e.g., nuclear fusion, solar production of hydrogen, "energy plants") would be commercially available within the 120-year time frame of this study.
- Possible reductions in energy demand due to lower heating requirements as the earth warms were assumed negligible.
- The heat diffusivity of the ocean was set at 1.18 $cm^2$/sec, and the effects of volcanic activity and variations in solar luminosity were assumed to follow historical patterns.

No attempt was made to evaluate the significance of these assumptions in quantitative terms. In our opinion, however, the assumptions are reasonable "educated guesses".

Two other key assumptions were subjected to a limited sensitivity analysis. These are the rate of economic growth in the less developed and developing countries after 2050, and the income (or GNP) elasticity of energy demand. In both cases, changing the value of these paramenters within reasonable ranges produced only minor changes in projected temperature.

## IMPLICATIONS OF FINDINGS

Our findings support the conclusion that a global greenhouse warming is neither trivial nor just a long-term problem. They also underscore the large degree of uncertainty embedded in the temperature projections. Taken together, these characteristics of our results point to the need for additional research aimed at reducing the range of uncertainty in temperature projections. Specific research needs should focus on (1) how atmospheric temperature responds to changes in greenhouse gases (i.e., narrowing the range of the temperature sensitivity parameter, $T_e$), and (2) the sources, fate, and effects of greenhouse gases other than $CO_2$ (specifically, nitrous oxide, methane, $CCl_2F_2$ and $CCl_3F$).

But even with better knowledge of the magnitude and pace of global warming, we will still be faced with the challenge of developing appropriate responses. Innovative thinking and strategy-building are sorely needed. Means must be found to explore the advantages of climate change where they appear, and to minimize the adverse effects.

Finally, our findings call for an expeditious response. A 2°C increase in temperature by (or perhaps well before) the middle of the next century leaves us only a few decades to plan for and cope with a change in habitability in many geographic regions. Changes by the end of the 21st century could be catastrophic taken in the context of today's world. A soberness and sense of urgency should underlie our response to a greenhouse warming.

# APPENDIX A

## ENERGY SUPPLY OPTIONS

The mix of fuels employed to satisfy energy demands varies considerably among geographic regions and is likely to shift substantially over the next several decades. Table A-1 is a compilation of energy production by fuel type in 1979 for the United States, the developed and developing market economy countries, the centrally planned countries, and the world. As shown, all nations are heavily dependent on fossil fuels; solids (mainly coal) are the primary fuels produced in all developed countries, while liquids predominate in the developing countries. This reflects both the domestic demand for these fuels and the relative abundance in each country. Electricity is primarily important in the developed part of the world, with nuclear power important only in the countries with developed market economies.

Not identified separately in this table are gases and liquids made from biomass and coal, use of biomass as a solid fuel, passive solar applications, and decentralized use of active solar systems. Biomass is a large source of energy in many developing countries, while all forms of active and passive solar systems are growing in popularity in the developed nations. In addition, a variety of new fuel sources and energy production technologies have appeared on the horizon. Key characteristics of both traditional

## TABLE A-1

## WORLDWIDE ENERGY PRODUCTION IN 1979

| | Primary Energy Production (EJ)[a] | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Electricity (GWh) | | | Total |
| Region | Solids | Liquids | Gases | Nuclear | Other | Total | |
| U.S. | 17.8 | 20.4 | 21.1 | 0.3 | 2.0 | 2.3 | 61.2 |
| Developed Market Economies | 32.7 | 29.9 | 32.0 | 0.5 | 4.7 | 5.2 | 100.5 |
| Developing Market Economies | 3.6 | 77.1 | 5.0 | 0 | 0.8 | 0.8 | 87.0 |
| Centrally Planned Economies | 44.0 | 30.5 | 16.9 | 0.1 | 1.9 | 2.0 | 92.7 |
| World | 80.2 | 137.5 | 54.0 | 0.6 | 7.4 | 8.0 | 280.2 |

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a/ Production for all fuels except electricity is in units of primary energy; for electricity, production is in units of final energy.

Source: United Nations, Dept. of International Ecnomic and Social Affairs, (1981), *Yearbook of World Energy Statistics*, *1979*, U.N., New York, N.Y.

and emerging fuel sources, and their likely utilization into the next century are discussed below.*

## CURRENT AND FORESEEABLE ENERGY SOURCES

Table A-2 summarizes the current estimates of energy sources which are likely to predominate throughout the next century. As indicated, it appears that conventional sources of oil and gas will continue to fuel world economies at least until the turn of the century, and that coal will gain an increasing share of the market throughout the next century. The high demand for liquid and gaseous fuels is likely to continue, due to their high energy content, transportability, storability, and utilization in end use technologies. As conventional supplies of oil and gas become increasingly expensive, unconventional oil and gas supplies and synthetic fuels from biomass and coal become economically more attractive. Use of non-fossil energy sources will also grow. Nuclear and solar fuels should gain a larger share of the electric market, although expansion of nuclear power on a sustainable basis depends on development of breeder technology. Solar applications in the residential and commercial sectors will continue to grow. The degree to which these trends materialize will depend in part, on continued reduction in the cost of shale oil, synthetic fuel, and solar options.

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* For more information on energy supplies, see, for example, Anderer, et al, 1981. Much of the information presented here is taken from this source.

## TABLE A-2

## SUMMARY OF ENERGY SUPPLIES

| Energy Category | Specified Fuel Types | Location of Major Deposits | Supply Levels | Comments |
|---|---|---|---|---|
| Conventional Gas | Gas recoverable with traditional procedures | Middle East, Africa, Eastern Europe, USSR, North America | About 9,500 EJ | Production should peak after 2000 |
| Unconventional Gas | Gas in geopressure zones and tight formations | Same as conventional gas resources | Perhaps 9,000-31,000 EJ | More exploration is needed to map these deposits |
| Conventional Oil | Oil recoverable with traditional procedures | Middle East, Africa, North America, Western Europe, USSR | About 12,500 EJ | Production should peak before 2000 |
| Unconventional Oil | Heavy oil needing enhanced recovery, tar sand oil, shale oil | Broadly distributed with 2/3 of shale oil in North America | About 12,500 EJ of heavy and tar sand oil, and about 16,000 EJ of shale oil | Production costs are considerably higher than for conventional oil |
| Coal (Solid) | Coal used as a solid fuel | U.S., China, USSR | About 95,000 EJ | |
| Biomass (Solid) | Biomass from energy farms and wastes, used as solid fuel | Widely distributed | About 160 EJ/yr from crops and perhaps 30 EJ/yr from waste | Availability of land, competition with food uses, and production costs limit its use |

TABLE A-2 (Continued)

| Energy Category | Specified Fuel Types | Location of Major Deposits | Supply Levels [a] | Comments |
|---|---|---|---|---|
| Synthetic Fuels | Liquids and gases from coal and biomass | See Coal and Biomass | See Coal and Biomass | Availability is related to production costs. Coal-derived synfuels appear less costly than biomass synfuels |
| Solar | Residential/commercial applications (passive and active), centralized solar electric | Dependent on the amount of solar radiation | Availability of land does not appear to be limiting (10 million km$^2$ may be available) | Res./com. applications are widespread, high capital costs limit solar-electric |
| Nuclear | Uranium ore | Africa, Southeast Asia, North America, USSR, E. Europe, Latin America | Depends on nuclear technology (fission vs. breeder) | |

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[a] Expressed in energy equivalents of primary energy, where appropriate.

SOURCE: Anderer, J. et al., (1981), Energy in a Finite World, IIASA, Ballinger Publishing Co., Cambridge, Mass.

## EXOTIC AND HYBRID FUEL SYSTEMS

The farther into the future projections extend, the more likely that totally new energy forms will come into play. Following are currently exotic energy sources, some of which may become commercially significant before the end of the 21st century.

- Nuclear Fusion -- Fusion involves the extraction of "heavy" hydrogen (deuterium) from water and the combination of two hydrogen atoms to form helium. Although it has long been hailed as the path to unlimited energy, scientific feasibility has yet to be established. Demonstrations of technological feasibility must then follow, with mastery of materials development and system engineering looming as major hurdles.

- Hydrogen -- Hydrogen may become the "energy carrier of the future." Most schemes for generating hydrogen are based on splitting water using solar energy directly (thermolysis or photolysis) or indirectly via electricity (electrolysis). Hydrogen would then be used as a substitute for natural gas. Although the technical feasibility of water splitting on a large scale has yet to be established, a "hydrogen economy" remains at least a distant possibility.

- Solar Satellites -- Collecting solar energy in space and transmitting it to earth via microwave is another long-range possibility. Due to the large size of the required collector, current launch and deployment costs render this scheme economically infeasible. However, future advances in space equipment may change this assessment.

- Energy Plants -- Rapid improvements in bioengineering may provide the basis for improving the efficency or redirecting the end products of photosynthetic processes to produce commercial fuels such as hydrogen. At this time, scientific feasibility of developing "super species" remains to be established.

- Combinations -- Concepts for combining end uses and supply generation facilities to better utilize waste heat already are being employed. These include co-generation of steam and electricity and district heating. Future combination may include the use of nuclear energy to generate heat for coal gasification and liquifaction. The requisite hydrogen for synfuel production may be provided by splitting water with solar energy. Other hybrid systems may emerge as the component parts become practical.

## ENVIRONMENTAL AND SAFETY CONSTRAINTS

Certain supply options are likely to be constrained by negative environmental effects (other than $CO_2$ emissions). Nuclear power, for example, is currently facing a severe handicap due to (1) the lack (as yet) of politically acceptable means of waste disposal, and (2) concern over reactor safety and nuclear fuel theft.* The growth of the nuclear industry hinges in large part on overcoming public fears, as well as on solving the purely technical issues involved in waste disposal, reactor safety, and fuel security. Other sources of energy (1) are more environmentally benign (e.g., solar), (2) are subject to technically feasible (but perhaps costly) environmental controls (e.g., high sulfur coal), or (3) create less visible problems (e.g., safety for oil rig workers). Environmental problems resulting from extensive use of future energy sources such as shale oil and synthetic fuels have yet to be completely understood. If major problems emerge, development could be delayed. At a minimum, the costs of mitigating these problems will make the affected fuels less economically attractive.

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* These problems have stymied the nuclear industry in the U.S. No new reactors have been ordered by utility companies since 1978 while 60 previously planned facilities have been cancelled over this 5-year time period. On the other hand, nuclear generating capacity has continued to grow in other countries. For example, total capacity expanded from about 50 to 70 gigawatts in all free world countries other than the United States (U.S. Dept. of Energy, 1981).

# APPENDIX B

## THE IEA ENERGY AND $CO_2$ EMISSION MODEL

The IEA/ORAU,* energy and $CO_2$ emission model was developed by Jae Edmonds and John Reilly at the Institute for Energy Analysis as an assessment tool for policy analysis. It provides a consistent representation of economic, demographic, technical, and policy factors as they affect energy use and production, and $CO_2$ emissions. The general structure and key analytical features of the model are described in the text. This discussion provides a more detailed description of the structure, data base, output, and usage of the model, all of which are extensively documented elsewhere.**

### ENERGY DEMAND

Energy demand for each of the six major fuel categories is developed for each of the nine regions separately. Five major exogenous inputs determine energy demand: population, economic activity, technological change, energy prices, and energy taxes and tariffs.

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* The Institute for Energy Analysis is part of the Oak Ridge Associated Universities.

** See the following volumes: Edmonds, Reilly, and Dougher (1981) and Reilly, Dougher, and Edmonds (1981).

An estimate of GNP for each region is used as a proxy for both the overall level of economic activity and as an index of income. While the level of GNP is an input to the system, it is derived from demographic projections of the labor age population and an assessment of likely labor force participation rates and levels of labor productivity. These estimates were generated in conjunction with Nathan Keyfitz of Harvard University and Philander Claxton of the World Population Society.

Improvements in energy technology beyond those induced by real price increases or income decreases is reflected in a parameter called "enhanced energy efficiency". In the past, technological progress has had an important influence on energy use in the manufacturing sector of advanced economies. The inclusion of an energy technology parameter allows scenarios to be developed which incorporate either continued improvements or technological stagnation as an integral part of scenarios.

The final energy factor influencing demand is energy price. Each region has a unique set of energy prices which are derived from world prices (determined in the energy balance component of the model),transportation costs, and region-specific taxes and tariffs. The model can be modified to accommodate non-trading regions for any fuel or set of fuels. It is assumed that no trade is carried on between regions in solar, nuclear, or hydroelectirc power, but all regions trade other types of fuels.

The four secondary fuels (refined oil, refined gas, refined solids [coal and biomass], and electricity) are consumed to produce energy services. In the three OECD regions (Regions 1, 2, and 3 in Figure 3-2), energy is consumed by three end-use sectors: residential/commercial, industrial, and transport. In the remaining regions, final energy is consumed by a single aggregate sector.

The demand for energy services in each region's end-use sector(s) is determined by the cost of providing these services, and the levels of income and population. The mix of secondary fuels used to provide these services is determined by the relative costs of providing the services using each alternative fuel. A logit share function is employed to calculate these shares.

The price of secondary fossil fuels is a function of the regional price of primary fuels and the cost of refining:

$$P_{jr} = P_{ir}(g_{ij}) + h_j$$

$$P_{ir} = (P_i + TR_{ir})\ TX_{ir}$$

Where: $P_{jr}$ is the price of secondary fuel j in region r; $P_{ir}$ is the price of primary fuel i in region r; $g_{ij}$ is the efficiency of refining i into j; $h_j$ is the non-energy cost of refining; $P_i$ is the world market price of fuel i; $TR_{ir}$ is the cost of transporting fuel i to region r, and $TX_{ir}$ is the tax on fuel i in region r.

The price of electric power is estimated as a weighted sum of the prices of the alternative electricity-generating fuels, and the cost of energy conversion. Likewise, the price of synthetic oil and gas from coal and biomass are functions of the price of coal (biomass) and the cost of liquification or gasification.

Prices calculated in this general manner serve as key inputs to the demand estimation process. Total regional demand for secondary energy services is calculated as a function of aggregate energy price, income level, and population (or level of economic activity -- GNP) in each region; price and income elasticities modulate the effect of the price and income values, respectively. Demand is then allocated among secondary fuels using (1) historic market shares and (2) the relative cost of providing energy services from each fuel within, as noted above, a logit share formulation.

For fuels which are not traded internationally (i.e., nuclear-, solar-, and hydro-electric), demands and supplies calculated this way are, by identity, equal. For the other fuels, however, a market-clearing mechanism is simulated in which prices for gas, liquids, and solids are altered in order to balance supplies and demands. This is described in the Energy Balance section.

## ENERGY SUPPLY

Three generic types of energy supply categories are distinguished: resource-constrained conventional energy, resource-constrained renewable energy, and unconstrained energy resources. There are eight different supply modes across these categories as shown in Chapter 3. Production of conventional gas and oil are represented by a logistics curve which reflects historic supply levels and estimates of remaining deposits:

$$\frac{F(t)}{1-F(t)} = \exp(a + bt)$$

Where: $F(t)$ is the cumulative fraction of the total resource exported by time $t$, and $a$ and $b$ are empirical parameters.

Production rates of these fuels are thus insensitive to price levels.

Production levels of unconventional oil and gas, nuclear, solar, and solids (coal and biomass) are modeled as "backstop technologies". That is, a base level of production is assumed over time if real prices remain constant. Shorter term supply schedules are then super-imposed on these long-term trends to reflect the increase or decrease in production due to price rises or declines. If the price falls below a breakthrough price level, then production ceases. These relationships are encompassed in the following general expression:

$$P = a\ [\exp(g/b)^{c}]$$

Where: $P$ is the price of the backstop fuel; $a$ is the breakthrough price; $b$ is a parameter which determines the "normal" backstop price; $c$ is a price elasticity control parameter; $g$ is the ratio of output in year $t$ to the base level output associated with the backstop price.

Production schedules of synthetic oil and gas are determined by the price (supply schedules) of solids, the cost of producing the synthetic fuel, and associated non-energy costs. The share of coal or biomass allocated to the production of synfuels is specified by a logit share equation, with the relative cost of synfuels versus other sources of gas and oil and the price elasticity of production as key terms.

Resource-constrained renewable fuels are considered constant-flow sources. That is, the rates of energy production are limited by the availability of the resource.

## ENERGY BALANCE

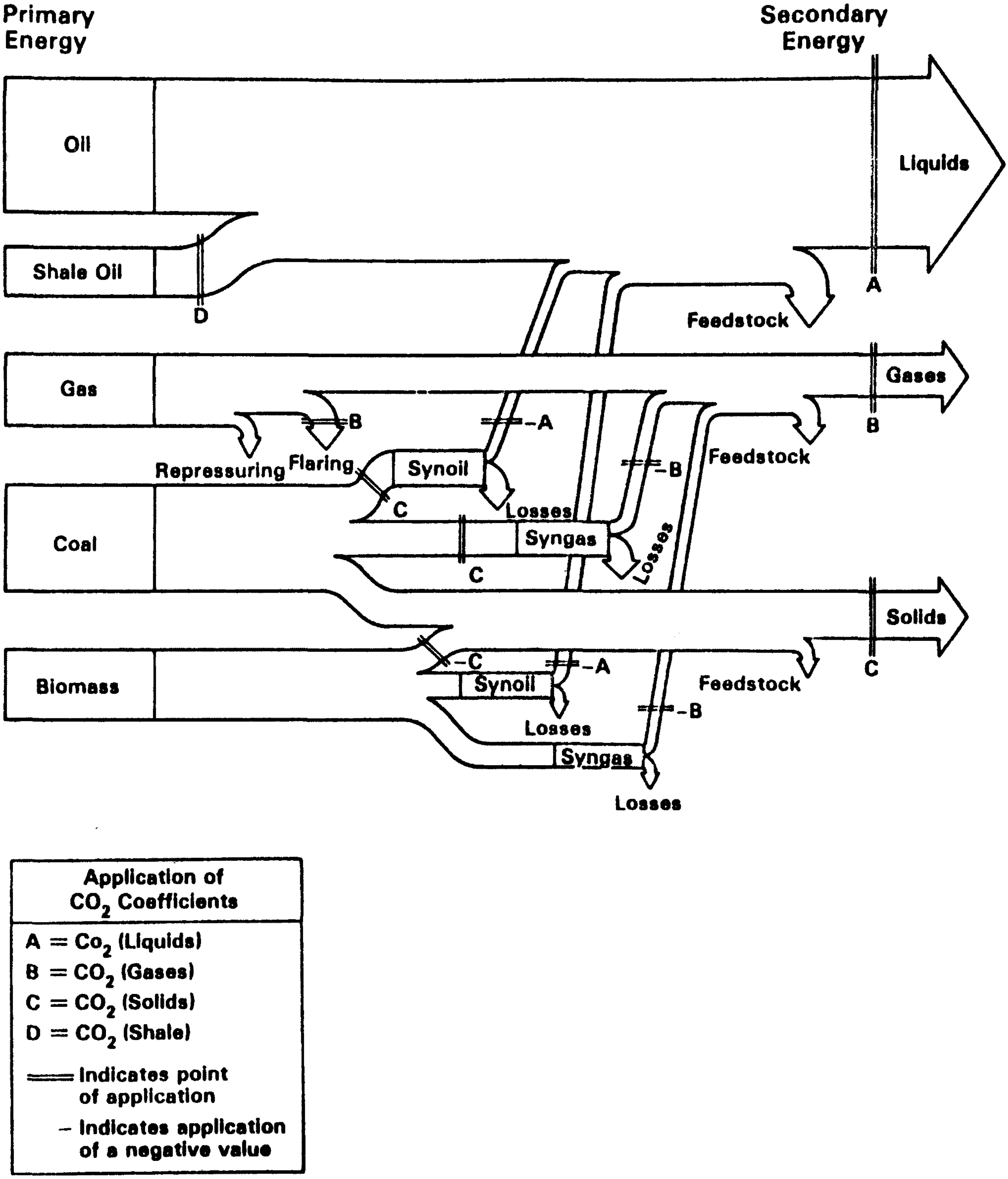
The supply and demand modules each generate energy supply and demand estimates based on exogenous input assumptions and energy prices. If energy supply and demand match when summed across all trading regions in each group for each fuel, then the global energy system balances. Such a result is unlikely at any arbitrary set of initial energy prices. The energy balance component of the model is a set of rules for choosing energy prices which, on successive attempts, brings supply and demand nearer a system-wide balance. Successive energy price vectors are chosen until energy markets balance within a pre-specified bound.

## $CO_2$ RELEASE

Given the solution from the energy balance component of the model, the calculation of $CO_2$ emissions rates is conceptually straightforward. The problem merely requires the application of appropriate carbon coefficients (carbon release per unit of energy) at the points in the energy flow where carbon is released. Carbon release is associated with the consumption of oil, gas, and coal. Large amounts of $CO_2$ are released from the production of shale oil from carbonate rock and from the production of synthetic fuels from coal. A zero carbon release coefficient is assigned to biomass, nuclear, hydro, and solar. The specific coefficients used in the modelling analysis and listed in Chapter 3 were compiled by IEA from various sources, and conform to the IEA fuel accounting conventions as shown in Figure B-1.

FIGURE B-1

APPLICATION OF $CO_2$ EMISSION COEFFICIENTS IN THE IEA MODEL



# APPENDIX C

## THE ORNL CARBON CYCLE MODEL

The Oak Ridge National Laboratory carbon cycle model represents flows and stocks of carbon on a global scale. Terrestrial carbon is modeled in considerable detail while ocean carbon is represented by a simple box-diffusion concept. A general overview of the model is presented here.*

Figure C-1 depicts the overall structure of the model. Carbon in living material is divided between ground vegetation and trees, and, within trees, between "woody" and "nonwoody" parts. Dead organic matter is divided between detritus/decomposer and active soil carbon. Finally, carbon in the ocean is subdivided into surface (260m) and deep layers.

For each of the carbon reservoirs, equations specify maximum stocks of carbon and rates of flow into and out of the reservoirs. In general, terrestrial flows are modeled as linearly dependent on carbon content of the $i^{th}$ donor reservoir ($F_{ij} = a_{ij} C_i$) or as a more complicated logistics function.

The logistic functions for trees includes a term for carbon release to the atmosphere from forest clearing. Permanent forest clearing is reflected by reductions in the parameters governing storage capacity. Where clearing is temporary, reestablishment of forests occurs in a delayed exponential fashion. (The forest clearing option was not activated for this study).

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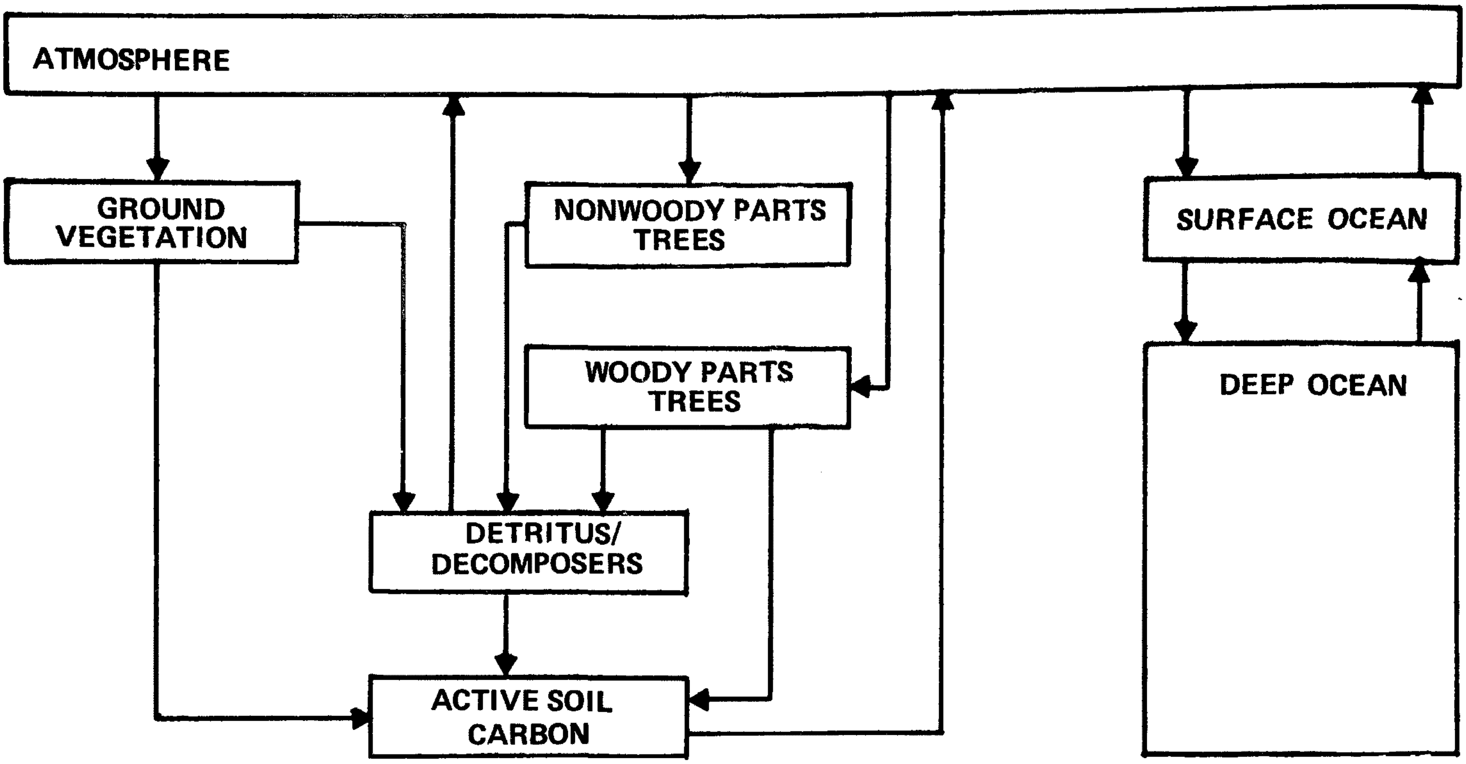
* For a more detailed discussion see Emanuel, et al. (1981).

FIGURE C-1

STRUCTURE OF THE ORNL GLOBAL CARBON CYCLE MODEL



**THIS FIGURE IS TAKEN FROM AN UPDATED MANUSCRIPT BY W.R. EMANUEL AND OTHER AT OAK RIDGE NATIONAL LABORATORY.**

Net uptake of carbon by the ocean is limited by the availability of carbonate ion. The rate at which gaseous $CO_2$ is dissolved in seawater depends on the rate of reaction with $CO_3^{--}$, which is the first step of a process by which $CO_2$ is incorporated into various seawater carbonate compounds.

Most flux equations are temperature-sensitive. Sensitivity to temperature is significant as a rise in temperature is the most direct consequence of an increase in atmospheric $CO_2$. The original version of the ORNL represented this temperature-$CO_2$ relationship by a simple exponential equation rather than through a series of heat-flux equations. This aspect of model was ignored in favor of the relatively sophisticated heat flux relationships in the GISS model. These relationships were utilized by coupling the two models (see the Appendix E).

The model inputs are estimates of fossil fuel carbon emissions on a yearly or longer time period basis from 1980 until some future year. (The IEA model outputs are on a 25-year basis. Estimates were provided on a 5-year basis by interpolating between the 25-year estimates). Outputs are atmospheric $CO_2$ for 5-year time intervals.

The model simulates historical patterns of carbon cycling from 1740 to 1980 on an annual basis. The resulting time trend in $CO_2$ was modified slightly so that the concentration in 1980 was 339 ppm. This corresponds to the level estimated by the GISS model in 1980 given estimates of fossil fuel carbon emissions in

1975 (the starting point of the IEA model) used in this study, and matches observed $CO_2$ levels for 1980. The model was then run to produce estimates of atmospheric $CO_2$ from 1980 to 2100.

# APPENDIX D

## THE GISS ATMOSPHERIC TEMPERATURE MODEL

The GISS model used in this study is based on a one-dimensional (1-D) radiative-convective (RC) model for estimating temperature increases associated with atmospheric $CO_2$ rises.* The 1-D, RC model computes vertical temperature profiles over time from net radiative and convective energy fluxes. Radiative fluxes, in turn, depend on changes in atmospheric gases, especially $CO_2$. The GISS model is an empirical representation of the 1-D, RC model, as modified by Hansen and co-workers to include terms for greenhouse gases other than $CO_2$.

### HEAT FLUX COMPUTATIONS

The heat flux into the earth's surface is estimated by an equation which contains all key temperature-related terms:

$$
\begin{aligned}
F(t) = {} & \frac{2.6\mathrm{x}10^{-5}(\Delta \mathrm{C02})}{[1 + .0022(\mathrm{C02})]^{0.6}} - \frac{5.88\mathrm{x}10^{-3}}{T_e} (\Delta T) + \frac{3.685\mathrm{x}10^{-4}}{T_e^2} (\Delta T)^2 \\
& - \frac{4.172\mathrm{x}10^{-7}}{T_e} (\Delta \mathrm{C02}) (\Delta T) + 1.197\mathrm{x}10^{-3} (\Delta \mathrm{CH4})^{0.5} \\
& + 5.88\mathrm{x}10^{-3} (\Delta \mathrm{N20})^{0.6} + 3.15\mathrm{x}10^{-4} (\Delta \mathrm{CC3}) + 3.78\mathrm{x}10^{-4} (\Delta \mathrm{CC2}) \\
& - 1.197\mathrm{x}10^{-4} (\Delta \mathrm{CH4})(\Delta \mathrm{N20}) + 2.40\mathrm{x}10^{-2} (\Delta V) + 2.10\mathrm{x}10^{-3} (\Delta V)^2 \\
& - \frac{1.17\mathrm{x}10^{-3}}{T_e} (\Delta T)(\Delta V) + 3.184\mathrm{x}10^{-1} (\Delta S)
\end{aligned}
$$

---

* See Hansen, et al. (1981).

Where: F(t) is the heat flux as a function of time in cal/min-$cm^2$.
$\Delta$C02 is the change in atmospheric $CO_2$ from the 1880 value (293 ppm) in ppm.
$\Delta$T is the change in atmospheric temperature (surface level) from the 1880 value in °C
$\Delta$CH4 is the change in atmospheric $CH_4$ from the 1880 value (1.6 ppm) in ppm.
$\Delta$N20 is the change in atmospheric $N_2O$ from the 1880 value (0.300 ppm) in ppm.
$\Delta$CC3 is the change in $CCl_3F$ from the 1880 value (0 ppb) in ppb.
$\Delta$CC2 is the change in $CCl_2F_2$ from the 1880 value (0 ppb) in ppb.
$\Delta$V is the change in atmospheric optical depth from a baseline level due to volcanic activity in dimensionless units.
$\Delta$S is the change in solar luminosity from a baseline level in fractional units.
$T_e$ is the equilibrium temperature--the assumed temperature rise when $CO_2$ doubles from the 1880 level (from 293 to 586 ppm).

The heat flux is estimated from time periods ranging from each month to each year (a semi-monthly time step was used in this study). The appropriate $\Delta$T value for calculating F(t) in each time period (t=n) is the value estimated for the previous period (t=n-1). For a simple one-layer ocean model, T is obtained by solving the following differential equation:

$$\frac{d\Delta T}{dt} = \frac{F(t)}{C_0}$$

Where: $C_0$ is the heat capacity of the mixed layer of the ocean per unit area (cal/$cm^2$).

Estimates of heat flux from the empirical equation described above were compared by Lacis with the RC model calculations. The two estimates agreed to within one percent for C02 values of 0 - 1220 ppm, and to within 5 percent for C02 values of 1220-1700 ppm (Lacis, et al., 1981).

Values for the parameters in the empirical heat flux equation were summarized in Table 3-4 and are detailed below:

$\Delta CO_2$: value obtained from the IEA and ORNL models
$\Delta CH_4$: 1.6 ppm through 1980, increased by 2% per year thereafter (Recent measurements of methane suggest a worldwide average of roughly 1.6 ppm. Concentrations are believed to have increased from between 0.5% and 3.0% over the last decade; levels are assumed constant before 1980 as a simplification).
$\Delta N_2O$: 0.300 ppm through 1980, increased at 0.2% per year thereafter (This is the best estimate for 1980, with levels believed to have changed only slightly over time.)

$\Delta CC2$ and $\Delta CC3$: 0 before 1980, increased as shown thereafter:

| Year | $\Delta CC2$ | $\Delta CC3$ |
|---|---|---|
| 1980 | 0.306 ppb | 0.176 ppb |
| 1990 | 0.469 | 0.269 |
| 2000 | 0.616 | 0.345 |
| 2010 | 0.749 | 0.407 |
| 2020 | 0.870 | 0.458 |
| 2030 | 0.979 | 0.500 |
| 2040 | 1.080 | 0.534 |
| 2050 | 1.166 | 0.562 |
| 2060 | 1.247 | 0.585 |
| 2070 | 1.320 | 0.604 |
| 2080 | 1.386 | 0.619 |
| 2090 | 1.446 | 0.632 |
| 2100 | 1.500 | 0.642 |

(Levels of chlorofluorocarbons began to increase from zero in the 1940s, with a rapid rise in the 1970s. The 1980 estimates are based on recent measurements. Assuming an immediate increase from zero to current levels in 1980 introduces some error in temperature estimates between 1950 and 1980, but does not influence future estimates.)

$\Delta V$: constant 0.007 each year from 1880 - 2100

$\Delta S$: 0 from 1880 - 2100

$T_e$: 1.5°C, 3.0°C, and 4.5°C

## DIFFUSION OF HEAT IN THE OCEAN

The ocean model consists of a mixed layer of depth $H_m$ = 100m and a thermocline with 63 layers and a total depth H = 900m. The mixed layer temperature is assumed to be independent of depth, while the thermocline temperature is defined by a diffusion equation with constant thermal diffusivity. The layering is different from that used in the ORNL model, but the difference is not important.

The temperature in the mixed layer ($\Delta T_m$) is a solution of the equation:

$$C[H_m]\left[\frac{d\Delta T_m}{dt}\right] = F(t) + F_D(t)$$

where C is the heat capacity of water, F(t) is the heat flux from the atmosphere into the ocean and

$$F_D(t) = -\lambda \frac{\partial \Delta T}{\partial z}\Bigg|_{z = H_m}$$

is the heat flux from the thermocline into the mixed layer.

Note that the z-axis is directed toward the bottom of the ocean. Also, since all values are in units of g, cm, sec, and cal; heat conductivity $\lambda$ is numerically equal to heat diffusivity K. The value for diffusivity was set at 1.18 $cm^2/sec$.

The temperature change in the thermocline ($\Delta T$) is determined by the diffusion equation:

$$C \frac{\partial \Delta T(z,t)}{\partial t} = K \frac{\partial^2 \Delta T(z,t)}{\partial z^2}$$

The boundary conditions for $\Delta T$ are:

$$\Delta T = \Delta T_m \quad \text{at } z = H_m$$

and zero heat flux at the bottom of the thermocline:

$$K \frac{\partial \Delta T}{\partial z} = 0 \text{ at } z = H \quad .$$

Thus it is assumed that no energy escapes through the lower boundary of the thermocline. Note that $\Delta T_m$ and $\Delta T$ are temperature changes of the mixed layer and the thermocline between the initial time (1880) and time t. It is assumed that in the year 1880 $\Delta T_m = \Delta T = 0$, and thus that the ocean temperture was in a state of equilibrium with the atmosphere at that time.

Required input data are atmospheric $CO_2$ levels on a yearly or longer time period basis. Five-year estimates were obtained from the ORNL, or alternatively, were obtained by multiplying a specified retention ratio times the interpolated 5-year estimates of carbon emissions from the IEA model. GISS outputs are estimates of atmospheric temperature increases on a 5-year basis.

# APPENDIX E

## COUPLING THE ORNL AND GISS MODELS TO ESTIMATE THE RETENTION RATIO

As noted in Chapter 3, the ORNL and GISS models were coupled in order to estimate that fraction of $CO_2$ emitted which remains airborne (the retention ratio). Recall that the rationale for coupling the models is based on (1) the temperature-sensitive representation of carbon flows in the ORNL model, and (2) the superior treatment of atmospheric $CO_2$-temperature relationships in the GISS model. The coupling procedures are diagrammed in Figure E-1, and are described in this appendix.

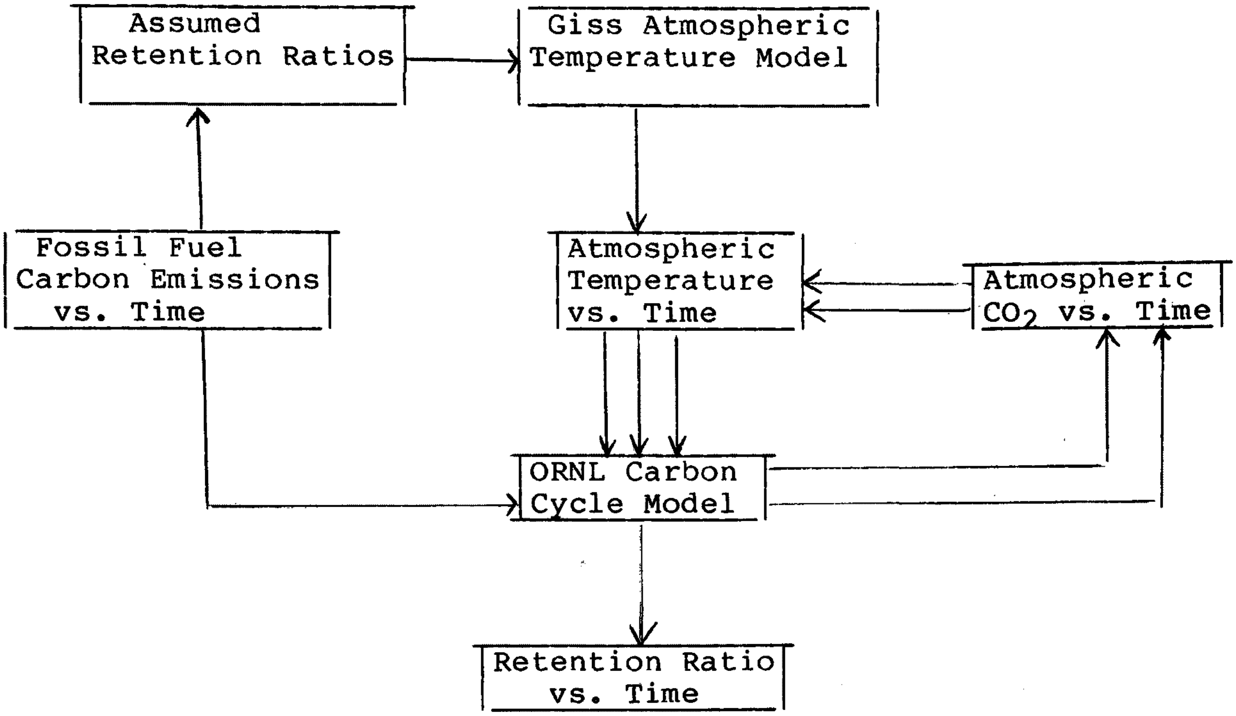
### CALCULATING INITIAL TEMPERATURE VS. TIME CURVES

The starting point is the estimation of a family of temperature-time curves using the GISS model. These curves are employed in the ORNL model to describe a range of future increases in atmosperic temperature (in response to rising atmospheric $CO_2$) which, in turn, will affect the rate of $CO_2$ exchange among sources and sinks. In essence, the time trends in temperature, generated through a more sophisticated (though still simplified) treatment of heat flux in the GISS model, replace very simple $CO_2$-temperature relationships in the ORNL model.

To generate the GISS temperature-time curves, it is first necessary to estimate an atmospheric $CO_2$-time curve which serves as the main driving function for the GISS model. The most

FIGURE E-1

## KEY FEATURES OF THE ORNL-GISS COUPLING METHODOLOGY



straightforward approach is to apply a series of assumed retention ratios to the time trend of $CO_2$ emissions generated by the IEA model. Values from about 0.6 in 1980 to about 0.8 in 2100 were used to generate the preliminary atmospheric $CO_2$-time curves.

The GISS model is then run with high and low temperature - $CO_2$ sensitivity ($T_e$) values, with and without other greenhouse gases, to produce a family of atmospheric temperature versus time curves. These curves are represented by a quadratic equation of temperature versus time with parameters a and b. The parameter a is the temperature difference between 2100 and 1980, and b is the temperature difference between 2040 and 1980 divided by a. These parameters are then used to calculate coefficients for the quadratic equation $T = ct + dt^2 + 293$, where T is the temperature rise after 1980 (°K) and t is the number of years after 1980.

Four new curves reflecting the extreme values observed for a and b are then specified:

| | | a | |
|---|---|---|---|
| | | Highest | Lowest |
| b | Highest | Case 1 | Case 2 |
| | Lowest | Case 3 | Case 4 |

These curves bound all possible changes in temperature given the time trend in atmospheric $CO_2$ specified previously. The four combinations of values for a and b are then transmitted to the ORNL model.

## CALCULATING $CO_2$ VS. TIME CURVES WITH THE ORNL MODEL

The ORNL model is next employed to estimate future increases in atmospheric $CO_2$, using the fossil fuel $CO_2$ emission scenarios from the IEA model and the four sea surface temperature-time trends from the GISS model. Since four separate temperature - time curves are employed, four separate $CO_2$-time curves are generated as output. Each $CO_2$ curve is represented by estimates of atmospheric $CO_2$ concentrations in 10-year intervals from 1980 to 2100. Thus, a 4 by 13 matrix of values (corresponding to the 4 time vs. temperature curves and the 13 inclusive decades between 1980 and 2100) is generated as output.

## ESTIMATING FINAL TEMPERATURE VS. TIME CURVES

The four "refined" time projections of $CO_2$ are returned to the GISS model to obtain a consensus temperature versus time curve. This is accomplished by selecting one of the $CO_2$ curves as a starting point. (Tests demonstrated that starting from any one of the four curves will yield the same result.) The GISS model is then run to obtain a corresponding temperature curve from 1980 to 2100. This temperature curve is compared with the four temperature curves originally generated by the GISS model and transmitted to the ORNL model. The new temperature curve is composed by interpolating among the four previous curves, and a new $CO_2$ curve is estimated corresponding to the interpolated temperature curve. (In essence, this is a two-way interpolation for each 10-year interval). The whole process is repeated until two successive temperature curves closely approximate each other. Usually, this takes no more than two iterations.

To check the "accuracy" of such an iterative approach, the final temperature-time curve from GISS was used as input to the ORNL model for a small sample of runs. The resulting $CO_2$-time curve from ORNL was compared to the final $CO_2$-time curve in GISS. In all cases, the two agreed within 2 ppm for each 10-year interval.

## COMPUTING RETENTION RATIOS

Once the final atmospheric $CO_2$ vs. time curve is obtained from the ORNL, it is divided by the $CO_2$ emissions vs. time curve to obtain a time-trend in retention ratios. In practice, 10-year average values were computed. These were then used with estimates of 10-year average $CO_2$ emissions (from the IEA model) to compute 10-year average atmospheric levels of $CO_2$. These were used as input to the GISS model for final estimates of atmospheric temperature trends.

# GLOSSARY OF ENERGY UNITS

## Definitions

Btu: British Thermal Units (Btus) are the basic energy units in the English System. One Btu is the energy needed to raise one pound of water one degree farenheit.

Joule: Joules (J) are the basic energy units in the metric system. One joule = 0.0009 Btus.

## Abbreviations

Watt-hour: Wh*
Watt-year: Wy
Quad: $10^{15}$ Btus

Barrel of Oil Equivalent: boe
Metric Tons of Coal Equivalent: mtce
Cubic Feet of Gas: $ft^3$ gas

## Prefixes

Kilo(k): $10^3$
Mega(M): $10^6$
Giga(G): $10^9$

Terra(T): $10^{12}$
Deta(D): $10^{15}$
Exa(E): $10^{18}$

## Conversions

1.0 GJ = $0.995 \times 10^6$ Btus
1.0 EJ = 0.995 Quads
1.0 kWy = 31.5 GJ
1.0 TWy = 31.5 EJ
1.0 mtce = 29.9 GJ
1.0 boe = 6.12 GJ
1.0 $ft^3$ gas = $1.06 \times 10^{-3}$GJ

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* Wh(e) means watt-hours of electrical energy

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