Transitional Strategies for the Reduction of "Greenhouse Gas" Emission in the United States Electric Power Sector

by

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MIT-CEPR 90-019WP May 1990

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Submitted to the Department of Electrical Engineering and Computer Science on May 11, 1990 in partial fulfillment of the requirements for the Degree of Master of Science in Technology and Policy

ABSTRACT

Environmental issues have become increasingly important in the political arena, particularly with growing concern over the "greenhouse effect", a potential global climatic warming caused by increases in anthropogenic emissions of greenhouse gases. The United States alone accounts for 25% of the worldwide emissions of CO_2, the most important of the greenhouse gases. The generation of electric power is responsible for one-third of United States CO_2 emissions in addition to emissions of methane and nitrous oxide, also greenhouse gases. In the long term, strategies to reduce such emissions will probably concentrate on non-fossil fuel sources, such as nuclear energy, solar energy, or biomass. Near term strategies for the reduction of these emissions, important because of lengthy time lags in the climate system, must concentrate on existing technologies. These strategies must also be compatible with other environmental and societal goals.

This study examines the emissions reduction potential in two regions of the United States electric power industry. Utility accepted models and data have been utilized to minimize concern over structural simplifications and parametric errors. Seven potential strategies were examined to determine their effectiveness for the reduction of CO_2 emissions. The costs and additional environmental effects of these strategies were also calculated.

The study finds that some carbon emissions, and large amounts of other environmental emissions, can be reduced at little or no cost. Larger amounts of emissions reductions appear to be possible at higher cost. The tradeoffs between cost and emissions reduction are quantified to facilitate strategy choice. Processes for the selection of economically feasible and politically acceptable climate change policies, through the use of such analyses, are discussed.

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ACKNOWLEDGEMENTS

The author would like to thank the MIT Center for Energy Policy Research for its support of this research endeavor. The author would also like to recognize the general financial support given over the last two years by the Hugh Hampton Young Fellowship Committee, the Bernard Rabinowitz Fellowship Committee, the Alfred Keil Fellowship Committee, and the MIT Center for Technology, Policy, and Industrial Development.

Much of the data used for this study were made available through the Electric Power Research Institute, Commonwealth Electric, and the MIT New England Project in the MIT Energy Laboratory.

The author would like to thank Richard Tabors, whose professional and personal support has been above and beyond the call, and the members of the New England Project — Clint Andrews, Steve Connors, Dan Greenberg, Warren Schenler, and Kristin Wulfsberg — who shared their experiences with things as esoteric as electric power planning and as mundane as getting a spreadsheet to work. Without their help, this project could not have been started, much less finished.

With Thanks To Those Who Gave Me Everything:

Burt and Rose
Burt and Ethelmae
Reuben and Charlotte

Contents

List of Figures

CHAPTER FIVE, CONT.

CHAPTER SIX

Chapter One - Introduction

The New Agenda

For most of modern history, international relations was confined to one topic: military security. Each nation could operate independently as long as military threats to its borders and people could be countered. As travel and communications capabilities increased, another topic entered the agenda: economics. With growing interdependence, security and economy became intermingled, and international relations became increasingly complex. Now, the international agenda has once again expanded to include a new topic: environment. With the discovery of environmental problems which extend beyond national boundaries, such as acid rain, ozone depletion, and global warming, environmental concerns have increasingly become international concerns. Just as the line dividing economy from security has faded, so now are the lines dividing environment from the other two.

The New Ethic

Environmental concern is not new. In fact the modern environmental movement in America traces its roots as far back as the 1860s. George Perkins Marsh, who warned of the dangers of swamp draining and tree cutting as early as 1864, has been referred to by some as the "first modern environmentalist"[1]. What is new, however, is the global scale of the issues that are now encompassed under the flag of environmentalism.

[1] McKibben, 1989.

These global environmental effects have brought with them a general uneasiness about the possible irreversibility of the large-scale environmental damage which people may be causing.

With this uneasiness has come an increased call for a new ethical framework which incorporates the environment as something worth preserving in its own right or, indeed, as something which people have no right to exploit for their own purposes. This sentiment also has deep roots, traceable to Marsh and to Thoreau's Walden, written at about the same time. Only recently, however, has the sentiment seemed popular, at least superficially, on such a wide scale.

Environmentalist Bill McKibben recently made the best seller list with his book The End of Nature[2]. Hailed as the greatest call to environmental action since Rachel Carson's Silent Spring exposed the dangers of DDT[3], The End of Nature puts forth as its thesis that nature is no longer in any way independent from mankind and has therefore ended being what it used to be. McKibben suggests that nature must be preserved and respected not for its measurable contributions to mankind's standard of living, but "for itself". Other recent authors have made suggestions along the same line[4].

While debate over the validity of such arguments is well beyond the scope of this discussion, it is worth noting that the voices of McKibben and others like him, are being heard. The president of the United States felt the need to cast himself as an environmentalist as part of his election strategy, despite the sometimes undesirable connotations which used to be attached to

2 McKibben, 1989.
3 Carson, 1962.
4 Stone, 1987.

the label. Margaret Thatcher, who once called environmentalists "the enemy within", stated in the past year that "the most pressing task which faces us at the international level is to negotiate a framework convention on climate change, a sort of good-conduct guide for all nations." Earth Day - 1990 celebrations became popular and widespread events worthy of healthy corporate support.

The Emotional Impact of Climate Change

The emergence of this new environmental awareness seems to have been catalyzed by one topic in particular — the "greenhouse effect." The concept of the greenhouse effect — potential catastrophic climate change caused by everyday human activity — is frightening. The issue has galvanized the environmental community, and the media, like no other environmental concern before it.

Perhaps the attention given to the greenhouse effect is due to the excuse it seems to give for other measures which many environmentalists and others have sought for years — conservation, solar power, saving the tropical rain forests. Perhaps the attention is caused by a vague feeling of confirmation about fears that something in the environment "had to give" eventually. Perhaps the attention is due to climate effects which are probably unrelated to the greenhouse effect — increasing temperatures in cities, the United States drought of 1988. Perhaps, of course, the direst predictions are correct and the attention is warranted. Nevertheless, the attention has been substantial.

In 1989, after Time had made its "Planet of the Year" declaration, the magazine began running regular articles about environmental issues, all of them fronted by a logo of the earth held together by twine, and the subheading "Endangered Earth"[5]. A recent New York Times front page story on the first day of President Bush's global warming conference quoted polls which found that 71% of Americans felt environmental protection was worth increased government spending and higher taxes, and that 56% felt it was worth the loss of jobs in their local community[6]. The Boston Globe found an editor ("Common Sense and Global Warming") and columnist ("Yuppie Credos and Greenhouse Effect Hypocrisy") sharply disagreeing with each other in opposite pages of a December, 1989, editorial section[7]. The examples are endless. Greenhouse expert Stephen Schneider refers to the new branch of climate science which the extensive newspaper and television debate has created as "mediarology"[8].

The science, engineering, and policy communities have taken up the call to action with a fervor as well. The last decade has seen an exponential growth in the literature on the subject. The last several years have seen numerous academic conferences on the issue[9]. International meetings of political leaders have been held on the issue[10]. Even religious leaders have joined the fray, meeting with scientists and politicians to discuss the moral and ethical sides of the issue at the Global Forum of Spiritual and Parliamentary Leaders on Human Survival (Moscow, January 1990). Many new

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5 Time, various 1989 and 1990.

6 New York Times, 4/17/90.

7 Boston Globe, 12/17/89.

8 Schneider, 1989.

9 Examples include the Climate Institute's 2nd North American Conference on Preparing for Climate Change, December 6-8, 1988, Washington, DC, and the MIT Energy Laboratory's Conference on Energy and the Environment in the 21st Century, March 26-28, 1990, Cambridge, MA.

10 In the past six months, George Bush has addressed the United Nations International Panel on Climate Change (IPCC) (February, 1990), convened a US conference on "global change" (April 1990), and announced an intention to host a conference for the negotiation of a framework treaty in November.

institutions have been created whose sole purpose is the study of climate change[11].

What is all the furor about? If the doomsayers are to be believed, the furor is about the possibility of changes in climate during the next century more dramatic than the human race has ever seen. The furor is about frequent droughts in United States agricultural areas, intensified hurricanes, plant and animal species which cannot adapt quickly enough, sea levels so high that coastal cities and some island countries may disappear, political and social changes which will occur with shifting agricultural lands, deserts, resources, and population. Ultimately, of course, the furor is about whether any of this will really happen and whether there is anything which can be done to delay it or stop it from happening.

Overview of Study

This study examines the problem of potential climate change, and the formulation of policies to face climate change, primarily through a detailed study of a small, yet significant, portion of the problem: the United States electric power sector. Chapter 2 discusses the general scientific background of the climate change issue and briefly summarizes previous studies which are similar to this one. Chapter 3 discusses the realities of the carbon dioxide issue, justifying the formulation of the present study and providing a theoretical framework for the modeling analysis and policy discussions which follow. Chapter 4 explains the modeling effort which was used for the detailed analysis of various policy strategies for emissions

[11] For instance, the MIT Center for Global Change Science, U.S. Department of State's Office of Climate Change, and Britain's Center for the Prediction of Climate Change.

reduction in two regions of the U.S. electric power sector. Chapter 5 outlines the results of this modeling effort. Chapter 6 discusses the underlying technical and economic characteristics of the successful strategies. The implications of these characteristics for final strategy choice are then discussed. Chapter 7 examines the political context in which climate change policies must be implemented and recommends policies through which such policies might be formed. Likely policy outcomes, based on the modeling results and the political context, are then outlined. Chapter 8 briefly discusses the more general lessons of the study and how similar methodologies might be applied in other sectors of human activity in order to address the climate change issue.

Chapter Two - Facing Climate Change

Complexity and Controversy

The problem of the "greenhouse effect", or perhaps more accurately global climate change, is undeniably complex, with the state of scientific knowledge varying from the factual to the uncertain and even purely speculative. This scientific complexity and uncertainty is responsible in great part for the difficulty associated with establishing effective climate change policy or even deciding whether or not to do so. There are a few general points on which there is fair degree of scientific consensus, some of which will be discussed here. There are numerous explanations of the science of climate change to which those desiring greater detail are referred[12].

The underlying principle of the greenhouse effect is fairly straightforward and undisputed, and is best illustrated by examining the basic energy fluxes of the earth-atmospheric system. These basic processes are pictured in Figure 2-1. Shortwave radiation from the sun is incident upon the earth's atmosphere. A portion of this radiation is reflected back to space, off of clouds, for example, some is absorbed and the remaining portion passes through to the surface. The earth reflects some percentage of this radiation[13] and absorbs the rest. The absorbed radiation is then reemitted indirectly, through the evaporation of water, or directly, as longwave radiation (heat). This change in character of the radiation is significant. Certain chemicals in the atmosphere which allowed the

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[12] Mitchell, 1989b; Ramanathan, 1988; Dickinson, 1986b (nontechnical introduction).

[13] This percentage is the earth's "albedo".

The Earth's Radiation Energy Balance

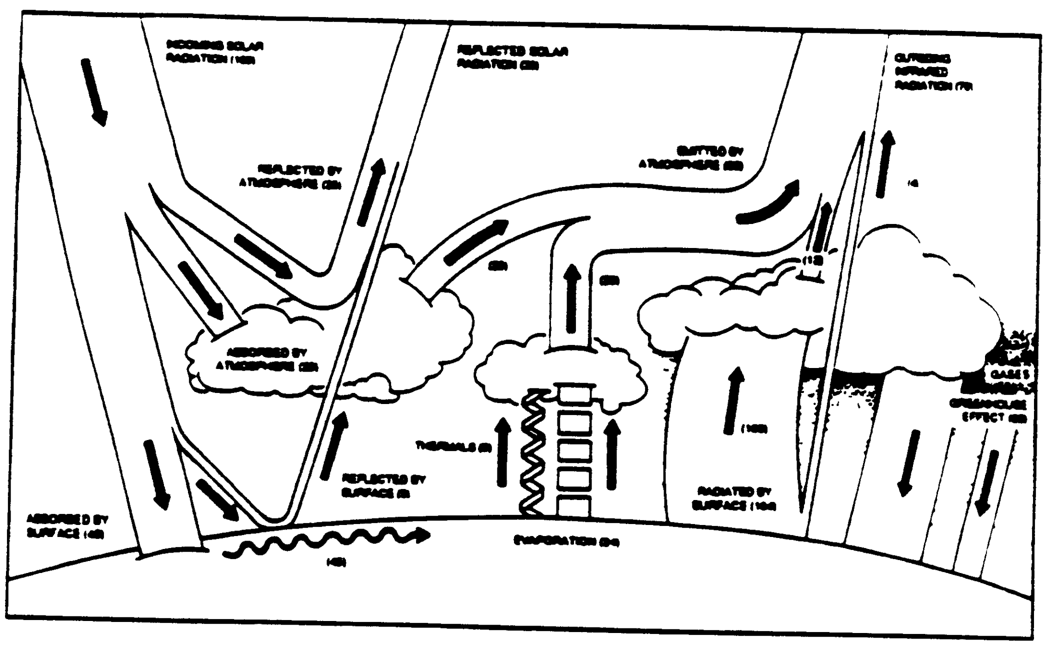

Figure 2-1

Source: Schneider, 1989.

shortwave radiation to pass unaffected when entering the atmosphere will absorb the longwave radiation which is leaving. These chemicals are the greenhouse gases, and include water vapor, carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), and nitrous oxide (N_2O). Some portion of the atmospherically absorbed longwave radiation is reemitted to space, but the remaining portion is reemitted back towards the surface. This energy which is now "trapped" between the surface and the atmosphere leads to a rise in surface temperature (and the greenhouse analogy).

This notion has its origins before this century in the work of Jean-Baptiste Fourier, who first described the effect[14] and Svante Arrhenius, who gave the first quantitative discussion of temperature increases due to atmospheric CO_2[15], and is not seriously in dispute. Likewise, this is not an undesirable phenomenon. The surface temperature of the earth would be some 33°C cooler, too cold for life to have developed, were it not for this effect[16]. The new cause for concern, however, is that human activities are unnaturally increasing the atmospheric concentrations of these greenhouse gases, and may subsequently be causing a rapid heating of the surface. The character of this heating — its timing, its magnitude, its distribution, its effects — are a source of great dispute.

Some "facts" about these characteristics have been developed by general agreement throughout the concerned scientific community. Whether these agreements constitute consensus, much less fact, is arguable[17].

[14] Fourier, 1824.
[15] Arrhenius, 1896.
[16] Schneider, 1989.
[17] Lindzen, 1989; Idso, 1987.

Nevertheless, these statements persist in climate change discussions. Included among these are the following:

1) Carbon dioxide (CO_2) is presently responsible for about half of the problem , followed by methane (18%), CFCs (14%), and N_2O (6%)[18].

2) Ice core data indicate a strong correlation between CO_2 concentrations and surface temperature, although cause and effect are difficult to establish[19].

3) Energy use, in the form of fossil fuel combustion is responsible for most of the greenhouse gas increase (57%) followed by agriculture (14%) and alterations of land use patterns, primarily deforestation (9%)[20].

4) Atmospheric concentrations of CO_2 have increased steadily since direct measurements began in the late 1950s, Hawaii. If the trend continues at the same rate — approximately 4.3% per year — a doubling of atmospheric CO_2 concentrations relative to preindustrial levels will occur by the year 2050[21].

18 US EPA, 1989.
19 Barnola, et.al., 1987; Genthon, et.al., 1987.
20 US EPA, 1989.
21 Oeschger and Siegenthaler, 1988.

5) General climate models agree that a such a doubling would create an increase in global mean surface temperature of 1.5 - 4.5°C. Models also tend to agree that this warming would be greater at the poles and less significant near the equator[22].

6) Among the likely effects of such a change are sea level rises of 3-5 meters[23] and altered precipitation patterns, with continent interiors becoming drier, and edges of continents becoming wetter[24].

The effects of such changes are unimaginable and unpredictable from man's current frame of reference. If temperature changes of the sort predicted were to occur, it would be beyond the range of human experience. Indeed, a change of 3-5°C occurred in the last 18,000 years since the height of the last ice age[25]. The models indicate the possibility of such a change within the next century.

The uncertainties are monumental, however. The predictions are based on the modeling efforts of a few relatively small groups of scientists[26]. By definition, models lack detail and must make assumptions which may or may not account satisfactorily for that detail. The general climate models are no exception. The climate is a very complex and unpredictable system. Changes in the system are only meaningful over

22 Schlesinger and Mitchell, 1987.
23 Robin, 1986; Wigley and Raper, 1987.
24 Hansen, et.al., 1987.
25 Schneider, 1989.
26 Hansen, et.al, 1988; Stouffer, et.al., 1989; Wilson and Mitchell, 1987; Washington and Meehl, 1989.

long periods of time. The limits of computer performance and availability force enormous simplifications. Many significant processes have been parameterized to approximate the more detailed system realities. Whether these parameters allow the models to accurately mimic the system, and thus provide reliable projections of future climate, is not at all clear.

Many effects are not included directly in the models. Foremost among these are the effects of clouds. Even if the effect of clouds could be included in the models, scientists are not clear what the effect would be. Some clouds are highly reflective from above. This reduces the amount of sunlight incident on the earth, and thus causes a cooling. If a greenhouse climate caused increased cloud cover, and thus a cooling through this mechanism, this would be a negative feedback, indicating that the predictions are too high. On the other hand, the water vapor in some clouds acts as a greenhouse gas, actually trapping some radiation below the clouds. If a greenhouse climate caused an increase in these types of clouds, and thus even more heating, this would be a positive feedback, indicating that the predictions are too low. Many other feedbacks are possible, and unaccounted for in the models[27].

In any case, the uncertainty about temperature changes is much greater than the frequently cited 1.5 - 4.5°C temperature range. This uncertainty has tremendous influence on the desirability of climate change abatement policies. If the temperature ranges will be larger than predicted, the need for action may be urgent or there may be nothing which can be done to avoid catastrophic changes to which the globe is already committed. If the temperature changes will be smaller — Lindzen suggests

27 Hansen, et.al. 1984; Wetherald and Manabe, 1988; Broecker, 1987; Lashof, 1989; Mitchell, et.al., 1989a; Wang and Stone, 1980.

a rise of 0.1°C[28] — who cares? Particularly, should anyone care enough to make any effort or sacrifice now in order to avoid the change?

The uncertainties in the climate system are responsible for only a fraction of the complexity which surrounds the issue as a whole. There are complex and poorly understood interactions with other environmental problems[29] and with the many varied and essentially fundamental human activities which exacerbate the greenhouse problem. The existing systems of electricity use, transportation, and agriculture are all called into question. Such basic human processes as economic growth and population growth contribute to the problem. Compounded with the fact that the problem is global in nature, probably requiring the eventual participation of many nations not particular predisposed to cooperation with one another, and the challenges can easily be perceived as insurmountable.

This study can obviously make no attempt to fully answer all of the questions which the climate change problem raises. What can be stated, however, is that the potential consequences of doing nothing are great. Making no effort to determine what policy options exist, and how effective or feasible they may be, would be foolhardy. This study begins to move in that direction through a detailed sectoral study, an approach which will be justified below. It will also be pointed out that the cost of different policy options ranges widely, from those which are very expensive to those which cost little or no money. The latter are of particular interest since they may serve as inexpensive insurance policies against the uncertainties of climate change.

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28 Lindzen, 1989.
29 Smil, 1985; Campbell, 1986.

Studying Climate Change

The climate change issue is a complex one which can be examined in a variety of ways. This section outlines various approaches which can be taken in attempts to study the climate change issue and provide policy alternatives.

Studying the Whole Problem

The most common type of climate change study can be termed "comprehensive." Since the problem is so large, and the activities which exacerbate it so ubiquitous, it is reasoned that only a studies which account for all of the problem can hope to have any impact. The disadvantage of such formulations is that the studies are predisposed to becoming vague, unreliable, or full of despair.

Studies become vague when only superficial recommendations can be made due to the limited or nonexistent nature of the problem analysis. This is typical of many statements by environmental groups or the media — i.e., "burn less fossil fuel". While such a recommendation may indeed suggest an appropriate direction, policy action requires a great deal more specificity.

Unreliability can occur when specific actions are recommended as a result of extensive studies or modeling based on large numbers of simplifying assumptions, typical of most studies discussed below. While these types of study do provide some sense of general policy trends which might be followed, little information is provided as to which policies should be implemented where, when they should be implemented, and finally, how, they should be implemented. Additionally, because of the simplifying assumptions, little faith is put in them by those who understand the detail of the concerned technological and political systems.

The final characteristic — despair — is inevitable when one attempts to encompass the entire problem of climate change under one policy strategy, as is the attempt of many comprehensive studies. In fact, it often appears that the only single policy strategy which can be formulated to encompass the whole problem is a do-nothing strategy in which society learns to adapt to climate change and perhaps wait for the invention of a technological fix which will solve the problem. Such policy recommendations are increasingly popular[30], but tend to treat many significant factors as trivial detail.

Separating the Chemicals

A second alternative for climate change studies is to concentrate on particular greenhouse gases, looking for methods of reducing particular chemical emissions. Since CO_2 is the primary contributor to the problem, it tends to be the focus of such studies[31]. A few other studies have focussed on CFCs[32] or methane[33]. The studies of CO_2 have tended to suffer from many of the flaws of comprehensive studies. Since the activities which contribute to the emissions of each of the gases are so varied, superficiality or despair are often the result here, as well. Additionally, since some CO_2 reduction strategies might increase methane emissions (increased natural gas use, for instance), and vice versa, the conclusions of such studies can be

30 Bach, 1984; T.C. Schelling in closing comments at the MIT Energy Laboratory Conference on Energy and Environment in the 21st Century.
31 Edmonds and Reilly, 1986a, 1986b; Rose,et.al., 1983; many others.
32 Ramanathan, 1975; Wigley, 1988.
33 Ehhalt, 1988.

misleading. It should be noted that since CFCs are purely man-made chemicals, used for a limited number of purposes, such policy formulations are probably appropriate in this case.

Separating the Sectors

A third possibility is to examine the specific human activities which lead to the emissions of greenhouse gases. The appeal of this approach is that this is the level where policies must be implemented. Even policies which focus on chemical concentrations must alter some aspect of human behavior in order to be effective. Among the primary activities which are of interest in the climate change problem are energy use — divided into the sectors of electric power, transportation, industry, and buildings — agriculture, and deforestation. The limitation to such a strategy, of course, is that even if successful policies can be found to appropriately manage one activity, other activities may be ignored or even unfavorably altered by the original action.

Separating the Regions

The problem can also be divided spatially. Instead of formulating global policies, for which there are few mechanisms for implementation or enforcement, there is some appeal to concentrating on individual nations or blocks of allied nations — the OECD or Eastern Europe, for example. Another common division of this sort is between the industrialized and non-industrialized countries. Vast differences in economic wealth, infrastructure, political stability, and past contributions to the problem, make the character of the problem very different for the developed and less-developed nations. Again, this type of formulation can ignore entire sections of the problem.

Separating the Time Frames

Finally, mitigation policies can be focussed on a variety of time scales. This can range from time scales on the order of a century (typical of comprehensive studies) to very short term studies which examine what can be done immediately. The latter suffers primarily from its inability to deal with the dynamics and time lags of the involved systems. The former lacks reliability. Any attempts to predict energy futures one hundred years hence should be viewed through the filter of past energy predictions. Not a single energy expert in 1970 was able to predict what the world of energy would look like in 1980. The system was poorly understood and subject to unprecedented shocks. There is no reason to believe that it is any less so now, particularly over century-long time frames.

Focus of Present Study

The focus of this study is not comprehensive, but rather is directed at one sector: electric power. The focus is further reduced to regions of the United States and to a transitional time period of twenty-five years. In brief, the rationale for this focus is a desired balance between the advantages and disadvantages of the possible formulations discussed above.

The system of focus is small enough and well enough understood for the modeling and analyses to be highly reflective of systemic realities and, therefore, to have meaningful results. On the other hand, the U.S. electric power sector is important enough (the specific contribution of this sector to the global problem is discussed in Chapter 3) that one can hope for policy actions to have significant impacts on the overall system. The "transitional" time period was chosen as lengthy enough to capture important dynamics and time lags, yet short enough to be within a reasonably predictable time horizon[34].

Again, this is not an attempt to solve the entire problem. The study does hope to show what policies might be advisable for altering a specific aspect of human behavior. It is hoped that the study can also serve as a model for pursuing answers to the same questions within other sectors of activity.

Similar Studies

Many studies of the energy / CO_2 issue have been conducted. A brief discussion of these studies will contrast and compare this earlier work with the present study. Of particular interest are the differences in the conclusions of several studies which cast doubt on the structural reliability of models used, as well as the similarities in assumptions across several studies which may lead to unwarranted consensus between them[35].

Models of energy / CO_2 interactions can be characterized along several dimensions. First, the models differ in scope — some examine the whole problem, while others examine isolated portions. Second, the

[34] The term "transition" has often been used to describe a time period in which the present energy system changes to a new steady-state ideal - Energy in Transition, 1985 to 2010 (CONAES, 1979); Rays of Hope: The Transition to a Post-Petroleum World (Hayes, 1977); Energy Transitions: Long-Term Perspectives (Perelman, et.al., 1981); Coal: Bridge to the Future (Wilson, 1980). While this study does focus on a similar time period, there is no expectation of a steady-state end-point, but merely a recognition that the dynamics of the system beyond this period are difficult to forecast or even discuss meaningfully.

[35] There are several detailed discussions of many of these studies to which the interested reader is referred: Keepin, 1986; Rotty and Masters, 1984; Ausubel and Nordhaus, 1983; Goldemberg, et.al, 1985; Perry, 1982; Hamm, 1986.

models differ in the level of detail with which energy / CO_2 interactions are represented. Third, interactions between the energy system and the economic system are handled differently. Fourth, the models differ in their level of aggregation of both geographic regions and separate sectors of the energy system. Fifth, the models differ substantially in their handling of both parametric and structural uncertainty.

The primary difference between previous studies and this one is one of scope. This study is for a relatively short period of time, 25 years, and for a single activity in limited geographic regions. Most other studies have been global, long-term (50-200 years) studies. It should be noted that this study is not completely exceptional in scope, however. Similar types of studies have been done in Sweden[36] and West Germany[37], for instance. These studies are complementary to this one since, in order for impact on the global situation to be maximized, the potential of various strategies must be evaluated in a variety of sectors and regions.

Ausubel and Nordhaus[38] outline three categories of models, based on the level of interaction considered between energy and CO_2. The first category consists of those which project historical CO_2 trends into the future, with no analysis of root causes, such as energy use. Included among these are projections based on CO_2 measurements at Mauna Loa[39]. The second category consists of those which are focussed primarily on the energy system, and to which CO_2 emissions are essentially a dependent output stream. Many prominent studies fall into this category[40]. The final

36 Bodlund, et.al., 1989.
37 Krause, F., 1982.
38 Ausubel and Nordhaus, 1983.
39 Oeschger and Siegenthaler, 1988.
40 IIASA, 1981, 1983; Lovins, 1982; Rotty and Marland, 1981.

category consists of those models in which CO_2 concentrations or emissions provide some feedback or constraint to the energy system. Primary studies included in this category are the studies of Edmonds & Reilly and Nordhaus & Yohe[41]. Many other studies have used one of these two as a modeling basis[42]. Because strategies for limiting emissions are considered, this study is in this category. This last category also includes studies which link energy / CO_2 models with CO_2 / climate (and often climate / economy) models, attempting to project climatic or economic impacts of energy use[43]. Such links would not be meaningful on a regional basis, and are not accounted for in this study.

Another distinction concerns the interactions between the energy system and the economic system. General equilibrium models — those which attempt to bring the supply and demand for energy and energy services into equilibrium with other aspects of the global economy — have not truly been achieved by any of the studies. Most of the models are in fact partial equilibrium models of the energy system. The study here is, in fact, only an approximation of a partial equilibrium model, since the effects of price elasticities are not explicitly examined. The economic aspect of the model in this study consists only of the utilities desire to minimize generation costs, given fuel prices and a certain level of demand. No effort is made to actually predict energy or electricity demand nor is there any feedback from price to demand. This latter drawback, the

[41] Edmonds and Reilly, (et.al.), 1983, 1985a, 1985b, 1986a, 1986b; Nordhaus and Yohe, 1983.

[42] US EPA, 1983, 1989; Araj, 1982; Rose, et.al., 1983; Mintzer, 1987; all use the Edmonds & Reilly model. Hamm, 1986, used the Nordhaus & Yohe model. Because of distinctly different conclusions, these two models have served as foils for one another in several settings (NRC, 1983; MIT, 1990).

[43] Mintzer, 1987; EPA, 1989; Edmonds and Reilly, 1985a; Edmonds, et.al., 1986b.

inability to account for price-driven demand reduction, undoubtedly introduces error into the strategy evaluations[44].

Another distinction is between different levels of aggregation in the models. Some of the models are globally aggregated, recognizing no differences between different geographical regions. The Nordhaus & Yohe model is a primary example. Others are disaggregated into a varying number of regions — nine in the Edmonds & Reilly model, seven in the IIASA model, and four in the Manne & Richels model[45]. This study is concerned with a region at a much smaller level than even the Edmonds & Reilly model, but does not attempt to explicitly account for interactions with the global system as a whole[46]. Different levels of aggregation in the energy system are also considered. Most of the models mentioned here examine the energy system as a whole. This study focuses only on the electric power sector.

The final distinguishing characteristic of the studies, and probably the most important, is the handling of uncertainty. This uncertainty can be of two forms: parametric or structural[47]. Parametric uncertainty refers to the inability to predict precise values for numbers used in the models. Examples of such numbers might be fuel prices, population growth, price elasticities, and so on. Structural uncertainty refers to questions about the validity of the model itself. Models are, by definition, simplifications of

[44] For instance, in this model, a carbon tax has the effect of causing the utility to reduce carbon emissions while generating a given level of demand. Costs of electricity generation are subsequently higher than they would have otherwise been. In reality, such a price increase should cause some reduction in demand (with further effects on costs and emissions), but this feedback is not accounted for explicitly in this study.

[45] Manne, 1990a; Manne and Richels, 1990b, 1990c.

[46] Even the US regions studied here are somewhat aggregated, however, since scale approximations of the systems have been used. See Chapter 4.

[47] Keepin, 1986.

reality. The extent to which a model distorts reality through these simplifications is generally unquantifiable and uncertain.

Parametric uncertainty is addressed through a variety of methods. Many studies, including this one, develop a set of scenarios based on best guesses of ranges in uncertain parameters, and then examine how model results change across these scenarios. Sensitivity analysis examines the changes in final output which result from incremental changes in uncertain parameters. Those parameters which cause the widest changes in outputs are the most "sensitive", and are, therefore, most important for ensuring accurate results.

A second (and not mutually exclusive) approach, adapted by Nordhaus and Yohe, uses a probabilistic method. Many scenarios are run based on wide ranges in parametric uncertainties. A small number of these scenarios are then chosen at random for analysis. Percentile ranges for model outputs (i.e., CO_2 emissions) are then calculated based on the random sample[48].

Structural uncertainty is much more problematic. For instance, Keepin points out that the sensitivity analyses of the two most ubiquitous models — Edmonds & Reilly and Nordhaus & Yohe — yield vastly different results[49]. Sensitivity analysis of the Nordhaus & Yohe model revealed that the "substitution parameter", a number indicating the ease with which nonfossil fuels can substitute for fossil fuels, was the single most important parameter in the determination of carbon emissions. In Edmonds & Reilly, however, carbon emissions were very robust (insensitive) to the equivalent parameter. The second and third most

48 The greatest difficulty with this method is the hidden assumption that all scenarios are equally likely.
49 Keepin, 1986.

important parameters in Edmonds & Reilly — exogenous energy efficiency and income elasticity of demand in developing countries — are not even included in the Nordhaus & Yohe model. Clearly, there is structural uncertainty in one or both of the models[50]. Which is a more accurate approximation of reality? Since both make sweeping assumptions about the energy system itself (not about parameters), it is unclear if either of these models is producing meaningful results. Whether skepticism of these models is justified is a moot point. Such discrepancies automatically foster skepticism which creates barriers to the discussion and formulation of policy. The choice of models in this study was based fundamentally on the assertion that structural uncertainty must be minimized if models are to have credibility with those who understand the structural realities of the system.

[50] There is even wide discrepancy among the conclusions of studies which all use the Edmonds & Reilly model.

Chapter Three - The Realities of Carbon Dioxide

A Theoretical Framework

This chapter provides a theoretical framework for the selection, examination, and evaluation of possible approaches to the CO_2 / electric power issue. The starting point of this discussion will be the traditional conception of the more general CO_2 / energy issue - "the pollution equation." It will be shown that the pollution equation does not indicate the hopelessness of the problem, as is usually concluded, but rather a variety of conceivable policy levers for significant reductions in carbon dioxide emissions. The importance of various regions and sectors of human activity will be examined quantitatively, highlighting the importance of the US electric power sector to the global problem. Finally, the realities of the electric power sector and its carbon emissions will be examined in detail, highlighting the role of such factors as system operating rules and choice of technology, as well as the policy levers which they provide.

Traditional Formulation - The "Pollution Equation"

Erlich and Holdren[51] first suggested the links between pollution, population, economic growth, and technology by combining such factors in a simple identity formula as follows:

$$\text{Pollution} = \left(\frac{\text{Pollution}}{\text{Activity}}\right)\left(\frac{\text{Activity}}{\text{GNP}}\right)\left(\frac{\text{GNP}}{\text{Population}}\right)(\text{Population})$$

[51] Erlich and Holdren, 1971.

The (Pollution / Activity) term is a measure of the polluting nature of the activity itself, largely a function of the technologies used by the activity. The (Activity / GNP) term is the "intensity" of the activity, or the amount of the activity used to generate one dollar of GNP[52]. The (GNP / Population) term is a measure of the average standard of living of a society. The equation has gained wide acceptance, yet while the equation can indeed provide insight into the pollution problem, particularly if examined at a deeper and more disaggregate level, the conclusions which are drawn from the equation are often misleading. A common use of this equation is to illustrate the factors which contribute to carbon emissions[53] from energy use:

$$\text{Carbon} = \left(\frac{\text{Carbon}}{\text{Energy}}\right)\left(\frac{\text{Energy}}{\text{GNP}}\right)\left(\frac{\text{GNP}}{\text{Population}}\right)(\text{Population})$$

or, for brevity's sake:

$$C = \left(\frac{C}{E}\right)\left(\frac{E}{\$}\right)\left(\frac{\$}{P}\right)(P)$$ [54]

where C= Carbon emissions,

E = Energy use,

\$ = Dollars of GNP,

and P = Population.

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52 Gross National Product. Gross Domestic Product, or any other measure of the level of economic activity within a society would be acceptable.

53 The term "carbon emissions" will be used interchangeably for "carbon dioxide emissions." In general, the two are proportional since most of the carbon released from energy use is released as carbon dioxide.

54 Notation of Wei, et.al., 1990.

Although the usage varies, the "energy" in the above equation will be considered final-use energy, in order to maintain consistency with the original pollution equation, which addresses human activities. Let us look at the equation for our specific interest, carbon emissions from electric power:

$$\text{Carbon} = \left(\frac{\text{C}}{\text{GWH}}\right)\left(\frac{\text{GWH}}{\text{GNP}}\right)\left(\frac{\text{GNP}}{\text{Population}}\right)(\text{Population})$$

where C/GWH is marginal carbon emissions (MCE)[55],

and GWH/GNP is electricity intensity.

Similar equations might be written for other sectors — transportation, for example:

$$\text{Carbon} = \left(\frac{\text{C}}{\text{Vehicle-mile}}\right)\left(\frac{\text{Vehicle-Mile}}{\text{GNP}}\right)\left(\frac{\text{GNP}}{\text{Population}}\right)(\text{Population})^{56}$$

A recent MIT conference[57] saw permutations of the pollution equation in the presentations of no less than five speakers. The formula

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[55] As with "marginal costs" (i.e., $ / GWH) in an electric power system, this value is marginal to the system and not necessarily to the technology with which the cost is associated. The marginal costs or emissions are the <u>average</u> cost or emissions per GWH of the technology which is loaded at the margin of the system.

[56] The final energy - primary energy confusion can be alleviated by the explicit addition of a conversion efficiency term. This would make the electric power equation

$$\text{Carbon} = \left(\frac{\text{C}}{\text{Fuel Unit}}\right)\left(\frac{\text{Fuel Unit}}{\text{GWH}}\right)\left(\frac{\text{GWH}}{\text{GNP}}\right)\left(\frac{\text{GNP}}{\text{Population}}\right)(\text{Population})$$

and the transportation equation

$$\text{Carbon} = \left(\frac{\text{C}}{\text{Gal. Oil}}\right)\left(\frac{\text{Gal. Oil}}{\text{Vehicle-mile}}\right)\left(\frac{\text{Vehicle-Mile}}{\text{GNP}}\right)\left(\frac{\text{GNP}}{\text{Population}}\right)(\text{Population})$$

[57] Energy and the Environment in the 21st Century, Cambridge, MA, March 26-28, 1990.

was used to point out the futility of efforts to limit carbon emissions due to population predictions and economic growth targets[58] and the possibility of the need to limit population or economic growth[59]. It is often used to highlight the importance of energy efficiency or the "immorality" of high energy intensities in countries such as the United States. A set of brief notes about the global warming issue released by a group of researchers at MIT points to the difficulty of reducing all of the factors[60]. It is suggested here that a great deal of subtlety about the carbon emissions problem is masked by these formulations, or at least by these interpretations.

Among the often overlooked subtleties are the following:

1) The terms of the equation are highly complex, non-linear functions of many other factors, some of which lead to interrelations and feedbacks between the terms.

2) The equation applies only to the emissions generated in a period of time small enough to assume fixed levels of energy use, GNP, and population during that period (i.e., a year). Rates of change are often ignored.

3) Since technology choice, energy use, economic activity, and population vary across regions, the equation only applies to one particular region, with a global assessment requiring a summation of such terms. There is a dominance

58 Yoichi Kaya, University of Tokyo.
59 John Gibbons, Office of Technology Assessment.
60 Wei, et.al., 1990.

by some of the terms (i.e., those representing industrialized nations) which can shift over time.

4) Since emissions vary across technologies and fuels, the term for any particular region will also be a summation across technology/fuel combinations. There may be dominances here, as well, due to variations in carbon content of fuels, technological effects on carbon emissions, efficiencies, relative presence of different technologies, relative utilization of different technologies, and the characteristics of, in our case, the power system itself. Changes in these factors can be due to altered use of existing technologies (altered dispatch rules, fuel switching, etc.) or through changes in the technology stock itself.

5) Only the first term, marginal carbon emissions, can go to zero[61]. If this term is zero, the values of the other terms will have no effect on emissions levels. Not only can this term theoretically go to zero, but it does so with the use of many non-fossil fuel sources (i.e., hydroelectric, nuclear, solar, wind, geothermal, biomass, etc.). While technology/fuel switches may be undesirable economically, politically, or for other environmental reasons, this factor is the only term which has no theoretical limit in the long run. This comment is most relevant with reference to improvement in energy intensity,

[61] Assuming, of course, that populations or GNPs of zero would place concerns about carbon emissions very low on a societal priority list and that a non-electric society is an unlikely development.

which may be the most cost-effective method for receiving short term emissions reductions, but has limits to the amount of improvement which can be achieved[62].

These observations indicate three possible methods for revealing policy levers for the reduction of carbon emissions:

1) Cross-regional order-of-magnitude approximations of terms can identify those regions in which emissions reduction will be the most effective, and those regions in which reduction would be meaningless in global terms. For example, such an analysis below leads to the conclusion that a worldwide 20% reduction in carbon emissions could be achieved by a slightly larger reduction in a few regions, even with an allowance for increased emissions in other less dominant regions.

2) Analysis of rates of change in terms, again in a cross-regional comparison, could help identify the times at which the dominances found above might shift. Such comparisons can also help quantify the rates at which technological substitution and efficiency improvements must occur in order to simultaneously satisfy environmental, economic growth, and population growth constraints.

[62] This is much like weight loss - no matter how much excess weight one has, some finite amount is necessary and cannot disappear. This should not be interpreted to dilute the possibility that the limit to conservation, while certainly above zero, may indeed be sufficiently below present levels to allow for environmentally acceptable reduction in carbon emissions.

3) Most important for this study, detailed analysis of those factors which contribute to the marginal carbon emissions and energy intensity terms can help with the formulation and evaluation of various technology or policy strategies.

Dominant Effects

We must first recognize that the pollution equation, as originally stated, applies only to one particular region, where a region is defined as any geographical area for which we can assume a single value for population, GNP[63], or any other value of interest in the equation. Therefore, to determine global emissions of carbon, we must look at a summation of terms:

$$C_{tot} = \sum_{j=1}^{M} C_j$$

where M is the total number of regions,

and C_j is the total carbon emissions from region j.

Similarly, the original pollution equation assumes a fixed value for marginal carbon emissions. Since carbon emissions vary according to technology and fuel use, and the characteristics of similar technologies may also vary across regions (i.e., newer coal plants in the industrialized world

[63] Gross "National" Product may be used in this definition to refer to the level of economic activity within a region which is actually subnational (i.e., the Northeast United States) or supranational (i.e., Western Europe).

may be more efficient than older coal plants elsewhere), an additional summation across technology / fuel combinations is also necessary to fully account for these differences. This can be stated:

$$C_{tot} = \sum_{j=1}^{M} \sum_{i=1}^{N} C_{ij}$$

where M = Total number of regions,

N = Total number of technology/fuel combinations in region j,

and C_{ij} = Carbon emissions in region j from technology i.

If we make an assumption (for the purposes of an order-of-magnitude) that fuels are similar in carbon content globally (i.e., coal used in the US contains the same weight of carbon per BTU of energy as coal used in the USSR), we can restate the equation as follows:

$$C_{tot} = \sum_{i=1}^{N} \left(\frac{C}{E}\right)_i \sum_{j=1}^{M} E_{ij}$$

where $(C/E)_i$ is the carbon per unit energy of fuel i,

and E_{ij} is the energy usage of fuel i in region j.

Note that we have also aggregated the original pollution equation, collapsing the GNP and population terms within the energy term. Since we have data of regional fuel use, this is more convenient for this calculation. We are not particularly interested at this stage in examining the factors which contribute to energy use (clearly GNP and population are among them). This also illustrates that the original pollution equation is actually at a rather arbitrary level of aggregation. The equation can be expanded or collapsed depending on the purpose at hand.

Returning to our calculation, we can use values for the global average carbon content of particular fuels — coal, oil and gas — given by Marland[64] and data on regional energy use by fuel type from the BP Statistical Review of Energy[65] we can estimate 1987 carbon emissions as shown in Table 3-1.

An aggregated regional distribution of these carbon emissions is shown in Figure 3-1. Of note here is that the US alone accounts for nearly a quarter of the global carbon emissions from fossil fuel combustion. The OECD countries together account for nearly one half, and the top three regions — the US, the USSR, and western OECD countries — account for 60% of the total. This implies that a global reduction of 20% could be obtained through a 33% cut in the largest three contributing regions or by a 40% cut in the OECD alone, assuming no changes elsewhere. If contributions were to double in the developing countries[66], global emissions could still be cut by 20% with a reduction of 40% in the industrialized countries[67]. This should not be interpreted as advocacy of any particular reduction targets, regionally or globally, but only as a demonstration that significant dominance of the carbon emissions problem is held by a few countries and regions[68]. Reductions, or the lack of such

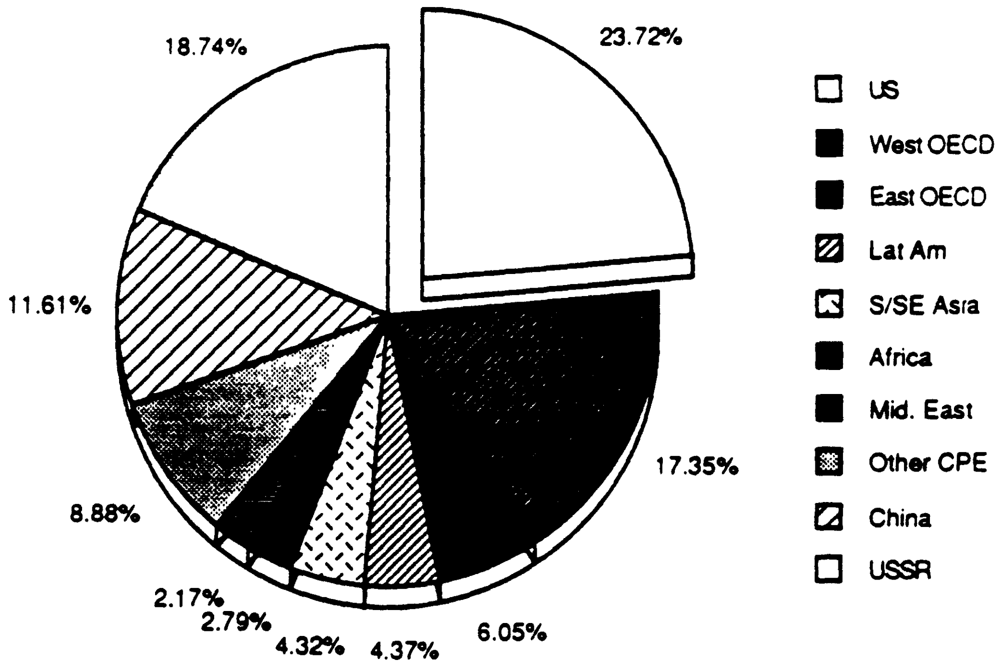
64 Marland, 1982. These are the numbers used by the Edmonds and Reilly model (i.e.,Edmonds and Reilly, 1985a).
65 British Petroleum, 1988.
66 Latin America, South and Southeast Asia, Africa, Middle East, and China.
67 United States, OECD, USSR, and other Centrally Planned Economies.
68 Similar calculations by others suggest an even larger disparity than indicated here (Edmonds and Reilly, 1985a; MacKenzie, 1988). This indicates the possibility of even greater impacts associated with emissions reduction impacts in the larger regions.

Table 3-1 Fossil Fuel Use and Carbon Emissions by Region

Region	Oil (mtoe)	Gas (mtoe)	Coal (mtoe)	Carbon (Tg)
United States	763.4	431.9	452.9	1323
Canada	69.4	41.2	33.4	114
Western Europe	585.2	206.7	259.0	854
Australasia	32.8	18.1	41.8	79
Japan	208.1	36.4	68.5	258
Latin America	220.6	73.4	22.7	244
Middle East	109.6	51.3	2.3	121
Africa	84.4	31.2	69.1	156
South Asia	61.0	17.6	124.2	184
Southeast Asia	125.0	15.9	45.8	156
China	103.9	12.8	553.4	647
USSR	449.2	520.2	378.9	1045
Other Cent. Planned	125.9	99.1	334.3	495
Total	**2938.5**	**1555.8**	**2386.3**	**5677**

Source: British Petroleum, 1988.

Worldwide Carbon Emissions by Region



Source: British Petroleum, 1988.

Figure 3-1

reductions, in these regions drive the level of global emissions and will continue to do so in the near future.

Rates of Change

To gain some perspective on how this situation can change over time, particularly as a function of economic growth, we will again return to the original carbon / energy equation and aggregate as follows:

$$C = \left(\frac{C}{\$}\right)(\$)$$

where $\$ = GNP$,

and $C/\$$ is carbon intensity.

The time rate of change in emissions, is then:

$$\frac{dC}{dt} = \frac{d}{dt}\left[\left(\frac{C}{\$}\right) * (\$)\right] = \left(\frac{C}{\$}\right) * \frac{d}{dt}(\$) + (\$) * \frac{d}{dt}\left(\frac{C}{\$}\right)$$

For emissions to decrease, dC/dt must be less than zero. If we assume positive economic growth ($d/dt\,(\$) > 0$):

$$-\left[(\$) * \frac{d}{dt}\left(\frac{C}{\$}\right)\right] > \left[\left(\frac{C}{\$}\right) * \frac{d}{dt}(\$)\right]$$

$$-\left[\frac{\frac{d}{dt}(C/\$)}{(C/\$)}\right] > \left[\frac{\frac{d}{dt}(\$)}{(\$)}\right]$$

$$-(C/\$)' \quad > \quad (\$)'$$

where, x' indicates the rate of change of variable x relative to its total value (these rates are approximately equivalent to percentage rates of change when the values are small)[69]. Economic growth, for instance, is then represented by:

$$(\$) = (\$)_0\, e^{(\$)'t}$$

where $(\$)_0$ is the GNP at time zero.

This implies that percentage improvements (that is, decreases) in carbon intensity must outweigh percentage rates of economic growth. This may be disaggregated again to show that the negative sum of percentage changes in marginal carbon emissions (C/E) and energy intensity (E/$) must be greater than percentage increases in standard of living and population in order for carbon emissions to decrease, as follows:

$$-[\,(C/E)' + (E/\$)'\,] \quad > \quad (\$/P)' + P'$$

This is perhaps intuitively obvious, merely stating that for global carbon emissions to decline, in conjunction with growth in population and standard of living, improvements in marginal carbon emissions and energy intensity must be faster. As with the static case of before, it is useful to account for regional differences in order to identify where and when

[69] Notation again from Wei, et.al., 1990.

changes must occur, particularly given likely population and economic growth rates. If we look at the same equation and account for summations across regions:

$$\frac{dC}{dt} = \frac{d}{dt}\sum_{i=1}^{N} [(\frac{C}{\$})_i * (\$)_i]$$

where $(C/\$)_i$ and $(\$)_i$ are the carbon intensity and GNP of region i,

and N is the number of regions.

$$\frac{dC}{dt} = \sum_{i=1}^{N} [(\frac{C}{\$})_i * \frac{d}{dt}(\$)_i + (\$)_i * \frac{d}{dt}(\frac{C}{\$})_i]$$

$$= \sum_{i=1}^{N} [(\frac{C}{\$})_i * \frac{d}{dt}(\$)_i] + \sum_{i=1}^{N} [(\$)_i * \frac{d}{dt}(\frac{C}{\$})_i]$$

Again, to decrease emissions, $dC/dt < 0$, which implies:

$$-\sum_{i=1}^{N} [(\$)_i * \frac{d}{dt}(\frac{C}{\$})_i] > \sum_{i=1}^{N} [(\frac{C}{\$})_i * \frac{d}{dt}(\$)_i]$$

$$-\sum_{i=1}^{N} [(\$)_i * [\frac{(\$)_i}{(\$)_i}] \frac{d}{dt}(\frac{C}{\$})_i] > \sum_{i=1}^{N} [(\frac{C}{\$})_i * [\frac{(C/\$)_i}{(C/\$)_i}] \frac{d}{dt}(\$)_i]$$

$$-\sum_{i=1}^{N} [(C)_i * (C/\$)'_i] > \sum_{i=1}^{N} [(C)_i * (\$)'_i]$$

$$- \sum_{i=1}^{N} \left[\left(\frac{C_i}{C_{tot}}\right) * (C/\$)'_i \right] \quad > \quad \sum_{i=1}^{N} \left[\left(\frac{C_i}{C_{tot}}\right) * (\$)'_i \right]$$

This final equation states that the summation of percentage improvements in carbon intensity from all regions, weighted by the relative levels of carbon emissions from those regions, must outweigh the summation of economic growth rates, again weighted by carbon emissions. As before, this implies that some dominance is present. Improvements in carbon intensity in large carbon emitters will have the largest positive effect. Economic growth in these countries would have the largest negative impact. Contributions by less dominant regions might have little impact.

If we accept certain economic growth rates to be inevitable or desirable, what rates of improvement in carbon intensity would be required to reduce emissions, and where? Using predictions of economic growth from Edmonds and Reilly[70], we see that an overall rate of improvement in carbon intensity of 2.4% would be necessary to reduce carbon emissions in conjunction with growth. If improvements were made in the US alone, 8% yearly improvement would be sufficient to cause a decrease in global emissions. If this were expanded to the countries of the OECD, 4.1% annual improvements would be required. Examining the largest three contributing regions (US, Western OECD, and the USSR), a 3.2% rate of improvement would be sufficient. These numbers assume no improvements or losses in carbon intensity rates elsewhere.

Presumably, this dominance will shift from the industrialized world to the developing world. Obviously, the timing of this shift depends

[70] Edmonds and Reilly, 1985a. Approximately 2% for industrialized regions, 3.8% for developing regions.

greatly on the rates of change in the factors of interest. If percentage rates of change in all factors are assumed to be constant (admittedly not possible or desirable over the long term for either positive or negative growth rates), then the carbon emissions over time are exponentially growing (or decreasing) according to:

$$C = C_o e^{C't}$$

Disaggregating into two regions, "North" (consisting of the industrialized regions defined earlier) and "South" (all remaining regions):

$$C = C_s + C_n = (C_{so} + C_{no}) e^{(Cs' + Cn')t}$$

The time at which the contribution from each region is equal ($C_s = C_n$) is found by:

$$T = \frac{\ln (C_{no} / C_{so})}{C_s' - C_n'}$$

Using the same economic growth rates as before, if carbon intensity improvement rates remain at today's values, the contribution from the two regions will not be equal for 72 years. With moderate improvements in carbon intensity in the North of 3% per year, the shift in dominance would occur in 32 years. Rapid improvements of 8% per year in the North would move this forward to 15 years. The implications of these numbers are that even if substantial improvements are made consistently in the industrialized countries, there will be some significant time lag before the developing countries will become equivalent contributors to total carbon emissions, even given growth in standard of living and population. The difficulty of gaining the participation of developing countries in emissions reduction programs, particularly programs in which the industrialized countries have not yet participated, is often cited as a barrier to climate change mitigation policies. The realities of the situation, however, seem to indicate that not only can policy measures in large contributing countries have large impact, but the delay associated with the shift in dominance to the developing countries is large - possibly large enough to allow for demonstration of the effectiveness and economics of emissions reduction in the industrialized world and for the transfer of technology and capital to the developing world.

Potential for Supply Technology

As mentioned previously, there are numerous factors which contribute to the marginal carbon emissions term. Since this term may be the key lever for manipulation of carbon emissions from electric power, examination of these factors may provide some illumination of the problem and its potential solutions.

Let us further disaggregate this term, examining the carbon emitted over any particular time period, T, in a particular electric power system. The marginal carbon emissions of the system are a weighted sum of the marginal emissions from each individual technology type[71]:

[71] Units are classed within a single technology types if all characteristics of the units are identical, including fuel type used. At the finest grain level, this summation could be across single generating units in order to fully account for differences.

$$MCE_{sys} = \sum_{i=1}^{N} \left(\frac{C}{GWH_i}\right)\left(\frac{GWH_i}{GWH_{sys}}\right)$$

$$= \sum_{i=1}^{N} (MCE_i)\left(\frac{GWH_i}{GWH_{sys}}\right)$$

where N = Total number of technologies in the system,

GWH_i = Total GWH produced by a technology i,

and GWH_{sys} = Total GWH produced by the system,

subject to $\sum GWH_i = GWH_{sys}$.

The importance of the weighting term (GWH_i / GWH_{sys}), which represents the fraction of the total system energy which is derived from any particular technology, is evident. If the level of utilization of a technology is low, a low MCE_i term will not have much effect on overall system emissions. This weighting term will be revisited later.

For many renewable technologies, such as solar or hydro, the marginal carbon emissions are zero. For those technologies which utilize an input fuel, marginal carbon emissions can be expressed:

$$MCE_i = \left(\frac{C}{MMBTU}\right)\left(\frac{MMBTU}{GWH_i}\right)$$

where MMBTU = the amount of energy in the fuel[72],

and MMBTU/GWH_i = the heat rate of the technology, HR_i.

[72] This is an industry standard unit which can be confusing. An MMBTU is a 10^6 BTUs, not 10^9.

Since carbon emissions are almost completely derived from carbon contained within the fuel, the Carbon / MMBTU term may be expressed

$$C / MMBTU = \left(\frac{C\ emitted}{C\ in\ fuel}\right) \left(\frac{C\ in\ fuel}{unit\ of\ fuel}\right) \left(\frac{unit\ of\ fuel}{MMBTU}\right)$$ [73]

where unit of fuel could be tons of coal, barrels of oil, etc.

and unit of fuel / MMBTU is the inverse of the heating value, HV.

The carbon throughput (C emitted / C in fuel) is only less than one if there is incomplete combustion or if carbon is scrubbed from flue gases[74]. Carbon / MMBTU is directly related to carbon - hydrogen ratios within fuels. Of the fossil fuels, coal has the highest Carbon / MMBTU ratio (approximately 0.03 tons C / MMBTU), followed by oil (.022) and natural gas (.017)[75]. Nuclear technologies utilize a fuel, but release no carbon.

Therefore, for technologies with input fuels:

$$MCE_i = \left(\frac{C\ emitted}{C\ in\ fuel}\right)_i \left(\frac{C\ in\ fuel}{Unit\ of\ fuel}\right)_i \left(\frac{1}{HV_i}\right) (HR_i)$$

[73] Note that the disaggregation of the (Pollutant / MMBTU) term is undesirable when dealing with pollutants which depend on technological conditions and not necessarily contents of the fuel. NO_x emissions, which depend on boiler temperatures and pressures, are one example.

[74] For other pollutants, the (Pollutant emitted / Pollutant in fuel) term can be significan''y less than one. For example, retrofitting of coal plants with scrubbers to remove sulfur dioxide emissions is an effort to lower this term to 0.3, 0.1, or below.

[75] These numbers are often expressed in grams per megajoule (g/MJ), or equivalently, Tg/EJ. The numbers given correspond to 25.8 g/MJ for coal, 18.9 g/MJ for oil, and 14.6 g/MJ for gas. These numbers are calculated directly from EPRI data for typical fuels, and are intended to be compatible with assumptions made in the EPRI technology data which was used in the modeling portion of this study. The values are generally larger than those given by Marland and used by Edmonds and Reilly (23.8, 19.2, and 13.7 g/MJ for coal, oil, and gas, respectively) and smaller than those given by Wei, et.al. (27.6, 22.7, and 15.8, respectively). Note that the sizes of these numbers relative to one another is essentially the same in all three sets, with the exception of oil in the EPRI-derived set, which is lower relative to coal than in the other two.

To gain some perspective on this outcome, let us examine the marginal carbon emissions for various fossil fuel-based generation alternatives in the United States, both existing and suggested. These are summarized in Figure 3-2.

Ranges given for particular technologies are reflective of the differing emissions characteristics associated with differences in age and size of power plants within any particular class of technology. Since the fuel used by any particular class of technology is the same, varying marginal carbon emissions are due to differences in efficiency. In general, older and smaller plants are the least efficient. Of note in Figure 3-2, is that within the existing systems, large emissions reductions could be obtained if all plants were as efficient as the most efficient existing plant of that class. For instance, the difference between the least efficient existing coal plant in the region (391 tons C / GWH) and the most efficient (265 tons / GWH) represents a 32% reduction. The second point of interest, is that while oil and gas technologies are generally lower in marginal carbon emissions than coal technologies, this is not necessarily the case. Third, combined cycle technologies, due to high efficiencies, have the lowest marginal carbon emissions within each fuel class. Finally, the existing fossil fuel technology with the lowest marginal carbon emissions, natural gas-fired gas turbine / combined-cycle[76] (139 tons C / GWH), is lower than typical existing coal plants (≈ 330 tons C / GWH) by over 55%.

It has already been stated that the pollution equation does not apply solely to carbon emissions. Just as we have done for marginal carbon emissions, we can compare the marginal emissions of any other pollutant

[76] Fuel cells are even lower, but are not yet commercially viable.

Marginal Carbon Emissions of Fossil Fuel Technologies

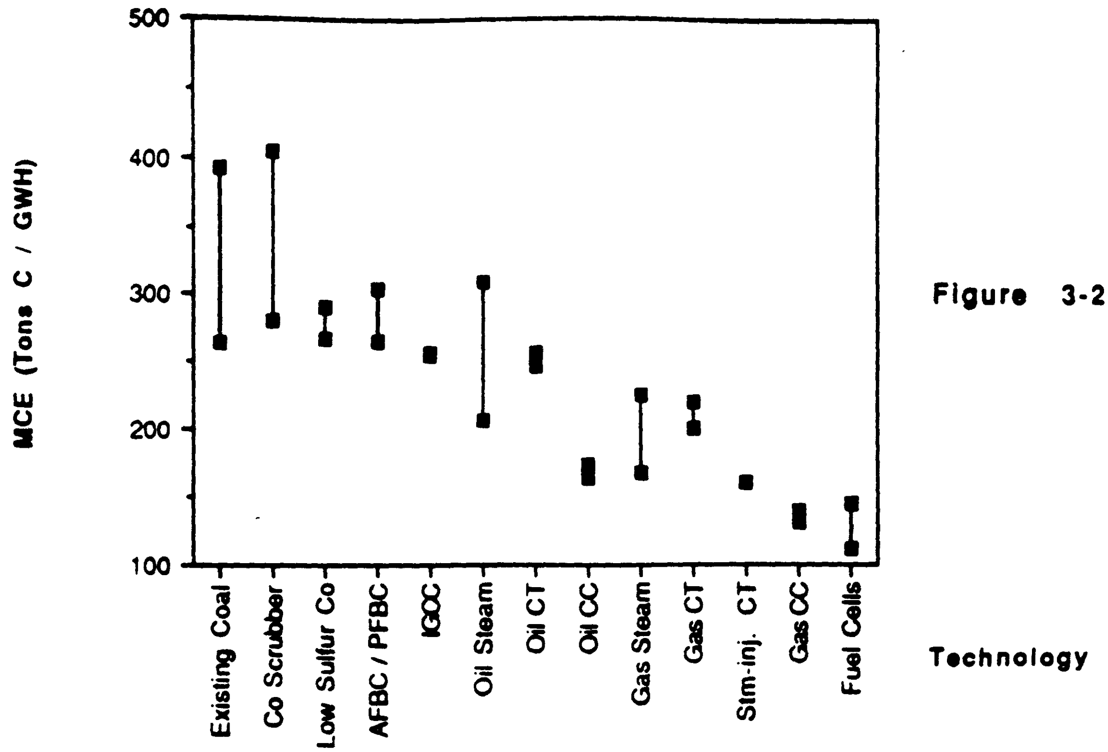


Figure 3-2

Marginal SO2 Emissions of Fossil Fuel Technologies

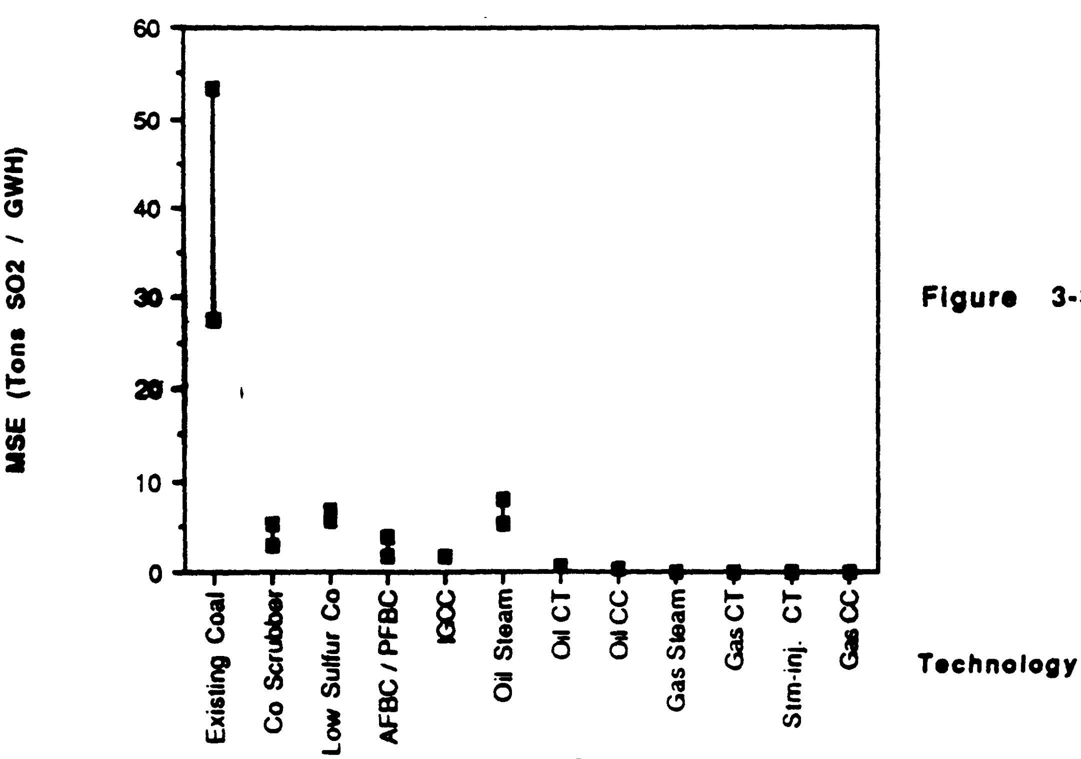


Figure 3-3

for various technologies. This is particularly interesting for sulfur dioxide, perhaps the most well-known of the pollutants emitted from electric power. The marginal sulfur dioxide emissions (MSE), tons SO_2 / GWH, of the same fossil fuel technologies, are shown in Figure 3-3.

The large marginal SO_2 emissions of the existing uncontrolled coal capacity, relative to other technologies, suggest that these technologies represent a dominant contributor to the total emissions of this pollutant from the electric power sector. We will see later (Chapter 5) that this is indeed the case. Note also, that while a general decline in marginal SO_2 emissions can be observed as one moves from coal to oil to gas technologies, larger carbon emitting technologies are not necessarily also larger SO_2 emitting technologies. This complicates the process of technology choice.

Let us now revisit the (GWH_i / GWH_{sys}) term, which provides the weighting values for the emissions from specific technologies. It should be reiterated here that this term is very important. Installation of technologies with low marginal carbon emissions will not result in lower system emissions unless energy generation from higher marginal emission technologies is displaced. The amount of generation from any particular technology is a function of the system (such elements as the capacity mix and dispatch rules), the characteristics of demand on the system, the availability of various technologies, and the marginal costs associated with operating specific technologies (including fuel prices).

Disaggregating:

$$\frac{GWH_i}{GWH_{sys}} = \left(\frac{GWH_i}{GWH_{i\text{-}pot}}\right) \left(\frac{GWH_{i\text{-}pot}}{GWH_{sys\text{-}pot}}\right) \left(\frac{GWH_{s\text{-}pot}}{GWH_{sys}}\right)$$

where GWH_i = GWH generated by technology i,

$GWH_{i\text{-}pot}$ = Potential GWH generated by technology i,

GWH_{sys} = GWH generated by the system,

and $GWH_{s\text{-}pot}$ = Potential GWH generated by the system.

The first term, (GWH_i / $GWH_{i\text{-}pot}$), is the capacity factor of the technology — the amount of energy which was generated from the technology relative to the amount which would have been generated had the unit been running at full load for the entire time period. This term is the most complex of these, depending on many factors. We will leave this term for revisitation.

The second term, ($GWH_{i\text{-}pot}$ / $GWH_{s\text{-}pot}$) is equivalent to the fraction of the system capacity mix which is represented by the technology. This is due to the fact that the time period of concern is constant for the two terms. This is expressed:

$$\frac{GWH_{i\text{-}pot}}{GWH_{s\text{-}pot}} = \frac{GW_i}{GW_{sys}}$$

The third term, ($GWH_{s\text{-}pot}$ / GWH_{sys}), is the inverse of the usage of the system. That is, (GWH_{sys} / $GWH_{s\text{-}pot}$), is essentially the "capacity factor" of the system. This term is independent of the technology-specific terms and can be placed outside the technology summation. The system potential is simply the GW of installed capacity times the number of hours in the time period. The energy generated by the system is the peak demand, in GW, of the system, times the number of hours in the time period, multiplied by the load factor of the system. The time period is constant to both terms and can be removed. We can then say

$$\frac{GWH_{s\text{-}pot}}{GWH_{sys}} = \frac{(GW_{sys}) * T}{[(GW_{pk}) * LF * T]}$$

$$= \frac{(1 + RM)}{LF}$$

where GW_{sys} is the installed capacity of the system,

GW_{pk} is the peak demand of the system,

RM is the reserve margin of the system,

and LF is the load factor of the system.

The (GW_{sys} / GW_{pk}) ratio is equivalent to 1 + RM, where RM is the reserve margin of the system, or the fraction of the system capacity which is in excess of peak demand. The load factor is a measure of the time spent at various levels of demand, relative to the peak demand. In other words, if much of the system operation is spent satisfying near peak demand, the load factor will be close to one. If relatively little time is spent at a peak which is significantly different from minimum demand (base load), the load factor will be smaller.

To illustrate this concept, the load duration curve for the Northeast region of the US is shown in Figure 3-4. The vertical axis is the level of system demand, normalized to one. The horizontal axis represents the probability (or percentage of the total time period) that the demand will exceed a given level. As the curve illustrates, the probability is 100% that the demand will exceed a certain minimum level (the baseload). The

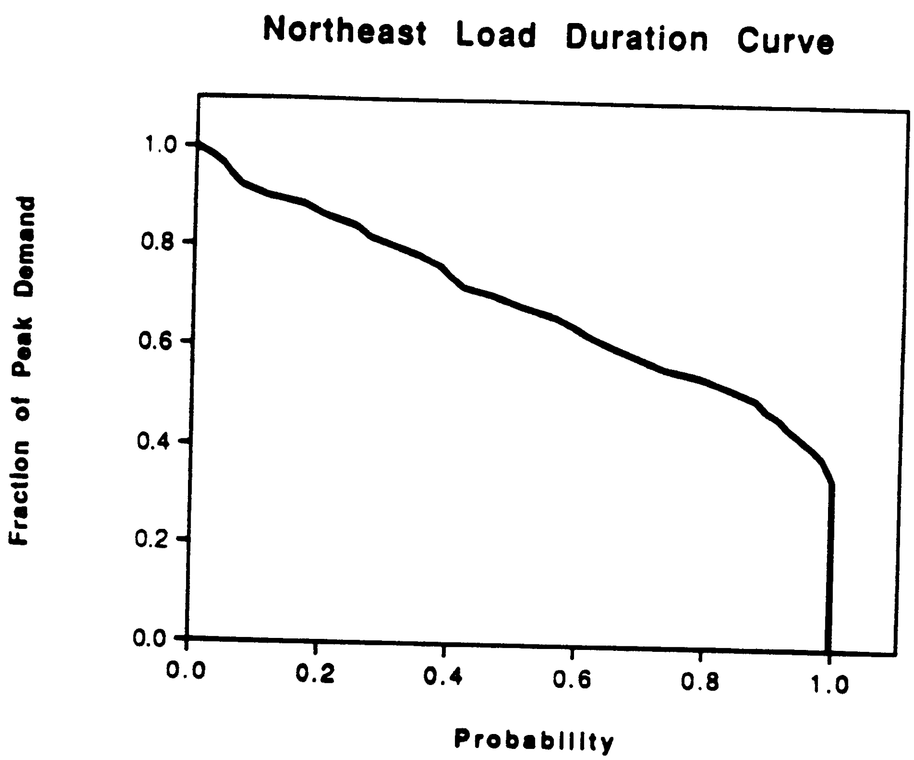

Northeast Load Duration Curve
Fraction of Peak Demand
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Probability

Figure 3-4

probability decreases with increasing demand until the maximum level of system demand, the peak, is reached. There is zero probability of demand exceeding the peak. The area under the normalized load duration curve is the load factor, LF.

Let us now return to the technology capacity factor term, (GWH_i / $GWH_{i\text{-}pot}$). The amount of energy generated from a particular technology, GWH_i, depends on several factors. In electric utility systems similar to those of the US, the system is operated primarily according to economic dispatch rules. That is, those technologies with the lowest marginal costs are dispatched first. As demand grows, more expensive technologies are dispatched until the point where no additional capacity is available or allowing demand to go unserved is less costly.

Those units which operate essentially all of the time that they are available, satisfying the minimum level of demand which always exists within the system, are called baseload capacity. Coal and nuclear plants are among the technologies which are dispatched in this mode, with a capacity factor of 65% being typical. The next level of demand is met by intermediate capacity, such as oil or natural gas-fired plants, with a typical capacity factor of 35%. The final level of demand (except for that which goes unserved) is met by peak capacity, such as oil or natural gas combustion turbines. These units typically have a capacity factor of approximately 10%. The actual value of the capacity factor, however, is fairly complex, being related primarily to the character of the system load (i.e., the load duration curve), the character of the capacity mix of the system, the loading order of the plants in the system (primarily based on marginal cost), and the availability of various technologies (less than 100% due to maintenance and unplanned outages).

Several methods are available for the calculation of the expected energy generation and capacity factor of a unit or technology. One method is chronology modeling. In this method, the system is simulated, with units dispatched, and subjected to outages, exactly as would occur in the actual operation of the system. While this provides accurate results, the method can be prohibitively time-consuming. A second method, used by some utility planning models, is through probabilistic production cost analysis. In depth description of this method is beyond the scope of this discussion. Note, however, that this method is utilized by the Electric Generation Expansion Analysis System (EGEAS), the model used in this study for the analysis of various emissions reduction strategies (See Chapter 4).

A third method, which will be used here, is somewhat less accurate, but allows for some insights into emissions reduction levers[77]. In this method, each unit is derated by its availability. That is, a 400MW unit with an availability of 90% would be treated as if it were a 360MW unit. Units are then simply "stacked" under the original load duration curve in order of marginal cost. The expected energy generation from each unit is then the area under the load duration curve which is met by the unit — an area which can be closely approximated by a trapezoid.

We can then state that the energy generated by technology i, in time period T, is approximated by

$$GWH_i \approx (1/2)\,(T)\,(DGW_i)\,(LDC_{i-1} + LDC_i)$$

[77] While this method is useful for illustrating simply which factors affect unit generation, actual unit generation numbers are too inaccurate for the types of analyses conducted in the primary portion of this study (See Chapter 5). More sophisticated modeling, such as that used in EGEAS, is necessary.

where T = time period in hours (8760 hrs for one year),

DGW_i = derated capacity of technology i = (AV_i) (GW_i),

AV_i = availability of technology i,

and LDC_{i-1} = the LDC at the point where unit i is loaded.

Once we have determined the expected energy generation from the technology, GWH_i, the capacity factor of the technology is then

$$CF_i = \frac{GWH_i}{GWH_{i\text{-pot}}}$$

$$\approx \frac{(1/2)\,(T)\,(DGW_i)\,(LDC_{i-1} + LDC_i)}{(GW_i)\,(T)}$$

$$\approx (1/2)\,(AV_i)\,(LDC_{i-1} + LDC_i)$$

where $LDC_i = LDC(\,\Sigma\,(DGW_i\,/\,DGW_{sys})\,)$,

$0 \leq AVi \leq 1$,

$0 \leq LDC_{i-1} \leq 1$,

and $0 \leq LDC_{i-1} \leq LDC_i$.

We will define a new variable, P_i, to represent an estimate of the probability that technology i will be in use at any particular time, or, equivalently, the fraction of the time period in which technology i is utilized. This value will be calculated as the median value of the portion of the LDC fulfilled by technology i:

$$P_i = (1/2)\,[LDC_{i-1} + LDC_i]$$

The capacity factor is then:

$$CF_i \approx (AV_i)\,(P_i)$$

As mentioned previously, in a typical electric power system, the ordering of technologies is determined primarily by marginal cost. Marginal cost is a function of the variable operating costs, consumables costs, and fuel costs (all in expressed in cost/ unit of energy, i.e. \$/GWH or ¢/KWH). In this way, the operating costs of the system are minimized. This ordering may be expressed as the following constraint:

$$MC_i \leq MC_{i+1}$$

There are some exceptions to this ordering caused by special types of units. The first exceptions are must-run units. If a technology must be run whenever available, regardless of marginal cost (as is the case with cogeneration units for example), the technology is loaded first. That is if N must-run technologies exist in the system, they will be identified as technology 0 through N-1.

The second exception is limited generation units. If an energy limitation causes a unit to be used less than would otherwise be desirable given its marginal cost, it is clear that the unit should be used to its full limitation. In this case the expected energy generation from the technology will be exactly equal to the energy limit. The position of the technology within the loading order is determined by finding that position under the load duration curve where a trapezoid with a width equal to the derated capacity of the energy-limited technology and an area equal to the energy limitation fits exactly. This is approximately equivalent to the following constraint:

$$P_i = \frac{\text{Energy Limit}}{(DGW_i)}$$

In the case of an energy-limited technology where the energy limitation is not binding, the technology is loaded similarly to typical technologies — by marginal cost.

Non-dispatchable technologies (NDTs), units whose energy generation is not controlled by the utility, are a third, and more complex, exception. Solar power is an example of such a technology. The unit generates energy only when the sun is shining — an uncontrollable event. NDT generation can be characterized, however, over a long period of time. In this case, the energy generated from these technologies may be considered to be an alteration of demand. When the technology is generating energy, the demand faced by other technologies is reduced. When taken over the entire time period, this is simply a modification of the load duration curve. Note that in this formulation, demand-side management (any effort to alter the demand seen by the utility supply) can also be considered a non-dispatchable supply technology. This is particularly useful for comparing the environmental effects of conservation, peak-shaving, and other demand-side programs directly with supply alternatives.

The final exceptions are storage technologies. Storage units presently represent only a small portion of electric power system capacity. Their use will become increasingly important, however, as the use of non-dispatchable, non-fossil technologies becomes more important. The ability to have the energy generated from these units when it is most needed would greatly assist NDTs in gaining economic feasibility. When determining the use of storage systems, two factors must be considered — charging and discharging. The charging problem — how much energy will be stored and when — is similar to that of a non-dispatchable technology. Energy will be stored when excess energy is available up to some easily determined limit. Because of this, the charging side of an energy storage technology can also be treated as an alteration to the load duration curve. The discharging aspect of the problem is similar to that of a limited-energy technology. This aspect is then treated in the same manner.

Finally, note that the primary ordering of technologies according to marginal cost is merely a function of the desire to minimize costs. The ordering of the units can be according to any other measurable criterion and all of the above observations will still apply. One example of such a criterion would marginal emissions, where units with the lowest emissions of some pollutant per unit of energy would be dispatched first. This would minimize the emissions from the system, given its capacity mix and demand, but would also raise costs.

Potential for End-Use Technology

Let us now turn our attention temporarily away from the supply side to the demand side — the end use of electricity. We can again return to the original pollution equation, this time examining all of the activities — energy services (such as lighting or refrigeration) — for which electricity is used. Clearly, once again, we have a summation as follows:

$$C = \left(\frac{C}{GWH_{sys}}\right) \sum_{k=1}^{P} \left(\frac{GWH}{ES_k}\right) (ES_k)$$

where C / GWH_{sys} is the MCE_{sys} term we examined previously,

P is the total number of distinct energy services,

GWH/ES_k is the electricity used per unit of energy service k,

and ES_k is the total amount of energy service k.

The individual ES_k terms might signify units of lighting, refrigeration, or space heating, for example. ES_k can be disaggregated into:

$$ES_k = \left(\frac{ES_k}{GNP}\right) \left(\frac{GNP}{Population}\right) (Population)$$

or simply,

$$ES_k = \left(\frac{ES_k}{Population}\right) (Population)$$

This is typical point of departure for many conservation advocates who feel that the economy, or at least people, can "get by" with lower amounts of energy services. This may or may not be true, but has given the word "conservation" the connotation of "heating living spaces below the comfort level"[78] or, more generally, "curtailment imposed by the rich upon the poor"[79]. The argument about how much energy society really

78 Lee, et.al., 1989.
79 Rose, 1983.

needs is the focus of many of the emerging "environmental ethic" arguments outlined in the opening chapter[80]. The validity or invalidity of these arguments aside, we can see that reduction of energy use without reduction in energy service is another theoretical method of conservation (lowering of the GWH / ES_k terms). Indeed, many have pointed out the vast opportunities for progress in this area[81].

The Complete Equation

We can now state the fully disaggregated equation for the carbon emissions due to the use of electric power in a single geographic region:

$$C = \frac{(1+RM)}{(LF)} \sum_{i=1}^{N} \left(\frac{C_{em}}{C_{fl}}\right)_i \left(\frac{C}{MMBTU}\right)_i (HR_i)(AV_i)(P_i)\left(\frac{GW_i}{GW_{sys}}\right) \sum_{k=1}^{P} \left(\frac{GWH}{ES_k}\right)(ES_k)$$

or, equivalently:

$$C = \frac{1}{(GW_{pk})(LF)} \sum_{i=1}^{N} \left(\frac{C_{em}}{C_{fl}}\right)_i \left(\frac{C}{MMBTU}\right)_i (HR_i)(AV_i)(P_i)(GW_i) \sum_{k=1}^{P} \left(\frac{GWH}{ES_k}\right)(ES_k)$$

Implied Policy Levers

Now we can examine each term, outlining the potential policy levers which each provides. Since most policy actions directed at altering one term will have an effect on one or more other terms, these interactions, and their implications for the effectiveness of policy actions will be a

80 McKibben, 1989, for instance.

81 Lovins, et.al., 1982; Goldemberg, et.al., 1987.

primary area of focus. Qualitative judgments will then be made about policy options which appear most attractive and are worth further study.

Carbon Throughput

There is very little opportunity for action to affect this term. For most fossil fuel combustion technologies, this term is essentially equal to unity. There are a few possible exceptions:

Carbon Dioxide Scrubbers

Several policy analysts have suggested the possibility of removing carbon dioxide from flue gases, a concept similar to that represented by sulfur scrubbers presently in use. There are several difficulties. First, the efficiency of the most attractive proposed technology for 100% CO_2 removal — air separation / flue gas recycle — is approximately 25% in comparison to 35% for non-scrubbed plants. The increase in cost of electricity generation associated with the retrofitting of a coal plant with a CO_2 scrubber is approximately 80%. The second problem is with the disposal of CO_2. The primary alternative for CO_2 disposal is deep ocean sequestering. For coastal power plants, the cost of such an operation is estimated to add an additional 20% to the cost of electricity generation. The costs would be substantially higher for inland plants. Additionally, the environmental impact of large scale efforts to sequester CO_2 in the oceans is unknown, although likely to be significant. The development of the technology and an understanding of its impacts are several years away[82].

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[82] Golomb, et.al., 1989.

Clearly, the technology holds some promise, but not as a transitional strategy.

Incomplete Combustion

While incomplete combustion does decrease the percentage of fuel-based carbon which is released, efficiency decreases, requiring the burning of more fuel., completely offsetting the original effect and at higher cost. There is no opportunity for emissions decreases here.

Limestone-Based Sulfur Scrubbers

Other effects on this term can come from the use of limestone-based SO_2 scrubbers. Since CO_2 is released from the limestone ($CaCO_3$) in the scrubbing process[83], the carbon throughput term is actually greater than unity for coal plants with scrubbers. This effect, in combination with the decreased efficiency of plants with FGD systems, leads to an increase in marginal carbon emissions of approximately 10% over coal plants without scrubbers.

Carbon Content

As discussed previously, Carbon/MMBTU is highest in coal, decreasing as one moves from coal to oil and to gas, reaching zero with some non-fossil technologies such as nuclear and hot dry rock geothermal. To take advantage of this fact, the usage of low emission fuels must actually displace the usage of higher emission fuels. This implies a need for high

[83] The overall reactions in conventional FGD processes are as follows:

$$CaCO_3(s) + SO_2(g) + 1/2\ H_20 \rightarrow CaSO_3 \cdot 1/2\ H_20(s) + CO_2(g)$$
$$CaCO_3(s) + SO_2(g) + 2\ H_20 + 1/2\ O_2 \rightarrow CaSO_4 \cdot 2\ H_20(s) + CO_2(g)$$

capacities of technology which use the low emission fuel (GW_i) and a high probability of usage (P_i). These terms are discussed below.

Heat Rate

By lowering heat rate (increasing conversion efficiency), emissions can be reduced. The most promising technology for this purpose is the combustion turbine - combined cycle. Versions of the technology exist for all fossil fuels, and result in substantial efficiency gains over conventional steam plants alone. The construction costs of such units are low enough that these units appear attractive independent of emissions considerations. The increased use of these technologies represents one of the "no-cost" alternatives for emissions reduction. Additional opportunities for efficiency gains, particularly in natural gas use, are embodied in steam-injection and fuel cell technologies. These technologies are less economically attractive than combined cycles, however.

There are, of course, policies which might decrease efficiency, causing increases in carbon emissions. The retrofitting of coal plants with sulfur scrubbers is one example. Decreases in efficiency, either through required scrubber retrofits or aging of plants, can have one counter-intuitive effect. If the decreases in efficiency are so great as to causes a plant to become uneconomical, it might be retired and replaced by a new unit with lower emissions than others in the system. One purpose of the study is to determine the possible emissions reductions which can be achieved through switches among technology and fuels. Therefore, the efficiency and carbon content factors will be fundamental considerations in the selection of policy options for modeling. Of particular interest were the potential effects of nuclear, integrated coal gasification / combined-cycle, and natural gas-fired technologies.

Availability

The only policy lever offered by the availability term is the possibility of limiting generation from high emissions technologies through policy-forced outages. By allowing the technology to operate only for a certain portion of the year, other technologies, presumably with lower emissions, must be utilized. It should be noted, however, that plants decrease in availability over time as forced outages increase. This effect, in combination with increasing heat rates, is the normal driver for the retirement of older less efficient plants.

Probability of Usage

As previously stated, the P_i term is the most complex. It is also, however, the most interesting, in that it provides a number of policy levers for emissions reduction. These are outlined below, with attention first placed on supply-side policies, followed by demand-side alternatives.

Supply-Side Policy Options

Changes in Dispatch Order

There are several potential policies for altering the dispatch order of the system. The first of these is to hardwire the dispatch, simply defining the order in which plants will be operated, presumably according to some complex weighting of costs, environmental emissions, and other factors.

This would be very difficult in practice, since the order would have to be redefined for every change in the capacity mix and since the criteria for ordering are unclear.

The second alternative is to change the criterion for unit dispatch from marginal costs to some other easily defined and measured criterion. Among the other possible criteria are marginal carbon emissions, which would minimize the carbon emissions at greater cost, or marginal SO_2 emissions, which would minimize SO_2 at increased cost, with a probable decrease in carbon emissions. The carbon dispatch option was one of the policies examined in the modeling portion of the study.

A third alternative is to maintain the marginal cost dispatch criterion, but to internalize other factors, such as carbon emissions, into the costs. This is done through taxes (based on carbon content of fuels, for example) or subsidies (i.e., to increase the use of renewable resources). The advantage to this option is that there is no need for reprogramming of dispatch centers, since they operate in the same manner as before. Emissions decrease because there are economic benefits associated with lowering them. A carbon tax strategy was among the policy strategies examined in the modeling portion of the study.

A fourth option takes advantage of the system's present capability to handle limited energy units. In this strategy, energy limits are placed on high-emission plants. This limits the emissions from these plants to a certain level, forcing additional generation to come from lower-emission (and higher cost) technologies. A related strategy is a system-wide cap on carbon emissions (a "bubble"-type regulation) which treats an aggregated group of high-emission plants as a single energy-limited technology, again requiring the use of lower emissions plants when the energy or emissions cap is reached.

The final option in this category, involves the capability of the system to define certain units as must-run plants. If low emission plants which would otherwise receive limited use (because of higher marginal cost) were defined as must-run units, generation from higher emission baseload plants would be automatically displaced.

All of these strategies are limited by one constraint: the ability of low emissions technologies to operate at significantly higher levels of energy generation. Clearly, a natural gas combustion turbine can not be expected to run continuously at baseload. Similarly, while a natural gas-fired combined cycle unit can run at baseload, fuel may not be available in as large a supply as needed. With both natural gas and oil, there are probably limits to the amount of fuel which can be obtained by utilities and on the amount of these fuels on which the utilities should be dependent.

Changes in Capacity Mix

The most straightforward way to alter the capacity mix of a system is to construct new power plants. New construction is normally driven by load growth, with new power plants coming on line as demand increases. Construction can also be driven by economic gains which are recognized by substantially increased efficiency from new plants[84]. While this has traditionally not been pursued by U.S. utilities, several studies[85], including this one, have shown that some technologies (particularly natural gas fired-combined cycle) have efficiency gains which offset the cost of construction.

[84] These economic gains are more pronounced with high fuel prices which increase the importance of efficient fuel conversion.
[85] Connors, et.al., 1989.

Finally, of course, construction can be mandated or subsidized as a matter of policy regardless of growth.

The construction of new low-emission capacity will generally have one of two effects on environmental emissions. If the technology also has low marginal costs (nuclear, for example), then marginal emissions will decrease substantially, since high-emission baseload has been displaced. If the technology has high marginal costs (natural gas combustion turbines) the effect on marginal emissions will be minimal, because only peak generation (generally a small amount of low emission generation) will be displaced. Higher carbon emission capacity (i.e., coal plants with FGD) will cause increase in marginal emissions in the same manner. If the new construction has been driven by increased demand, overall system emissions may or may not increase in spite of the system's decreased marginal emissions.

The final way that capacity mix can be altered is through the retirement of existing capacity. This is normally driven by economics, retiring plants when increasing heat rates and forced outages have made them uneconomical. Retirement might also be forced by regulation. This can be done directly, by mandating the retirement of certain types or ages of plants, or indirectly by tightening environmental regulations so that retirement of high-emissions capacity is forced. One of the policy strategies examined in the modeling portion of the study examined the effects of early retirement of coal-fired capacity.

Construction of Non-dispatchable Technologies

Non-dispatchable technologies (NDTs) are those technologies whose energy generation is controlled by factors external to the utility system, and whose marginal emissions are typically zero. Solar and wind systems are examples of such technologies. This characteristic causes these technologies to have fundamentally different effects than more traditional supply options. The construction of non-dispatchable capacity is a supply side option which essentially has demand-side effects. In other words, non-dispatchable technologies alter the character of the demand faced by the other supply technologies in the system. The effect of various non-dispatchable options depends greatly on the character of the electric generation they produce, as well as the character of the remaining capacity mix.

The effect of NDTs is generally difficult to predict. For instance, solar insolation, wind velocity, or river flow can typically be expected to have certain characteristics (seasonal variations, for example), but the hour-to-hour generation of the technologies is generally unknown. In general, however, the construction of NDTs will result in the displacement of the need for generation at the margin of the system — the highest cost generation. Since this is, generally, also generation with low emissions, the environmental effects of the first NDT units added to the system may be minimal. This is similar to the effects of conservation discussed below. The primary difference, is that if NDT construction is significantly larger, it may begin to reduce the need for generation from intermediate and baseload units which tend to have high emissions. Environmental effects could then be substantial.

Demand-Side Policy Options

Conservation

For the purposes of this discussion, we will define conservation to be the lowering of peak demand while maintaining load factor at an approximately constant level. It is clear that this type of effort would result in a lowering of emissions from a given system, since by definition less energy must be generated from the system as a whole, therefore generating fewer emissions. There are some counterintuitive effects of conservation, however. First, if no change in loading order occurs, the energy displaced is energy from the top of the loading order. These plants are generally low emissions plants. If the system is being operated according to marginal costs, a GWH saved through conservation does not displace a GWH from a coal plant, but rather a GWH from a peaking plant — oil or natural gas. This means that the carbon emissions reduction will be minimal and the sulfur dioxide reduction will be negligible due to the dominance of emissions from coal baseload. Second, it is the inverse of conservation — load growth — which acts as the natural driver for changes in capacity mix. In the absence of policies to alter capacity mix, conservation programs can lead to higher emissions than what might have otherwise occurred if low emissions technologies been constructed. This is seen in the modeling portion of this study. Conservation was not modeled explicitly as a planning alternative, but rather various potential load growth futures were modeled to examine the effects of changes in load growth on system costs and emissions.

Peak Clipping

Peak clipping consists of demand side efforts to reduce the level of peak demand. The motivation for this is economic. If the peak is smaller, then the highest marginal cost units will not be operated. This reduces emissions, but only from the peaking technologies which are generally minimal contributors to system emissions.

Valley Filling

This policy consists of efforts to increase demand during off-peak time periods. This can be advantageous economically if the right circumstances hold true — specifically, if long-run marginal cost is less than the average electricity price — because it lowers the average cost of electricity. This leads directly to an increase in emissions, since the capacity requirements for baseload become greater. The increased emissions come from the increased use of intermediate load capacity, which can vary from inefficient coal capacity (high marginal emissions) to natural gas-fired combined cycles (low marginal emissions) depending on the characteristics of the system.

Load Shifting

Load shifting consists of efforts to shift demand from peak hours to off-peak hours — a combination of peak clipping and valley filling. Assuming again a marginal cost dispatch, this reduces costs and has an indeterminate effect on emissions. Essentially energy generation from peak capacity is displaced exactly by energy generation from intermediate capacity. The emissions can go in either direction depending on the technologies involved. A shift from gas-fired combustion turbines to oil-fired combustion turbines would increase emissions. A shift from gas-fired combustion turbines to gas-fired combined cycles would cause a decrease in emissions.

Flexible Load

The final type of demand-side management consists of efforts to gain control of the load shape through such activities as contracts with customers to reduce the quality of electricity services — i.e., through interruptions of supply — in exchange for certain incentives. Obviously, the effect of such efforts depends on many factors. Once again, however, such efforts are most likely to affect the amount of peak generation, which generally consists of low emissions technologies.

Technology Capacity

Clearly, the level of emissions of a technology is directly related to the amount of capacity of that technology which is available for generation. The interaction between this factor and the P_i factor can not be underemphasized. If, due to high costs of a technology relative to the rest of the system capacity or other factors, the P_i term is low — that is, if the technology is a peaking technology — even a high level of capacity will not contribute greatly to system emissions. If there is little capacity of a technology, it will have little effect on system emissions even if operated at baseload ($P_i = 1$). Once again it will be noted that the traditional driver for changes in this term are demand growth and retirement of existing capacity. Some additional change might be motivated by economic incentives or by regulation.

End-Use Efficiency

This is probably the greatest target for conservation (the countervailing effects of which were discussed earlier) and certainly the most socially feasible. Many energy services can be fulfilled by existing technologies which are substantially more efficient than present technologies in widespread use. Among these are high efficiency light bulbs (each bulb uses 75% less energy than an equivalent incandescent bulb) and high efficiency electric motors (each motor saves 50% over conventional counterparts). These are substantial effects since lighting accounts for over 25% of U.S. electricity demand and motors for approximately 50%[86]. The methods for implementing these technologies, and the costs of such programs, are a matter of great controversy. Additionally, energy efficient appliances do not necessarily lead to less energy use. For instance, the efficiency of office equipment — copying machines, computers, printers — has increased dramatically, but so has the total number of these machines. The total demand for these services has actually increased with the efficiency improvements[87]. In any case, the implications for environmental emissions are exactly as discussed in the Conservation section above.

Total Electricity Services

Finally, the amount of each energy service and the number of energy services actually needed by a society are the subject of many heated philosophical debates. Only two observations will be made here. First, past trends have shown an increase both in the quantity and kind of

[86] Lovins, et.al., 1982; Goldemberg, et.al., 1987.
[87] Norford, et.al., 1989.

electrical services needed. For example, one emerging electrical service — the electric car — designed to decrease emissions and energy use in the transportation sector, may substantially increase demand for electricity, and thus environmental emissions from the electric power sector. Second, the emerging environmental ethic discussed in Chapter 1 indicates the possibility that such trends might be reversed, although an evaluation of changes in this factor is beyond the scope of this study.

Chapter Four - Methodology of Study

Rationale

As discussed in Chapter 2, much of the previous study of the energy/CO_2 interaction has been based on models of global energy use and climate, typically focussing on time scales of a century or more. The desirability of this approach is clear. Predicted climate changes may not be noticeable for many years. The effects of actions we have taken in the past, and are taking now, will not be felt for many years due to time lags in the involved systems. Finally, contributions to the problem come from everywhere on the globe, and the character of those contributions is changing with time. The desire to attack the whole problem, with the rationale that no single part of the problem is big enough to make a difference, is compelling. The presence of easily accessible models with which to study the problem in this manner[88] have made the likelihood of doing so even greater. This is evidenced by the many studies which these models have spawned[89].

But while these studies provide a strong sense of the scale of the problems, and the general trends of possible solutions, they lack several key elements, as discussed in Chapter 2. The present study attacks the problem in a different manner. It is assumed that at some time beyond the reasonably predictable horizon, perhaps twenty to thirty years, some of the now-proposed advanced electricity generation technologies may be available for widespread use. Among these may be such things as fusion, solar

[88] Edmonds and Reilly, 1985b; Nordhaus and Yohe, 1983.
[89] See Chapter 2.

power from satellites, extensive hydrogen storage of solar power, off-shore nuclear fission, or off-shore coal and biomass gasification. The near-term development of any of these technologies is not assumed, however. Given the time lags associated with the global CO_2 problem, it may be very important to reduce emissions in the intermediate period, particularly in those regions of the world which are dominant contributors to CO_2 emissions. Such reductions will only come about through altered use of existing and near-term technologies.

One drawback to many studies of the electric utility industry, particularly academic studies, is an appreciation of how electric power systems actually operate and change over time. This is reflected through the use of models and/or data which either do not reflect the physical realities of power system operation or are abstract enough that they appear not to do so. The large scale global models which aggregate system operation into a few parameters are clear examples of this. For instance, the Edmonds & Reilly model, which has been used as a basis for many studies including some at the Environmental Protection Agency and the Department of Energy, assumes that the electricity generation stock is turned over — completely replaced — every twenty-five years. Another EPA model, the utility CO_2 emission model (UCEM), assumes that all new capacity is operated to its maximum potential, with remaining demand met by conventional coal technology[90]. Neither of these models captures the complexities which determine how new technology actually penetrates the system and coexists with existing capacity. We have seen that these are important factors in determining both emissions and costs of various

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[90] Princiotta, F.T., 1990.

policies. Whether these models actually represent accurate simulations of the U.S. electric power system is irrelevant. They are not perceived to do so by the very people to whom they might be useful — utility planners. Because utility planners understand the way power systems work, they recognize the leaps of faith which are made in these models, and are subsequently suspicious of any conclusions which might be drawn from its use. The same comments are relevant for the data used in such studies. If utility planners can not confirm that the data used in an external study is an accurate reflection of the realities of the system, any conclusions drawn from the use of that data are inherently suspect and unlikely to be heeded.

For this study, a model and data base have been selected based on the electric power industry's past acceptance of their use for this type of study. The model used is the Electric Generation Expansion Analysis System (EGEAS), developed for the Electric Power Research Institute (EPRI) in the early 1980s. The primary data on existing power systems were taken from the EPRI Regional Utilities Database, a set of synthetic utility databases developed for large-scale regional studies of the US power system. EPRI's Technology Assessment Guide was the primary source of data on technological alternatives for electricity supply expansion as well as for most of the primary modeling assumptions. All other data were taken from additional EPRI sources, except where noted.

EGEAS

The model used for the study was version 4.0 of the Electric Generation Expansion Analysis System (EGEAS), a model developed for

EPRI by researchers at MIT[91]. The user provides the model with information about the plants in an electric power system and potential alternatives for future capacity expansion. Among the data provided are size of plant, age of plant, performance data (heat rates, forced outages, etc.), capital costs, operating costs, fuel use, environmental characteristics, and financial data. Additional data concerning the general system, such as fuel prices and inflation rates, are also provided. Most of the data can be defined to vary over time. EGEAS can then be used to determine optimal plans for future capacity expansion and to simulate the system operation for some time in the future (using expansion plans defined by the user or generated internally). The system simulation provides the user with trajectories of such data as costs (capital cost outlays, production costs, etc.), fuel usage, and environmental emissions. These outputs are reasonably accurate due to the sophisticated probabilistic production costing algorithm used by EGEAS. This algorithm allows for the inclusion of many power system subtleties (limited energy units, storage units, and scheduled maintenance, for instance) without the prohibitive computational time requirements of chronological models. The model was run on a MicroVAX 3400.

EPRI Regional Systems Database

Version 3.0 of the EPRI Regional Systems (ERS) Database was used to provide the existing plant data for the study[92]. ERS is a set of six synthetic databases, each representing a region of the U.S., which accurately

91 EPRI, 1982a.
92 EPRI, 1989h.

reflect the characteristics of the power systems within those regions. The regional divisions are illustrated in Figure 4-1. The databases are considered "synthetic" since they do not provide data for every existing generator, but instead provide scaled-down versions of the actual systems. Whereas each of the defined regions has an electric generating capacity on the order of 100 GW, each region of the synthetic database has a capacity of approximately 20 GW. The units in the scaled-down system have been chosen to accurately reflect the capacity mix and the performance characteristics of the actual units in the system. Because of this, the data of primary concern in this study — costs, environmental emissions, fuel use — are proportional to those which would be obtained in a full-scale simulation. Issues which depend on geography or system size — transmission requirements, environmental deposition, fuel transportation — can not be dealt with accurately through the use of the ERS, but are of secondary importance to the study. Environmental data, not provided in the ERS, were obtained from EPRI technology-specific assessment reports[93] and from generic emissions estimates calculated by the Environmental Protection Agency[94].

Technology Assessment Guide

Information concerning technology alternatives for future expansion was obtained from the EPRI's Technology Assessment Guide (TAG)[95]. The TAG is a set of consistent data concerning the actual or estimated costs and performance characteristics of various existing and near-term

93 EPRI - Numerous reports listed in references section.
94 US EPA, 1985.
95 EPRI, 1989f.

EPRI (and NERC) Regions

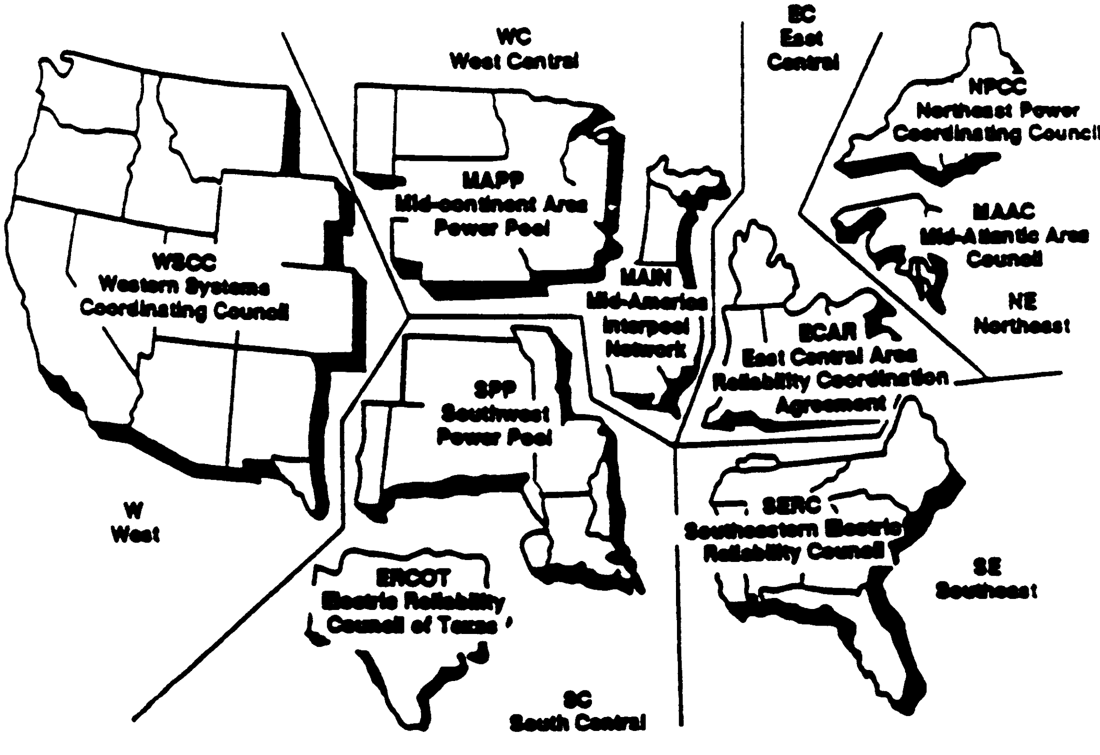

Figure 4-1

Source: EPRI, The EPRI Regional Systems Database, 1989d.

technological alternatives for future electricity generation. These alternatives — consisting of various coal, oil, gas, nuclear, and renewable technologies — were used directly in EGEAS as planning alternatives for the expansion optimization modes. The TAG was also used as the primary source of information about various fuels, including chemical composition, heating value, and region-specific price. Additional information about fuels was obtained from various EPRI reports, the Industrial and Marine Fuels Reference Book[96], and the Standard Handbook for Mechanical Engineers[97]. Some environmental data were provided in the TAG. Additional data were again obtained from EPRI technology-specific assessment reports and the EPA. As this data is intended to be consistent with the ERS, regional differences were accounted for in the TAG.

Regions Considered

For this study, two regions were examined: the Northeast and the East Central. The Northeast consists of New England, New York, New Jersey, Delaware, eastern Maryland, and eastern Pennsylvania. The East Central regions contains Indiana, Ohio, West Virginia, Kentucky, lower Michigan, western Pennsylvania, western Maryland, and western Virginia. See Figure 4-1.

These regions were chosen because of their vastly different characteristics. The Northeast is characterized by a diverse generating mix, large power purchases, extensive cogeneration, fairly high reliability, and fairly high electricity costs caused by poor access to low cost fuels. The East

[96] Clark, G.H., 1988.
[97] Baumeister, 1978.

Central is characterized by its coal-dominated capacity mix, high reserve margin, and fairly low cost electricity due to its proximity to low-cost coal. The distribution of electricity generation and carbon emissions across the various US regions is shown in Figures 4-2 and 4-3. The effect of differences in capacity mix is clear. While the two regions generate essentially the same level of energy, the East Central region has significantly larger carbon emissions[98]. The regions are also of interest in this study due to the political tension between the two which has been caused by the allegations of environmental damage in one (acid deposition in the Northeast) caused by air emissions in the other (Sulfur dioxide and nitrogen oxide emissions from the East Central). The Northeast region was studied first to allow for qualitative comparisons with similar and more detailed MIT studies of New England[99]. Additional qualitative observations will be made with reference to a third region, the West. This region is of interest because of the greater opportunities for renewable-based generation from such technologies as solar, wind, and geothermal.

Technologies Considered

Only near-term technologies were considered. That is, all of these technologies are either available or expected to be available, without large technical breakthroughs, in the next 15 years or so — most of them within the next five years. For the regions considered, these technologies were limited exclusively to fossil fuel, nuclear, and municipal solid waste

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[98] It should be noted that these figures represent electricity generation (and emissions from that generation) within a region, regardless of where that electricity is used. Since the Northeast region has significant power purchases, some from the East Central region, this comparison is somewhat biased.
[99] Connors, et.al., 1989.

Distribution of Electricity Generation in the United States

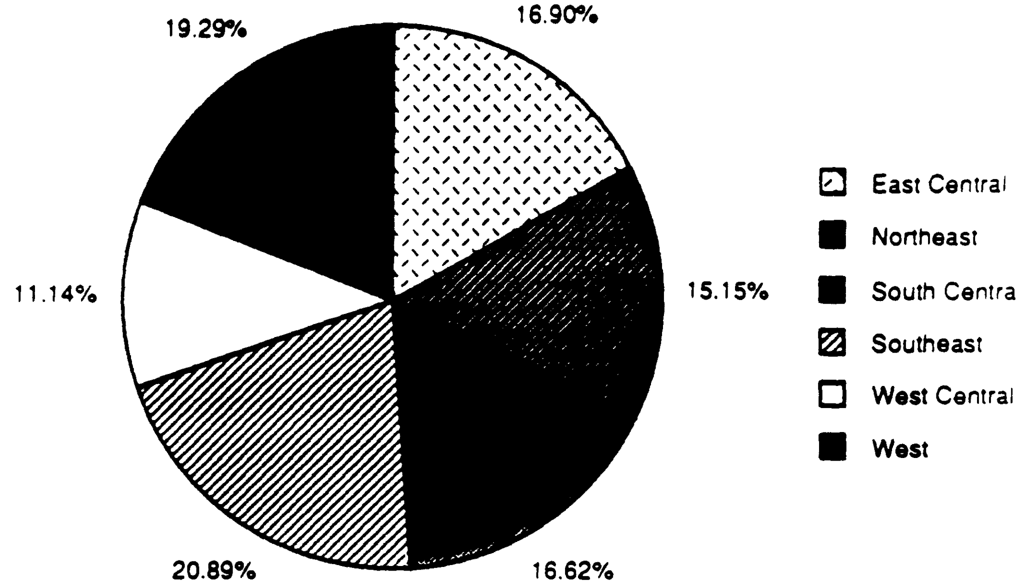

Figure 4-2

Distribution of Carbon Emissions in the United States

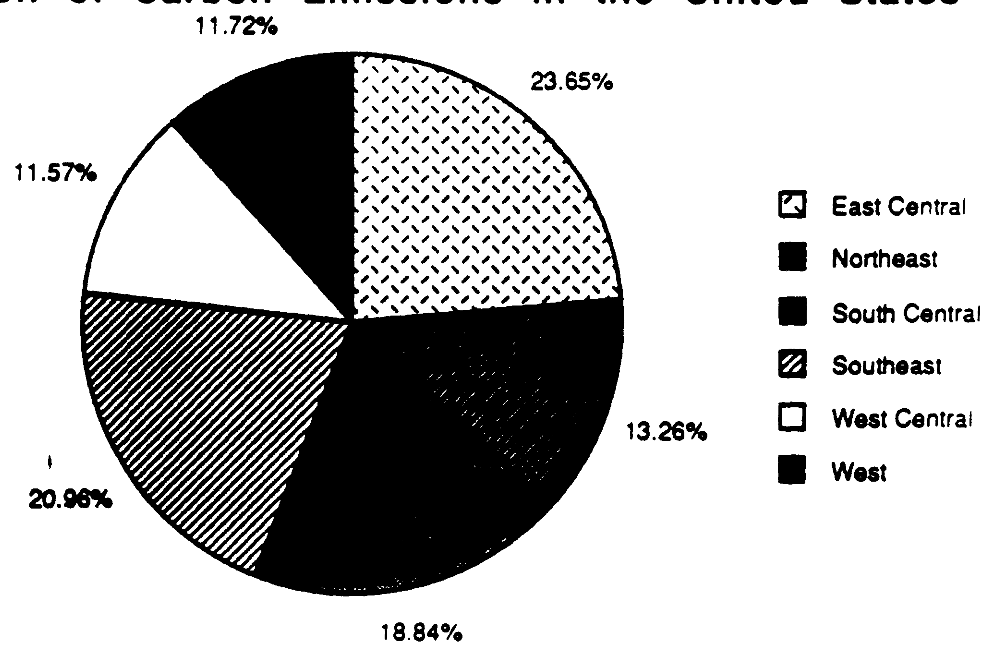

Figure 4-3

alternatives. Other renewable-based technologies, such as solar, wind, and geothermal, were not included because of EPRI assessments that these technologies are only feasible within the West region[100].

Among the coal technologies considered were the following:

1) Conventional Pulverized Coal with Wet Limestone Flue Gas Desulfurization (Sulfur Scrubbers): Several versions of this technology were considered, including different sizes as well as subcritical and supercritical units. Regional differences, caused mainly by the availability of different coal types were also considered.

2) Conventional Pulverized Coal with Spray Dryer FGD: These units are fired on low-sulfur coals and use different scrubber technology.

3) Conventional Pulverized Coal with Regenerable FGD: This technology is for high-sulfur coal and has 90% SO_2 removal.

4) Advanced Pulverized Coal - State of the Art Power Plant: This plant represents the inclusion of all conceivable and immediately available technological improvements for coal combustion, still using the conventional pulverized coal process, with advanced flue gas desulfurization.

[100] While clearly the feasibility of several of these technologies is more limited and longer term in other regions, their complete exclusion is not inherently necessary.

5) Atmospheric Fluidized Bed Combustion (AFBC): This technology is one of the prime candidates for "clean coal" combustion. SO_2 and NO_x emissions are reduced, because they are removed in the combustion chamber instead of from flue gases. Several versions of this technology were considered, including bubbling bed and circulating bed (differentiated primarily by the rate of air flow through the combustion chamber) and various coal feedstocks (bituminous, subbituminous, and lignite).

6) Pressurized Fluidized Bed Combustion (PFBC): This technology is similar to AFBC, but operates above atmospheric pressures. In general, PFBC is more efficient than AFBC, but the technology is several years behind in development. The variations of PFBC which were considered were turbocharged boilers (bubbling bed and circulating bed) and combined cycles.

7) Integrated Gasification Combined Cycle (IGCC): This technology is the other prime "clean coal" candidate. In this process, coal is gasified and the gas is used to fire a gas turbine - combined cycle unit. By utilizing "waste streams" (of steam, for example) from various stages of the process as inputs for other stages, the units can achieve high efficiencies. Additionally, SO_2 and NO_x emissions are very low. The

technology was considered in various sizes and for various coal feedstocks.

The liquid and gas-fueled technologies which were considered included the following:

1) Combustion Turbine (CT): This technology, fired on either distillate oil or natural gas, is well established as an inexpensive technology for the fulfillment of peak demand. Among the versions considered were oil and gas fired units, conventional and advanced units, and various sizes.

2) Steam-Injected Gas Turbine (STIG): In this technology, steam from the gas turbine is reinjected into the turbine in order to increase efficiency. The units are only marginally economical at this time.

3) Combustion Turbine - Combined Cycle (GTCC): This technology is a combination of a conventional combustion turbine, fired on distillate oil or natural gas, with the addition of a steam bottoming cycle. The bottoming cycle, uses steam from the gas turbine to generate additional electricity, thus gaining a great deal in efficiency over stand-alone gas turbines. The versions considered included oil-fired and gas-fired units, as well as conventional and advanced units.

4) Fuel Cells - Fuel cells operate similarly to batteries with the continual addition of chemical energy from a fuel gas. Since there is no intermediate conversion of chemical energy to thermal energy, the efficiency of conversion to electricity can be very high. Although costs of the technology are high, the major environmental emissions of the units are lower than any other fossil fuel-fired technology.

The other technologies considered were the following:

1) Municipal Solid Waste (MSW): This technology is not particularly attractive economically or environmentally for the production of electricity, but has the benefit of reducing the solid waste problem. Two versions of this technology, mass burn and refuse-derived fuel, were considered.

2) Advanced Light Water Reactor — Evolutionary: This technology consists of incremental technological improvements to conventional light water reactors.

3) Advanced Light Water Reactor — Passive Safety: This technology is similar to conventional light water reactors, but contains inherent safety features. "Passive safety" implies that the prevention of core meltdown does not require proper operation and human management of complex cooling systems, but is guaranteed by the physical properties of the system.

4) Modular High-Temperature Gas-Cooled Reactor (MHTGR): This is another nuclear technology with passive safety features. The additional benefits of this technology are its generation of process heat which can be used for industrial applications and its modular design, which would allow for streamlined licensing procedures.

Uncertainties Considered

The primary uncertainties considered within the study were fuel price and load growth. An attempt was made to choose a set of possible futures which would provide a reasonable resolution with which to view possible outcomes, without prohibitively increasing computational requirements. It was decided that two fuel price trajectories — base and high — and four load growth trajectories — base, low, high, and very high — would be selected for analysis. Each possible combination of these uncertainties — high fuel price and low load growth, for instance —constituted a "future". The basic fuel price uncertainty was obtained from DRI forecasts[101]. A fuel price uncertainty with higher fuel prices for oil and gas was then created. Significantly higher prices for coal or uranium were not judged likely enough to be worthy of consideration. The base load growth cases for each region were taken from the ERS. Although each varied with time, the projected growth was approximately 1.5% per year in the Northeast region and approximately 1.0% per year in the East Central region. Low growth cases were 1% less per year than the base

101 DRI, 1989.

case for each region; high growth cases were 1% higher; very high growth cases were 3% higher.

Strategies Considered

Various potential strategies for future electric power, some designed explicitly for the reduction of CO_2 emissions and some designed for other policy goals, were then defined. Several of these are based on proposed legislation or policies, while others are based on direct manipulation of the policy levers identified in Chapter 3. The study undertaken defined seven basic policy strategies for analysis. These are:

1) Base: The base strategy was defined as a business-as-usual strategy in which utilities continue to attempt to minimize costs, within moderate constraints for SO_2, NO_x, and particulate emissions. No limits on carbon emissions were assumed. In this case, nuclear options were not considered, since extended use of nuclear power will undoubtedly require a change in at least regulatory environment, if not general public acceptance.

2) Nuclear: The nuclear strategy differed from the base in that nuclear options were offered as the only available baseload capacity option (new coal-fired options were removed) in the optimization runs. In the Northeast, the nuclear option was marginally more economical than the IGCC option, while marginally less so in the East Central.

4) <u>No Nuclear / No Coal</u>: In this strategy, the system was forced to choose only natural gas and oil based technologies for expansion, thus forcing combined cycle and combustion turbine technologies.

5) <u>Dispatch Modifier</u>: The optimal expansion pathway of the Base strategy was used to define the plant additions. The units were operated according to marginal carbon emissions instead of marginal cost. While the expansion pathway in this case was by no measure "optimal", the dispatch modifier does cause a minimization of carbon emissions, for a given capacity mix and demand. Note that carbon dispatch is almost identical to sulfur dispatch, with the exception of "clean coal" technologies — IGCCs, AFBCs, and conventional coal with FGD. These technologies have high carbon emissions and lower sulfur emissions, slightly altering their loading order positions in the two forms of environmental dispatch. Only carbon dispatch was modeled; possible differences with sulfur dispatch will be examined qualitatively.

5) <u>Early Retirement</u>: For all coal plants, the existing operating life was reduced by 10 years (generally from 50 to 40). This is an attempt to phase out those plants which have the highest marginal emissions of both CO_2 and SO_2 — older coal plants. This requires a substantial increase in construc-

tion, particularly in the early years and specifically in the coal dependent East Central region.

6) Carbon Tax: A substantial tax on the use of fossil fuels was assumed based on carbon content ($5.70/GJ for coal; $2.30/GJ for oil; and $1.10/GJ for natural gas)[102]. This is an attempt to internalize the costs of carbon emissions by tying economic benefits to the reduction of carbon emissions[103].

7) Conservation: No attempt was made to explicitly model conservation efforts. For each region, however, four possible load growth paths were defined and simulated separately in order to determine what benefits, if any, might be obtained through switches from high growth futures to low growth futures.

Optimization Methodology

Each combination of future (a load growth and fuel price combination) and strategy defined a scenario. It was then necessary to determine the optimal expansion path, or choice of technology alternatives,

[102] These taxes, in 1985$, are the same as those used in several EPA studies. In the EPA studies, the taxes were phased in over a period from 1985 to 2050. In this formulation, the taxes were implemented immediately (1989) and are, thus, even more extreme.

[103] It should be noted that a carbon tax is likely to induce not only technology and fuel switching as examined here, but conservation as well, due to steep increases in the price of electricity. The modeling of the carbon tax here assumes that the same level of demand must be met by this strategy as with the others (equivalent to assuming a price elasticity of demand of zero) since this demand feedback can not be explicitly modeled within the framework of EGEAS. The result is that the carbon tax appears more costly and less effective for emissions reduction than is likely to be the reality.

for each scenario. EGEAS offers three methods of optimization, all of which were used at various stages of the analysis:

1) Linear programming: The linear program (LP) is a simplistic method for roughly screening large numbers of alternatives. By assuming a constant capacity factor for each unit (not a strong assumption as discussed in Chapter 3), the LP selects, from up to thirty alternatives, those alternatives which are most economical at some level of system demand. The method overlooks a great deal of the reality of electricity system operation, and is not useful for the development of optimal expansion plans or the calculation of costs or emissions. The LP is useful, however, for pointing out those technologies which are most likely to be chosen as alternatives by other optimization methods. Since the computational time of other methods is directly related to the number of alternatives which are considered, the LP can serve as a useful pre-screening tool.

2) Bender's Decomposition: The Bender's decomposition (BD) method was the primary optimization method used in this study. The method is essentially a nested linear program with iterations between a master problem and subproblem which allow for much greater accuracy than the LP. Unit generation is calculated through the use of the Baleriaux

production costing algorithm mentioned in Chapter 3[104]. The main disadvantage of the BD method is its selection of fractional units for capacity expansion. This is not a weakness in this study, however, since the system databases are synthetic, the goal of the study was not to develop specific expansion plans (i.e., build one coal plant in 1992 and two gas-fired units in 1993), but rather to reveal the character of possible expansion plans. Additionally, the BD method in EGEAS properly accounts for the planned and forced outages of units, despite the fractional unit expansion plans, thus not distorting cost, fuel use, or emissions data. As expected, system costs are lower when fractional units are allowed than with solely integral units, simply because the fractional unit option provides greater flexibility for unit construction.

3) Dynamic programming: The dynamic program (DP) algorithm is the most accurate of the optimization methods available within EGEAS. The DP provides expansion plans with integral units, but is nearly prohibitive in its computational requirements. As stated above, integral unit capability is not a feature of interest in this study. The DP was used primarily, to verify the accuracy of the BD method for a few scenarios.

104 EPRI, 1982a.

Simulation Methodology

Once determined by one of the optimization methods, the twenty-five year expansion path for each scenario was simulated using the prespecified pathway option of EGEAS. This option provides an accurate yearly simulation of system operations, providing detailed information about costs, supply reliability, fuel use, and environmental emissions. The prespecified pathway can be run utilizing fractional or integral units. For all scenarios, except those associated with the dispatch modifier, the fractional unit option was used since the optimal expansion path was calculated in fractional units. The quirks of the modified dispatch option in EGEAS require integral unit simulation, so the fractional units of the base case were rounded to best mimic the fractional expansion plan. As this was already a simulation of a suboptimal plan, this added inaccuracy (which tends to increase system costs) is not significant.

Model Output

The EGEAS model provides detailed data about a variety of system parameters. Cost data includes annual capital costs, operating costs, fuel costs, and total system costs. Annual environmental emissions are also calculated. Emissions of interest in this study are the greenhouse gases carbon dioxide (calculated as elemental carbon - C), methane (CH_4), and nitrous oxide (N_2O), the acid rain precursors sulfur dioxide (SO_2) and nitrous oxides (NO_x), as well as total suspended particulate (TSP), a local pollutant. The model also calculates the energy generation, fuel use, and price for each fuel and technology type. Financial data and individual unit data are also available, but were not used extensively in this study.

Chapter Five - Results

Overview

The large number of variables considered within the study leads to an inherently complex set of results. For each of the two regions, four possible growth paths, two fuel price trajectories, and six policy strategies were considered. Thus, 96 scenarios have been modeled. Within each scenario, nearly forty fuels may have been utilized by more than sixty supply technologies, with changes in capacity mix, fuel usage and technology usage over the 25 year time period. The environmental emissions (six emissions were calculated) and the various system costs (capital, operating, fuel, etc.), which also vary over time, are of primary interest. Clearly, a comprehensive listing of all of these data would be tedious and of limited utility. Lewis Carroll once pointed out that there is nothing more useless than a map which has been drawn on a one-to-one scale — it is hoped that this mistake can be avoided here.

To alleviate this problem, the results are given in "cross-sections" of the multi-dimensional space described above. This is accomplished by systematically illustrating the changes in one or two variables given constant values of other variables. For instance, data are given which illustrate carbon dioxide emissions over time for all six policy strategies, given a single region, and a single future (one load growth / fuel price combination). Similarly, all emissions are shown for a single strategy, region, and future, and so on. A basic set of these cross sections is given, augmented by those additional cross sections which provide particularly unusual, salient, or counterintuitive information.

Expansion Plans

The first variable of interest is technology choice — that is, which technologies were among those used for future electricity supply? We are also interested in when, where, and under what circumstances particular technologies are the most attractive expansion alternatives. The choice of technology is driven by the relative costs of the various technologies and the needs of the system. These drivers can vary over time as well as across regions, futures and policy strategies. In general, capacity expansion followed similar patterns in all scenarios. Different scenarios resulted primarily in shifts in the timing of the general expansion pattern. Differences in technology choice from the basic pattern were caused primarily by significant shifts in relative fuel prices and when mandated by policy (i.e., the nuclear strategy).

The general expansion pattern consists of a zero-construction time period while present overbuilt capacity levels out, followed by the construction of efficient intermediate / peaking capacity, followed finally by inexpensive baseload capacity. The most frequently chosen intermediate technology was the natural gas-fired combined cycle (GTCC). In some high fuel price scenarios, oil-fired combined cycle units were more attractive for some portion of the study period. Additionally, in some scenarios which required only a small amount of peak capacity, at minimal capital cost, stand alone combustion turbines (gas or oil-fired, depending on prices) were more attractive than the combined cycles. Two baseload technologies were similar in economic attractiveness — integrated coal-gasifier combined cycle (IGCC) and the advanced light water reactor. In the East Central region the IGCC was marginally more economically attractive, while in the Northeast, the situation was reversed. Due to the greater uncertainties surrounding the assumptions for nuclear reactors, the IGCC expansion paths were considered to be the "base" strategy. Additionally, in a few scenarios where high growth and low fuel prices cause capital and operating cost considerations to outweigh the fuel savings from greater efficiency in a few years of the study period, conventional pulverized coal plants with sulfur scrubbers were chosen instead of IGCCs.

Environment-Cost Tradeoffs

The primary focus of this analysis is identifying the extent to which various strategies can reduce environmental emissions and the associated costs of implementing these strategies. This formulation implies a desire to find the most cost-effective strategies — those which give the most "bang for the buck." We will examine this and similar features through the use of tradeoff curves. Each tradeoff curve examines the performance of various strategies with respect to two attributes of interest in the study (i.e., cost and CO_2). Each axis will be plotted such that lower values of the attributes (i.e., low cost and low emissions) are more desirable. This will allow the reader to visually evaluate the performance of various strategies. If any strategy is closer to the lower-left corner of the graph than a second strategy — that is, if the first strategy is better for one attribute without being worse for the other — the first strategy is said to dominate the second. Some subset of the strategies will not be dominated by any other strategy, and thus represent an "optimal set"[105]. If we were concerned only with the two attributes depicted, and we were confident of the

[105] A Pareto optimal set for the two attributes of interest.

assumptions which led to the positions of the various strategies, there would be no reason to choose a strategy outside of the optimal set, since there would always be one strategy with which we can gain better performance on one or both of the attributes. Additionally, choices between strategies within the optimal set can be made with full understanding of the associated tradeoffs (i.e., the increased costs of additional emissions reduction).

Several words of caution should be added. Any particular tradeoff curve depicts only two attributes, with no regard for others. While our primary interest is in the tradeoffs between costs and carbon emissions, we will also examine the tradeoffs between these two attributes and another important environmental emission: sulfur dioxide. Quite contrary to conventional wisdom, those strategies which provide for the most improvement in SO_2, do not necessarily provide subsequent improvements in carbon emissions. This helps to demonstrate the complexity of technology and strategy choice.

There are many other attributes — reliability of electric service, capacity siting requirements, risk of nuclear accidents, volume of solid wastes, dependence on foreign energy sources, etc. — which are important, but for which explicit tradeoffs cannot usefully be illustrated (each additional attribute would add a dimension to the tradeoff curve, assuming it could be adequately quantified). These issues are explicitly considered, however, when discussing the conclusions which might be drawn from a viewing of the given tradeoff curves in isolation.

Each tradeoff curve is valid only for a certain set of assumptions, and will change with changes in load growth and fuel prices. Similarly, the tradeoffs are different for different regions. The most important changes which occur with these differing assumptions are illustrated. This helps identify those assumptions to which strategic planning may be most sensitive, as well as those strategies which are relatively robust with regard to uncertainties.

The primary examined are the net present value of total costs (annual costs discounted to 1988$ by a discount rate of 10%), total carbon emissions, and total SO_2 emissions — all totalled over the entire 25 year study period (1989 - 2013). No discounting is applied to the emissions numbers[106]. To avoid the confusion of three-dimensional presentation, only tradeoffs between two attributes are presented. For any particular set of assumptions, the three dimensional tradeoff is represented by the three explicit tradeoff curves (cost vs. carbon, cost vs. SO_2, and carbon vs. SO_2)[107].

First, we will examine the tradeoffs for the Northeast region under the base future assumptions (base load growth and base fuel price). These tradeoffs are shown in Figures 5-1, 5-2, and 5-3. Note again that in all tradeoffs, a position toward the lower-left corner (approaching zero emissions or zero cost) is most desirable. Note also that the following abbreviations are used to represent the strategies: Nuclear - NUC; No Nuclear / No Coal - NNNC; Early Retirement - ER; Dispatch Modifier - DM; Carbon Tax - CT.

Of particular interest in the carbon versus cost tradeoff is the nearly dominant position of the nuclear strategy. The nuclear strategy has lower carbon emissions at lower cost than all other strategies except the no

[106] The discounting of costs is motivated by opportunity costs -- the rate of return which could have been earned through investment of money elsewhere. No such analog exists for environmental emissions.
[107] The three-dimensional tradeoff is fully defined by any two of the three two-dimensional tradeoffs, but the extrapolation of the third tradeoff requires some avoidable mental gymnastics which detract from the utility of the tradeoff curve representation.

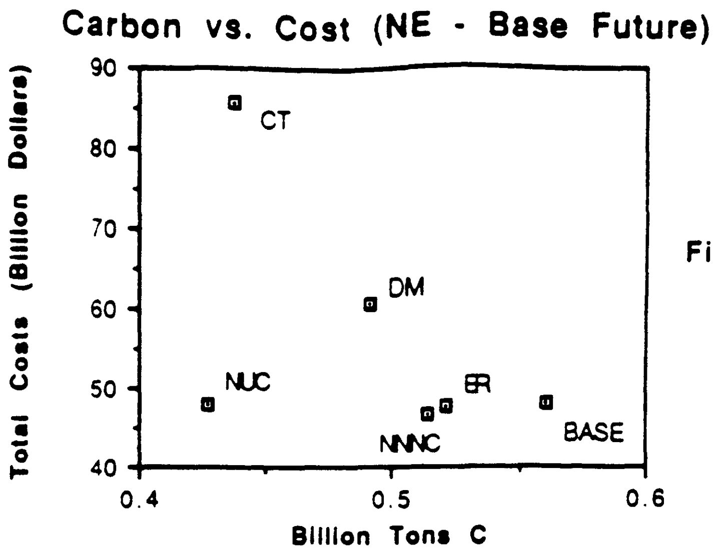

Figure 5-1

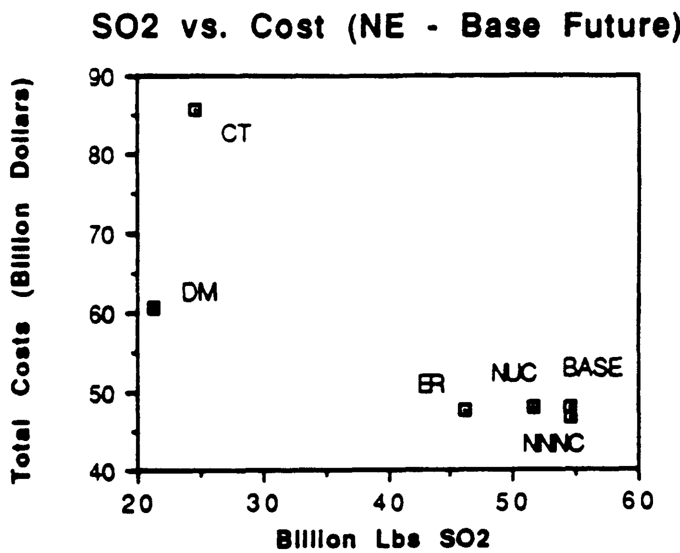

Figure 5-2

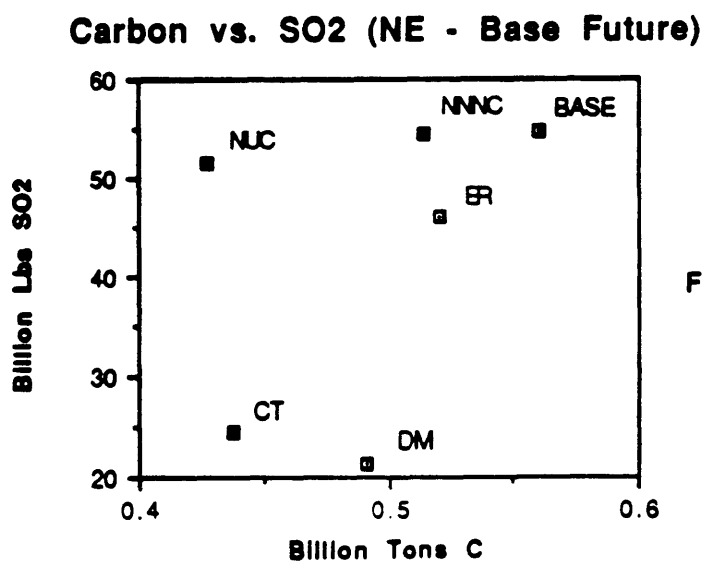

Figure 5-3

nuclear / no coal strategy[108]. The presence of three strategies which reduce carbon emissions, relative to the base case, at essentially no cost (nuclear, no nuclear / no coal, and early retirement) supports one of the primary underlying hypotheses of this study. Finally, in the absence of the nuclear option (a strong possibility due to other environmental and political considerations), there exists an optimal set (carbon tax, dispatch modifier, and no nuclear / no coal[109]) where the tradeoffs between carbon emissions and cost are clear.

The SO_2 - cost tradeoff, Figure 5-2, shows a small optimal set — dispatch modifier and early retirement. There is again a group of strategies which produce different amounts of emissions for essentially the same cost as the base case. The difference in SO_2, however, is not as great as that observed in the carbon emissions tradeoff. This is perhaps most dramatic with reference to the performance of the nuclear case, which significantly reduces carbon emissions, but appears to have little effect on SO_2. This a result primarily of the role which is played by coal, in general, and by IGCCs in the base case. As we have seen in Chapter 3, carbon emissions are driven by the amount of coal-fired generation in the system. SO_2 emissions, however, are driven by the amount of <u>uncontrolled</u> coal-fired capacity. In the base strategy, most need for future generation expansion is met by IGCCs. The IGCCs add to the coal-fired generation — increasing carbon emissions — but begin to displace uncontrolled coal

[108] It should be noted here that some of the cost numbers are misleading. Higher cost strategies (particularly the carbon tax and dispatch modifier) would be likely to induce conservation, a negative feedback on costs not accounted for in this formulation. Additionally, the carbon tax produces a large sum of money which can presumably be redistributed. Finally, no nuclear / no coal costs may be understated because of decreased reliability, the costs of which are estimated, but highly uncertain. These factors are discussed in greater detail in the strategy-specific evaluations below.

[109] Given margins of error, particularly appropriate for such a large scale study, the early retirement option is not clearly excluded.

generation — reducing SO_2 emissions. The nuclear option does decrease annual levels of both emissions, but the reductions in total SO_2 are not significantly greater than in the base case because a similar amount of uncontrolled coal capacity remains in place. This is also the reason why the early retirement option seems to be somewhat more effective.

The tradeoff curve for the two environmental emissions, when costs are disregarded, reveals a clear optimal set — nuclear, carbon tax, and dispatch modifier. Also of note are the no nuclear / no coal and early retirement strategies, which, while not in this optimal set, are both clearly dominant over the base case. The carbon tax appears to be the most effective at reducing overall environmental emissions — given similar levels of concern over both emissions — but its significantly greater costs have been seen in the other tradeoffs. Finally, when examining the entire tradeoff set it should be noted that three strategies (nuclear, early retirement, and no nuclear / no coal) dominate the base case on all three attributes.

The tradeoffs for the East Central base future, shown in Figures 5-4, 5-5, and 5-6, contain similar patterns, but are qualitatively different in a few respects. It can first be noted that the carbon - cost tradeoff once again shows the nuclear strategy to be dominant. Removing the nuclear strategy, all of the remaining strategies are in the optimal set. It appears that the no nuclear / no coal strategy and the base strategy are nearly dominated by the dispatch modifier since their costs are only marginally smaller for substantial increases in emissions. The scales of the axes are somewhat misleading, however. The difference in cost between the dispatch modifier, $43.2($10^9$) and the base case, $38.6($10^9$) is 12% of the base case costs; the difference in emissions, 695 to 669 million tons, is less than 4%.

Carbon vs. Cost (EC - Base Future)

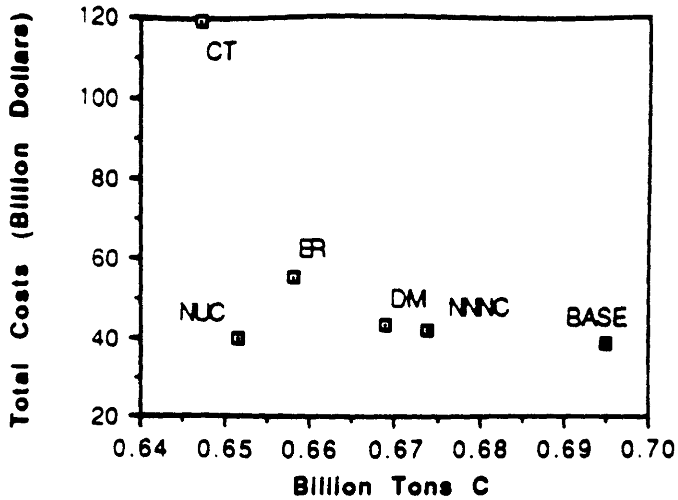

Figure 5-4

SO2 vs. Cost (EC - Base Future)

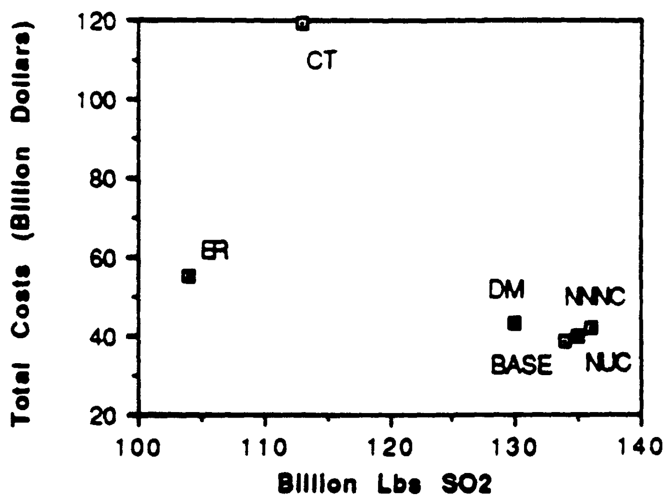

Figure 5-5

Carbon vs. SO2 (EC - Base Future)

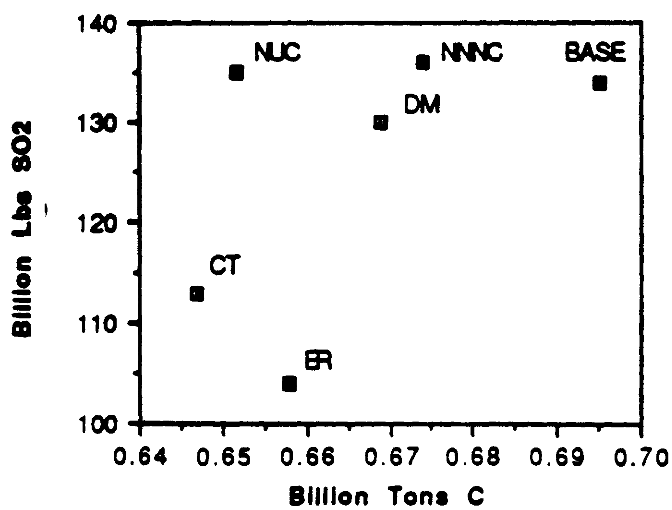

Figure 5-6

These minimal effects are due to two independent factors. First, the dependence of the East Central region on coal makes even marginal emissions reductions costly, since a large amount of new non-coal capacity is needed. Second, the projected growth rate in this region is smaller than for the Northeast. This delays the time at which new (less-polluting) capacity will be needed. Many of the strategies have similar performance characteristics until new capacity is built. If this is only for a few years in the study period, the overall effects are smaller.

The effects of uncertainties can also be demonstrated with tradeoff curves. Returning again to the Northeast region, we can observe some of the effects of load growth (and its inverse — conservation) by examining tradeoff curves for various growth assumptions. For example, Figures 5-7, 5-8, and 5-9 display the carbon - cost tradeoffs for the low ($\approx$0.5%), high ($\approx$2.5%), and very high ($\approx$4.5%) growth scenarios. In general, the pattern remains similar to that which was previously observed for the base growth future. The primary change in the pattern which occurs with increasing growth is the shift of the early retirement strategy relative to the other five. In the low growth scenario, the early retirement option appears very attractive, dominated only by the nuclear case. As growth increases, however, the attractiveness of the option decreases. In the highest growth case, the early retirement option is worse on both attributes than even the base strategy. This indicates the possibility of synergistic effects between early retirement strategies and conservation. We can also observe that, as growth increases, the differentiations between the emissions levels of different strategies become greater — in both absolute and percentage terms — while the differentiations between costs remain approximately constant in absolute terms (decreasing as a percentage). Note also that only

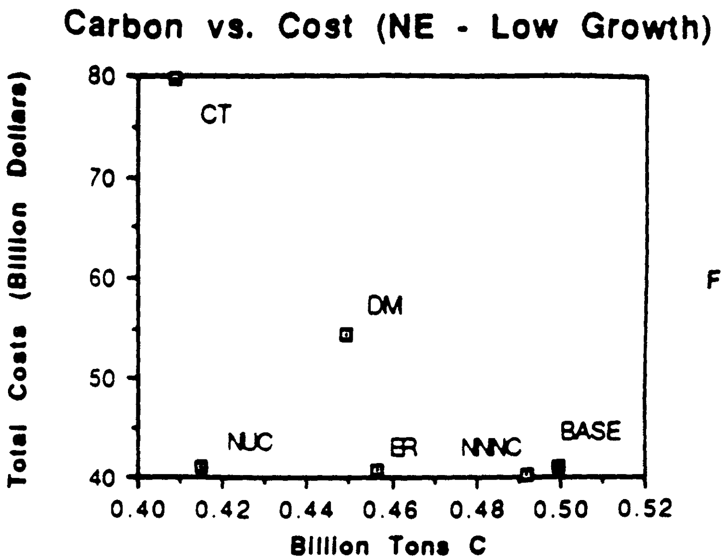

Figure 5-7

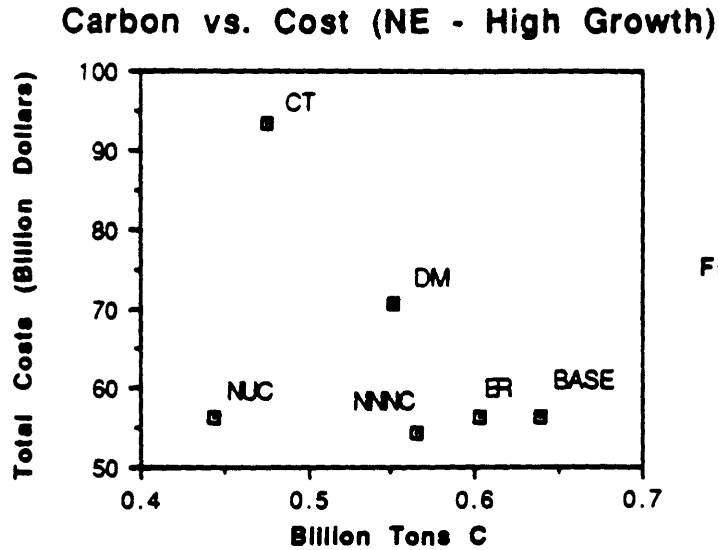

Figure 5-8

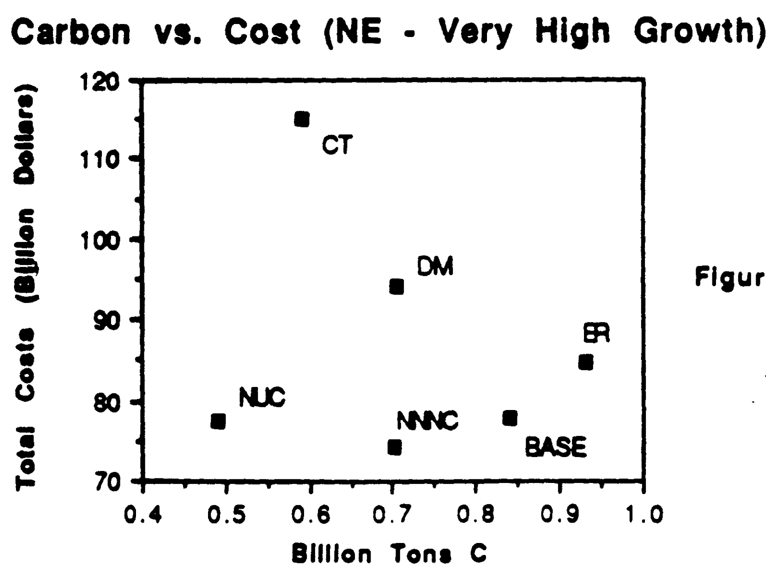

Figure 5-9

the nuclear strategy has carbon emissions which are fairly insensitive to load growth.

In the case of SO_2 emissions, all of the strategies are fairly robust to load growth. All strategies exhibited changes of less than 12% in total SO_2 emissions from the low growth future to the very high growth future. Tradeoffs remained essentially the same.

Time Series Data

The logical extension of the tradeoff curve analysis is a more detailed comparison across strategies of single attribute performance. This can be accomplished through the use of time series data for specific attributes (i.e., carbon emissions) to more closely illustrate the timing and rates of change for strategy differences which were observed in the tradeoff curves. Again, each graph is valid only for a single region and for a single combination of load growth and fuel prices. Data for the base case future — base growth rate and base fuel prices — will be of primary interest.

The first attribute of interest is carbon emissions. Figure 5-10 displays the carbon emissions over the study period for the Northeast region and the base future. The nuclear strategy is the only one which actually lowers the annual emissions rate by the end of the study period[110]. The carbon tax holds emissions approximately stable[111]. All strategies are superior to the base case in all study years. This figure also illustrates that

110 This should not be confused with the "lower" emissions observed in the tradeoff curves. There, a reduction referred to a lower total amount of emissions than would have been obtained in the base strategy and did not necessarily indicate a reduction in the annual rate of emissions.

111 This is substantially different from a stabilization of atmospheric carbon dioxide concentrations, which would require a global reduction in carbon emissions of approximately 50% (EPA, 1989). A stable emission rate will still lead to increased atmospheric concentrations.

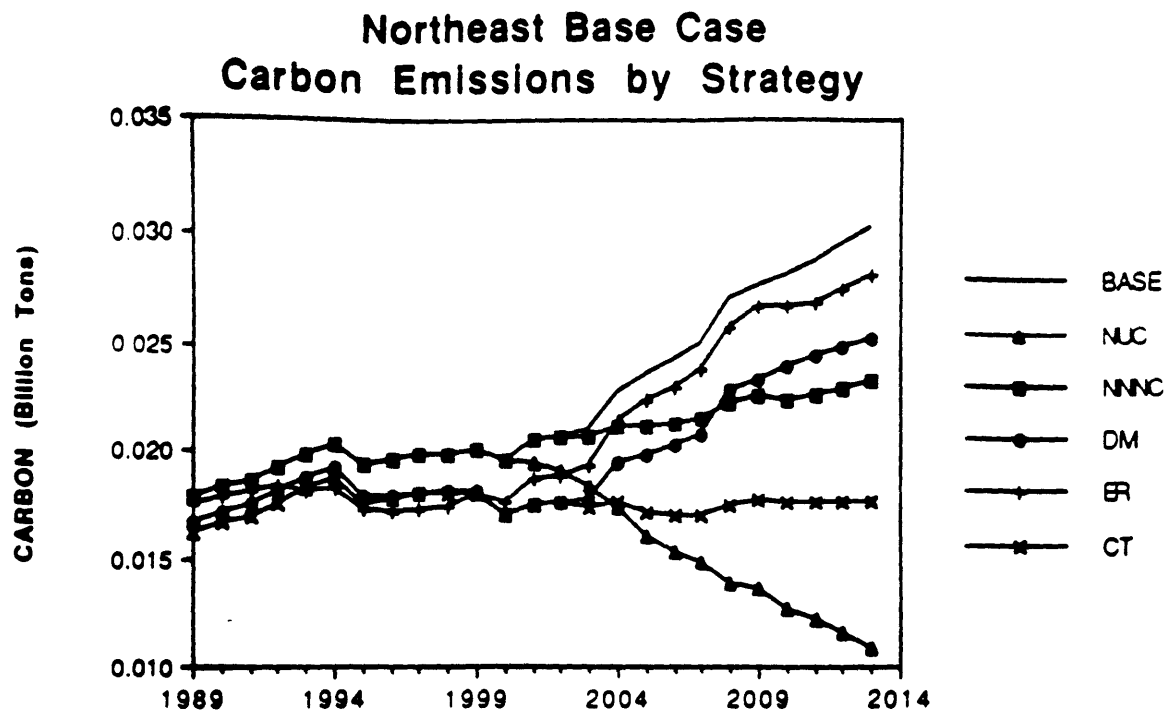

Figure 5-10

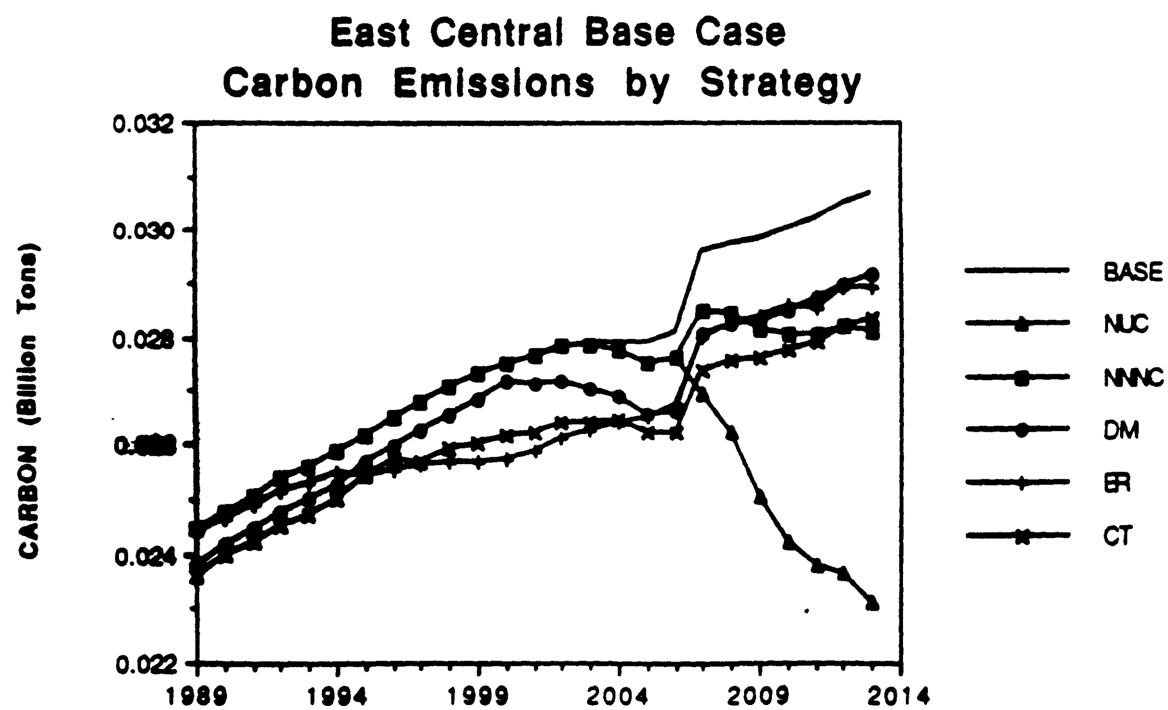

Figure 5-11

those strategies which mandate technological choice — nuclear and no nuclear / no coal — have an effect only when construction with the mandated technology becomes necessary, typically well into the study period. This is seen in Figure 5-10 in the branching off of these two strategies from the base strategy trajectory in the year 2000. Those strategies which alter the system or its operating rules — dispatch modifier, early retirement, and carbon tax — have an effect immediately upon implementation, the first year of the study period in this case. This implies that certain combinations of the two types of strategies might be most effective in both reducing emissions early and then sustaining those reductions as time progresses.

The same graph for the East Central region, shown in Figure 5-11, provides a similar "ranking" of the various strategies, although again with differences in degree, consistent with observations made in the tradeoffs. Again, the nuclear strategy is the only strategy which reduces emissions below base year levels. While this reduction is not substantial, the rate of reduction is high in the final years of the study. The carbon tax does not provide the same stabilization of emissions as was observed in the Northeast. The same pattern of early year reductions in the system-oriented strategies and later year reductions in technology-oriented strategies is observed.

We can also examine the time series data for other emissions. Again, SO_2 is of particular interest. The SO_2 emissions for the base future in the Northeast region are displayed in Figure 5-12. The most striking feature here is that all strategies, including the base strategy, lead to a reduction in SO_2 emissions, primarily due to the presence of the IGCC as the default technology of choice. The most dramatic reductions are seen in the carbon

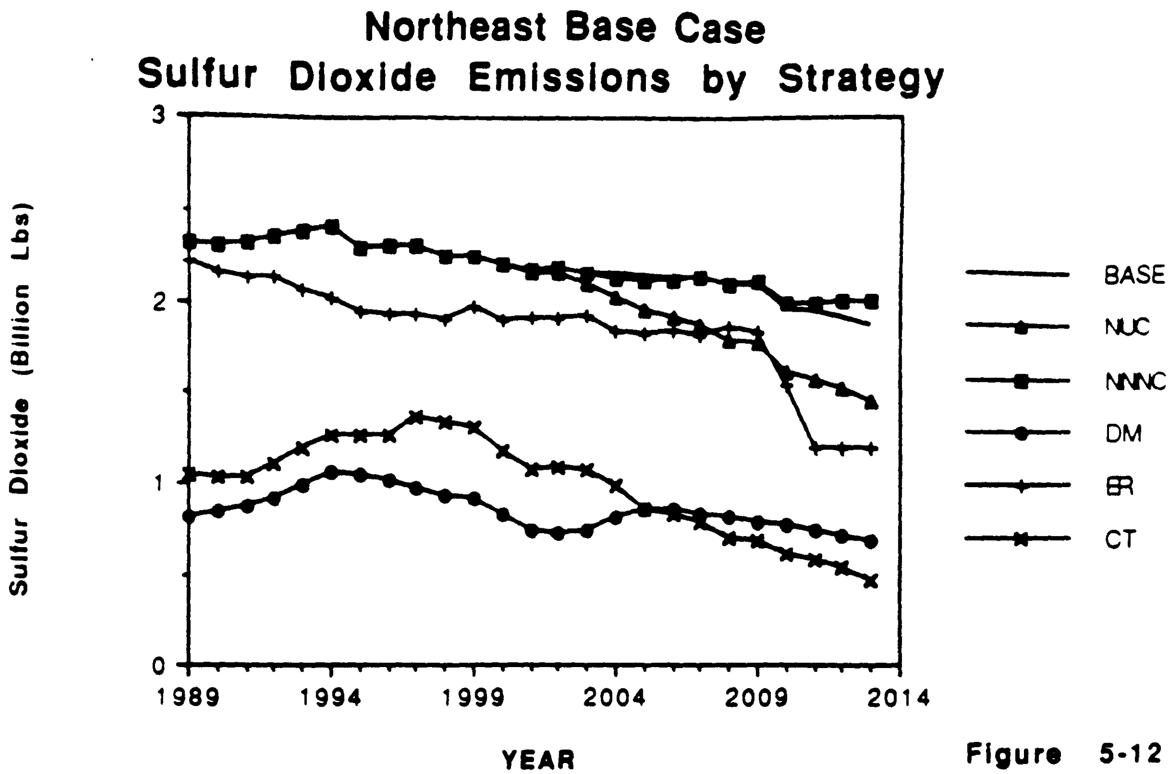

Figure 5-12

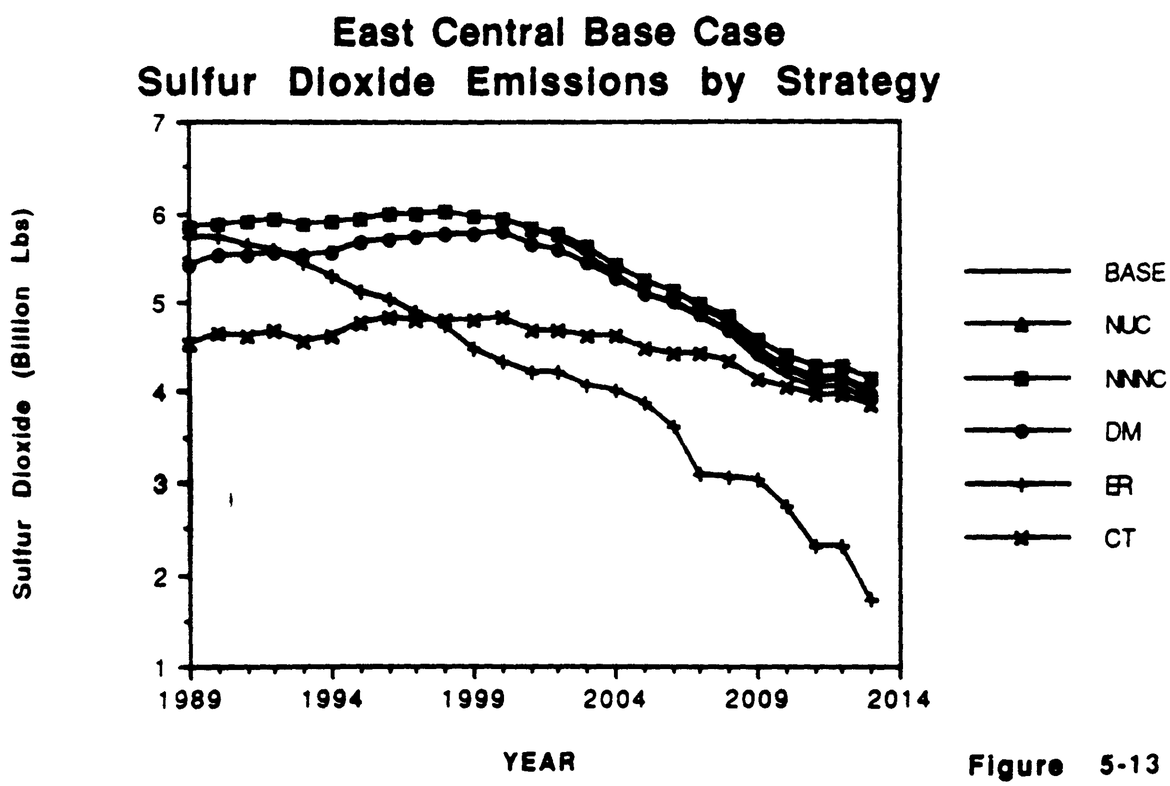

Figure 5-13

tax and dispatch modifier strategies, as was observed in the tradeoff curves. Note that while the dispatch modifier has a lower total amount of emissions, the rate of reduction in the later years of the study is greater with the carbon tax. Also of interest is the increase in emissions — relative to the base strategy — observed in the no nuclear / no coal strategy. In the absence of regulation which forces natural gas fired technologies into the baseload, additional gas-fired capacity will not displace high emissions capacity. In fact, the absence of new baseload capacity in this strategy forces the less efficient — and, thus, more polluting — existing coal capacity to generate more energy than they are required to produce in the base strategy. Emissions actually increase with the exclusive addition of low emissions technology.

Dramatic regional differences are shown in Figure 5-13, which illustrates the SO_2 emissions for the East Central region. Again, all strategies reduce emissions below their 1989 levels by the end of the study period, with none ever increasing substantially. The dispatch modifier, which was so effective in the Northeast, does little here, because there is so little diversity in the capacity mix. Also the carbon tax, which causes significant decreases when implemented — the base year — is not significantly more effective than other strategies at reducing emissions in later years, because of the incentive to avoid coal technologies, even if they are "clean coal" technologies. The most effective strategy is the early retirement strategy, which actually directly removes the most polluting capacity from the mix.

Several other emissions were tracked in the model. The first of these was methane (CH_4), another greenhouse gas. Methane emissions for the Northeast are shown in Figure 5-14. Again, the nuclear case is the

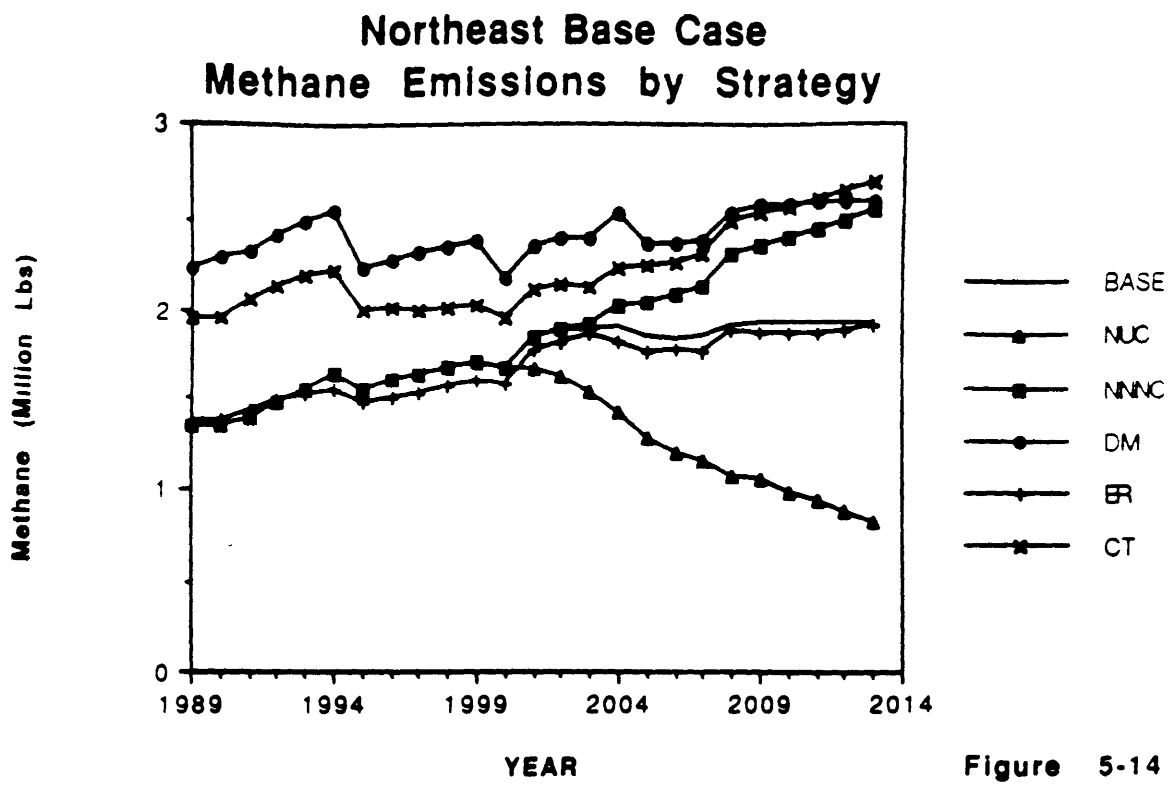

Figure 5-14

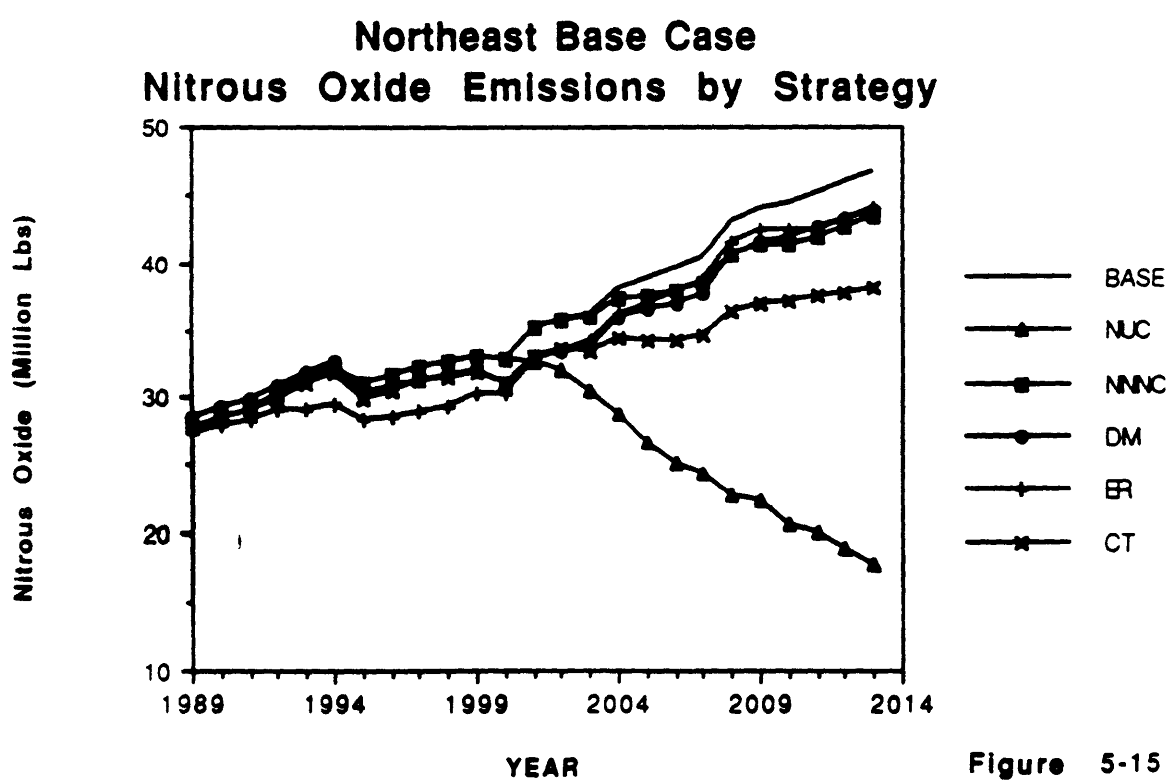

Figure 5-15

most effective at reducing methane, because it displaces high emissions capacity with zero emissions capacity. For the other strategies, however, the methane emissions patterns are virtually inverses of the carbon emissions patterns seen in Figure 5-10. Strategies with lower carbon emissions tended to use a significantly larger amount of natural gas (consisting primarily of methane) — which increases methane emissions due to incomplete combustion and leaks. Although none of the increases are very large, this is an important effect because methane is over twenty times more effective as a greenhouse gas, per molecule, than is CO_2[112]. At these emissions levels, however, it is calculated that positive effects of CO_2 decreases substantially outweigh the negative increases of CH_4 increases.

The other major greenhouse gas from fossil fuel combustion is nitrous oxide, N_2O. Nitrous oxide is nearly 200 times more effective as a greenhouse gas than CO_2, but its atmospheric levels are relatively small[113]. Also, fossil fuels are not a primary source of these emissions, as they are for CO_2 and CH_4[114]. The emissions of N_2O for the Northeast are shown in Figure 5-15. It is seen that N_2O emissions almost exactly track CO_2 emissions shown in Figure 5-10. Policies for the reduction of CO_2 appear to have similar desirable effects on nitrous oxide.

Two other non-greenhouse emissions were calculated — nitrogen oxides (NO_x), an acid rain precursor, and total suspended particulate (TSP), a local pollutant. The NO_x emissions for the Northeast are shown in Figure 5-16. NO_x emissions are reduced by all strategies, but less in the

112 Dickinson and Cicerone, 1986a; Ramanathan, et.al., 1985; Wang and Molnar, 1985.

113 Ibid.

114 The processes by which N_2O is produced in fossil fuel combustion is not well understood. Emissions here are based on very uncertain assumptions. Hill, et.al., 1984; Pierotti and Rasmussen, 1976; Crutzen, et.al., 1979; Campbell, 1986.

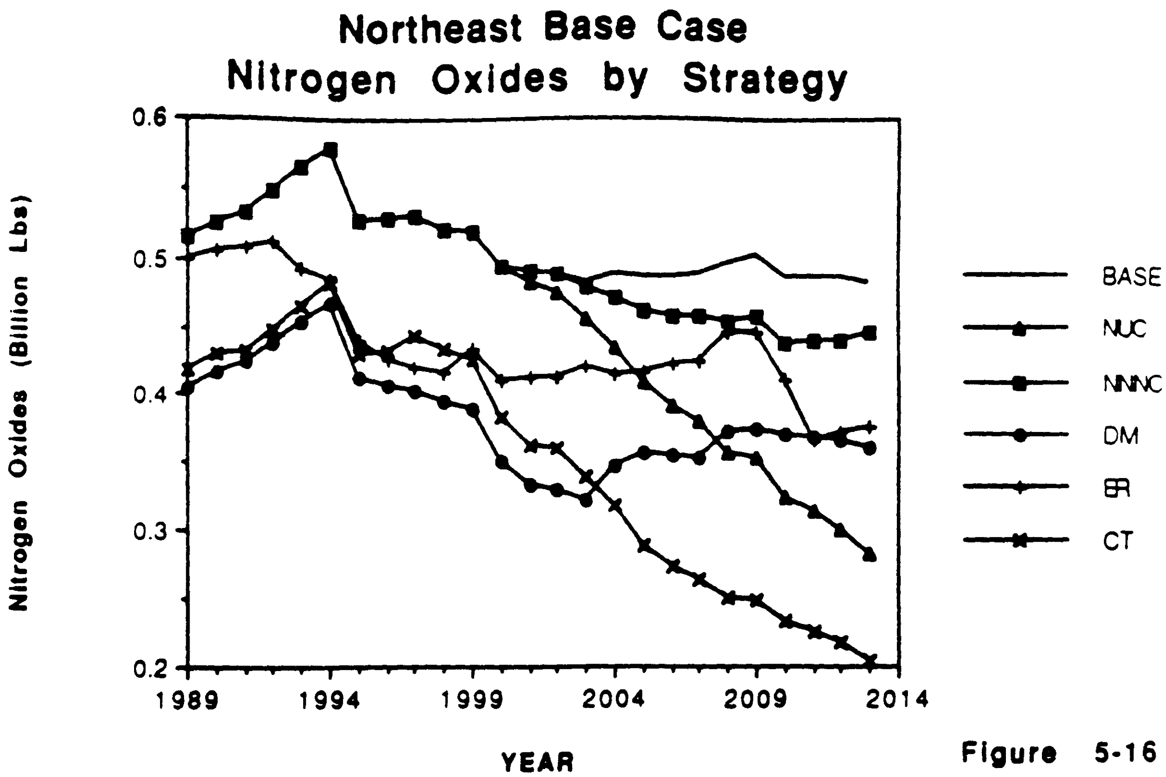

Figure 5-16

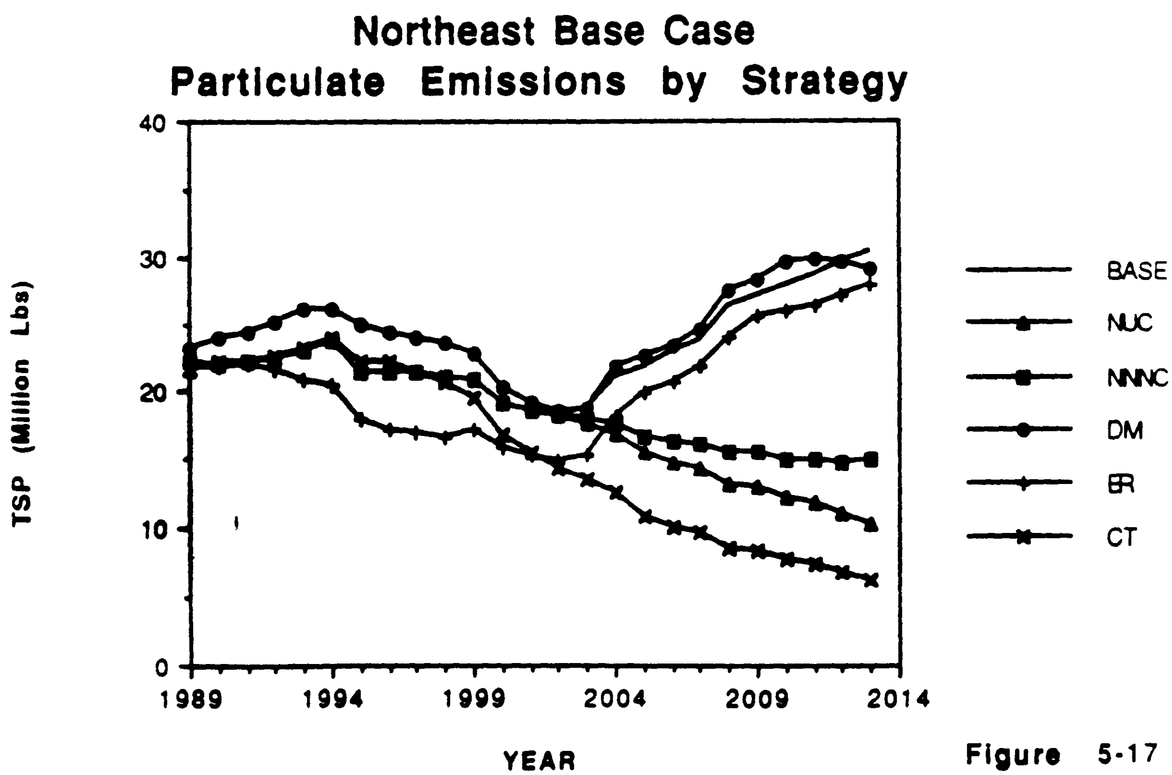

Figure 5-17

base strategy than the others. Since NO_x is a pollutant which is not fuel related — unlike CO_2 — CO_2 reduction policies have a somewhat indeterminant effect, although again the carbon tax and nuclear strategies seem to be the most effective. Particulate emissions ar shown in Figure 5-17. All strategies have essentially the same pattern of gradual reductions in the first 12-14 years of the study. Those strategies which then result in the construction of new coal capacity —IGCCs — begin to see an increase. The others continue the downward trend.

In chapter 3, we saw that the total emissions were a function of both demand (total GWH) and marginal emissions (emissions / GWH). Since demand-side price effects have not been included in this analysis, the primary effect of the strategies examined is on marginal emissions. This is seen in the illustrations of marginal carbon emissions (MCE) by strategy fro the Northeast (5-18) and East Central (5-19). The patterns are very similar to the total emissions curves of Figures 5-10 and 5-11. Note that in the East Central, the system-wide MCE is close to 300 tons C/GWH in the early years, essentially the same MCE as for a typical coal plant (Figure 3-2). Because all of the strategies decrease the share of coal capacity in the mix, or at least displace older coal with more efficient coal, the system MCE is held fairly steady or even drops. In the Northeast, the original MCE is much smaller — approximately 200 tons C/GWH — because of the diversity of energy sources. Because coal plays a role in almost all of the strategies, it is difficult to lower this value much more. Note, however, that the nuclear strategy reduces the MCE to below 100 tons C/GWH.

The marginal SO_2 emissions (MSE) for the two regions are shown in Figures 5-20 and 5-21. The patterns are almost exact mirrors of the total emissions graphs, with marginal emissions decreasing with all strategies in

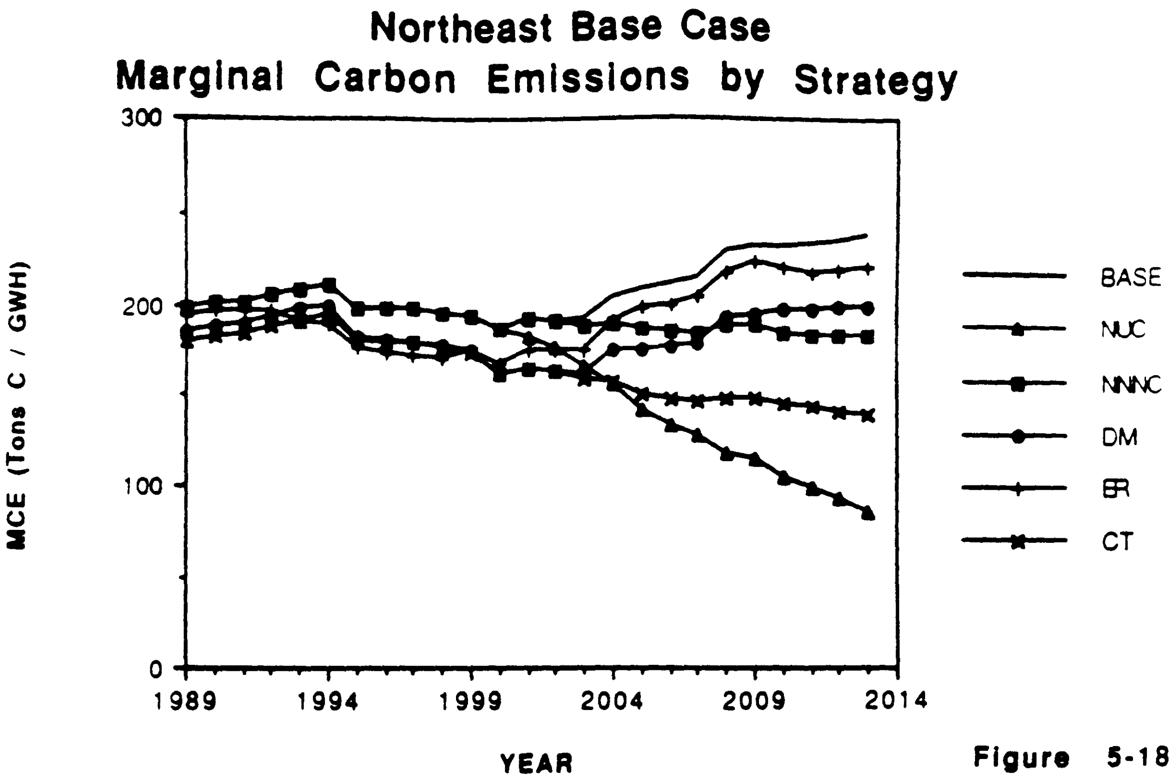

Figure 5-18

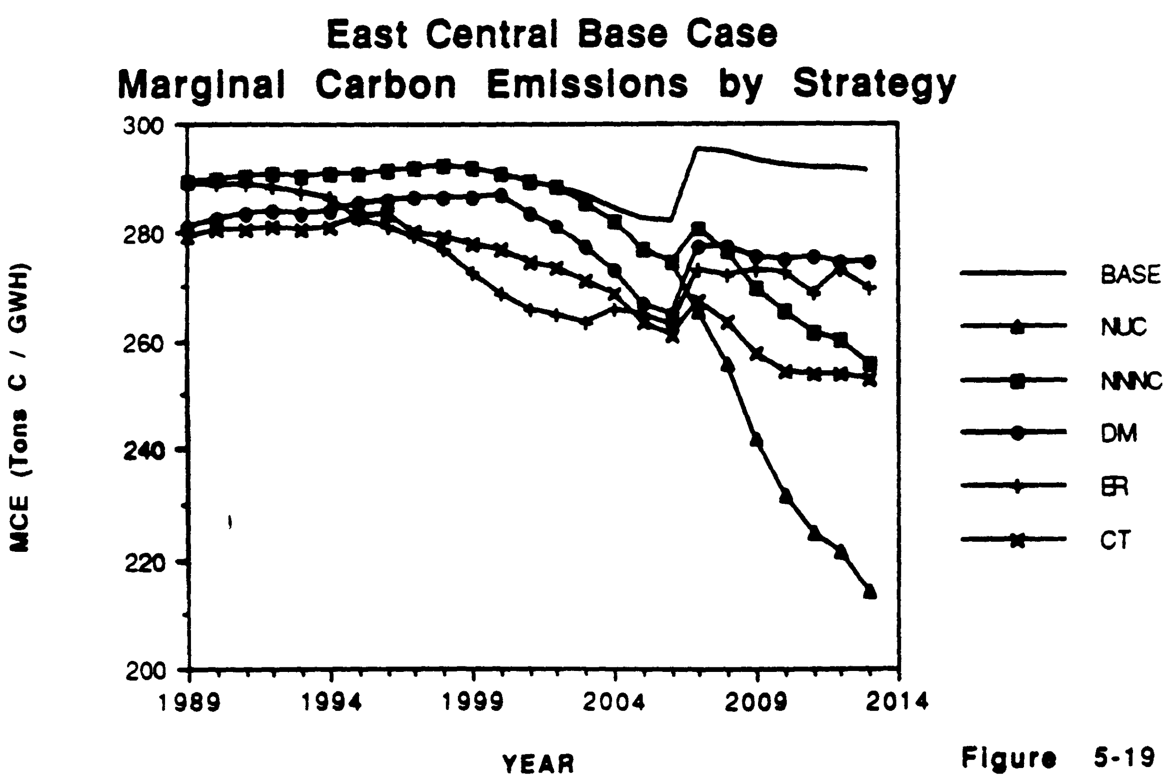

Figure 5-19

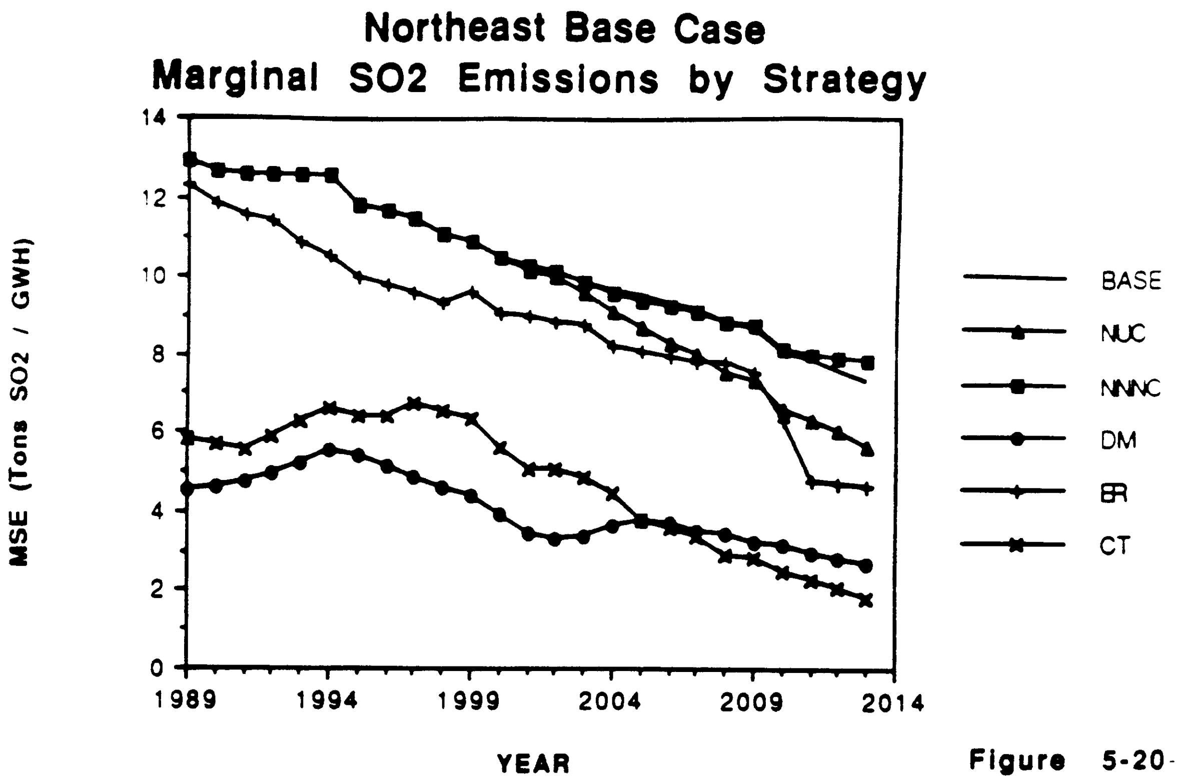

Figure 5-20

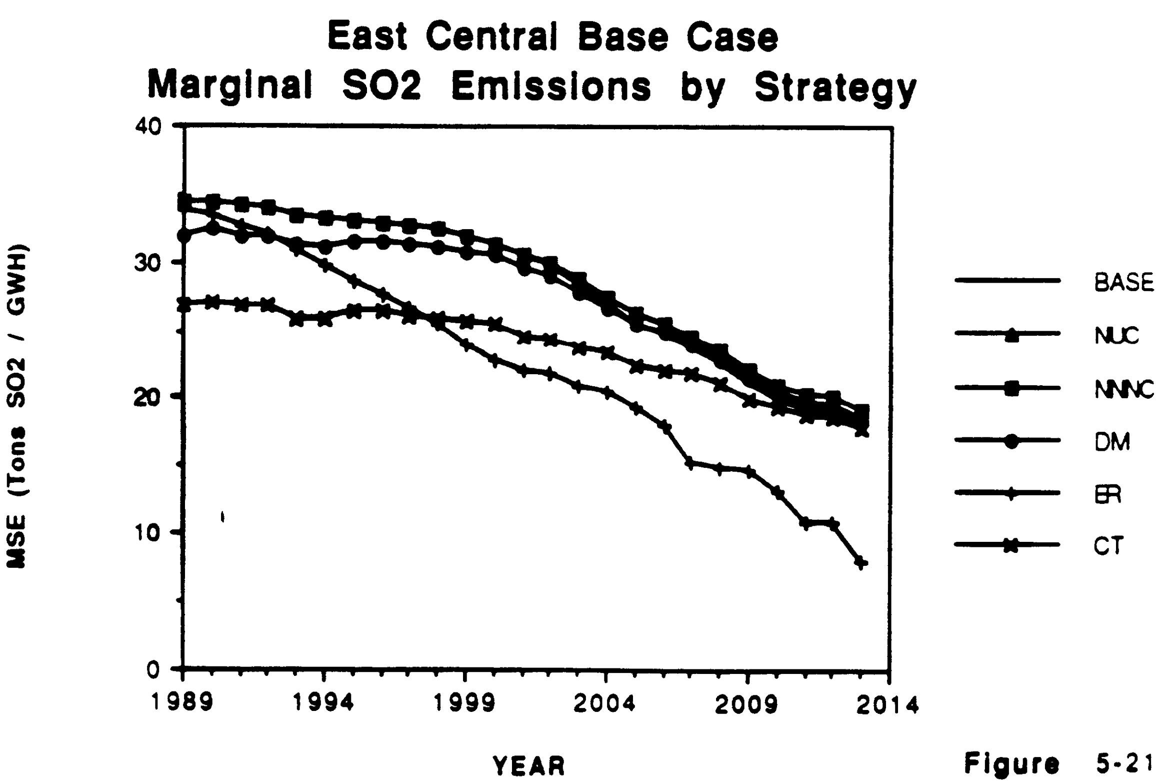

Figure 5-21

all regions. Note the regional differences. The system MSE in the Northeast is approximately 13 tons SO_2/GWH with the base strategy; the value is lowered to 3-9 tons SO_2/GWH by the final year, depending on the strategy chosen. The East Central system MSE is nearly 35 tons SO_2/GWH in the base year; the value is reduced to 20 tons SO_2/GWH by all strategies except early retirement, which reduces the value to below 10 tons SO_2/GWH.

A major determinant of the marginal emissions is the fuel which is used. We have already shown that, in the case of CO_2, carbon content in fuels is especially important, because there is little opportunity to prevent the carbon from being released as CO_2. The coal use streams are shown for the East Central region in Figure 5-22. Most strategies show an increase in coal use of approximately 20%, from 38-43 million tons per year to 42-52 tons per year. The only exception is the nuclear strategy which reduces coal use below 1989 levels only in the final years of the study. Note also that the base strategy shows the largest increase in coal use, as is expected.

In the two regions of study, the major alternative fuel is natural gas, since its emissions are significantly smaller. The natural gas use streams for the East Central are shown in Figure 5-23. Note that in the absence of CO_2 reduction strategies, natural gas use remains trivial over the entire study period, even with some GTCC construction in the base strategy. Note that the dispatch modifier strategy and the base strategy have *exactly the same amount of natural gas capacity.* With the dispatch modifier, natural gas use is approximately 50 million MCF[115] in the final years,

[115] A standard industry unit. One MCF = 1000 cubic feet, not 10^6.

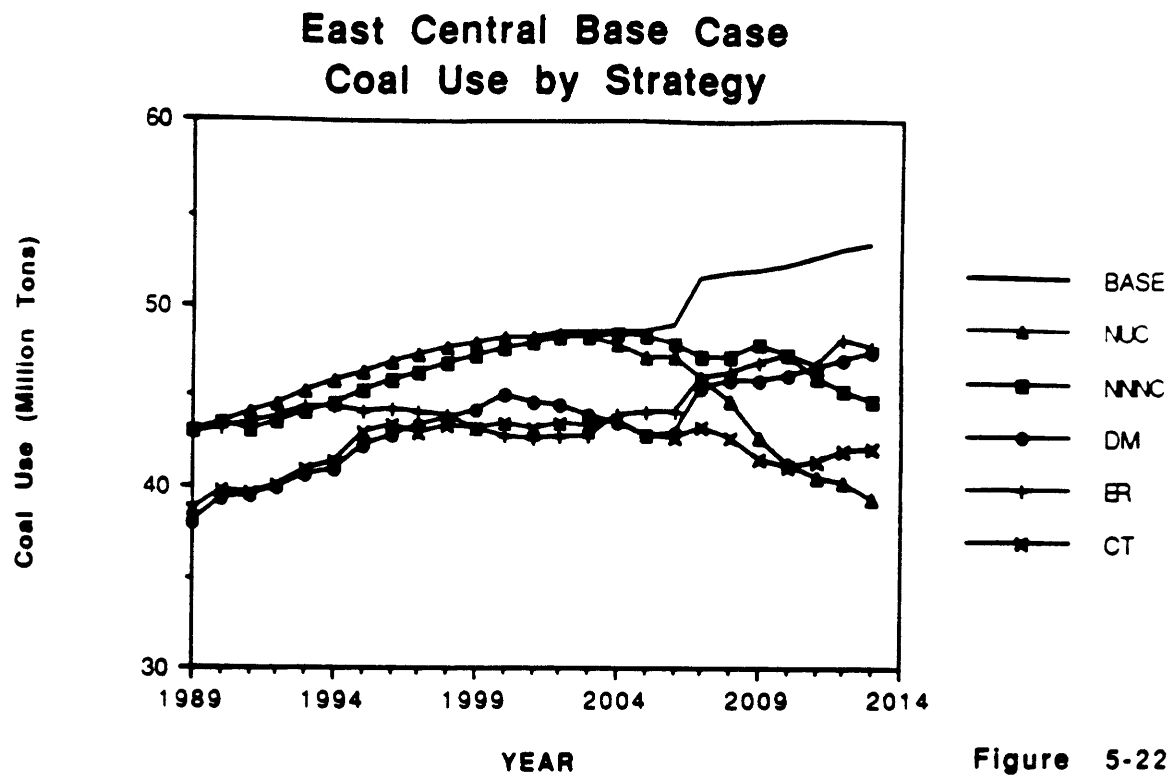

Figure 5-22

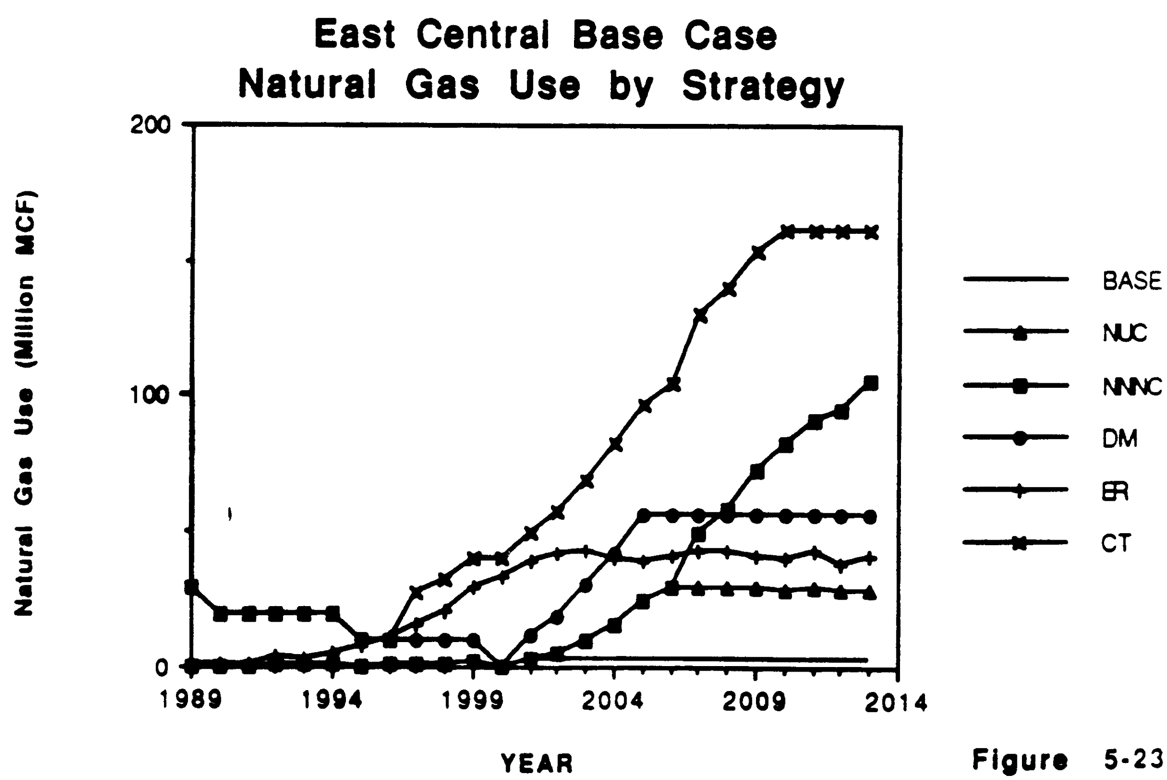

Figure 5-23

approximately two orders of magnitude greater than the base strategy, where the natural gas capacity is used only minimally. The no nuclear / no coal strategy uses approximately twice this amount and the carbon tax approximately three times this amount. Whether this amount of natural gas would be available, particularly at assumed prices, is discussed below.

Detailed performance of specific strategies

Now that we have seen some general comparisons across strategies, we will examine more closely the performance of each individual strategy. Expanded analyses of all environmental emissions, costs, fuel use, and shifts in energy generation source over time, are of particular interest. Only those data considered most useful will be discussed.

Base

In the Northeast region base future, the base strategy resulted in rapid increases in the emissions of carbon and total suspended particulate (TSP), with slight reductions in the levels of acid rain precursors — SO_2 and nitrogen oxides (NO_x). These emissions, normalized to 1989 levels, are shown in Figure 5-24[116]. The increases in carbon and TSP are due to the increased generation from coal capacity. Reductions in acid-rain precursors are due to the increased reliance on low-emissions coal capacity: IGCCs. If the base strategy instead relied on more conventional pulverized coal technology, with flue-gas desulfurization, all emissions would be higher than seen here.

116 The emissions of the other greenhouse gases from fossil fuels -- methane (CH_4) and nitrous oxide (N_2O) -- are not shown because their greenhouse contributions are minimal relative to carbon emissions. Except in the nuclear strategy, methane emissions tend to be inversely related to carbon emissions. On a normalized graph, nitrous oxide emissions are indistinguishable from carbon emissions.

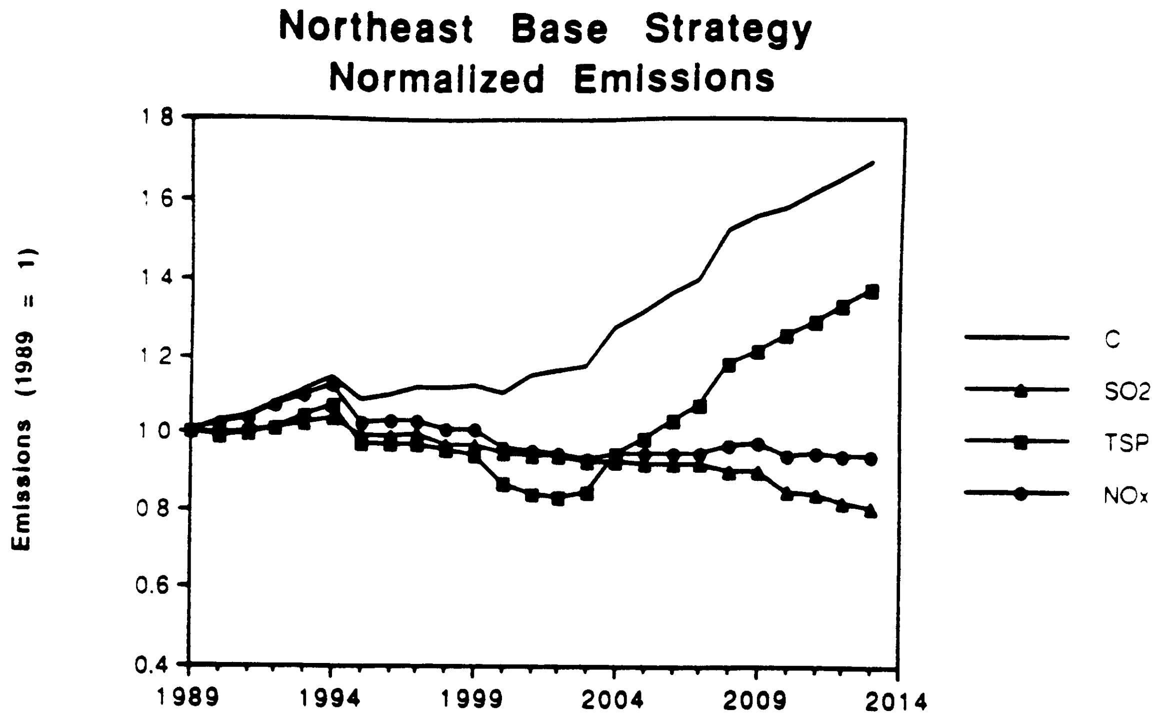

Figure 5-24

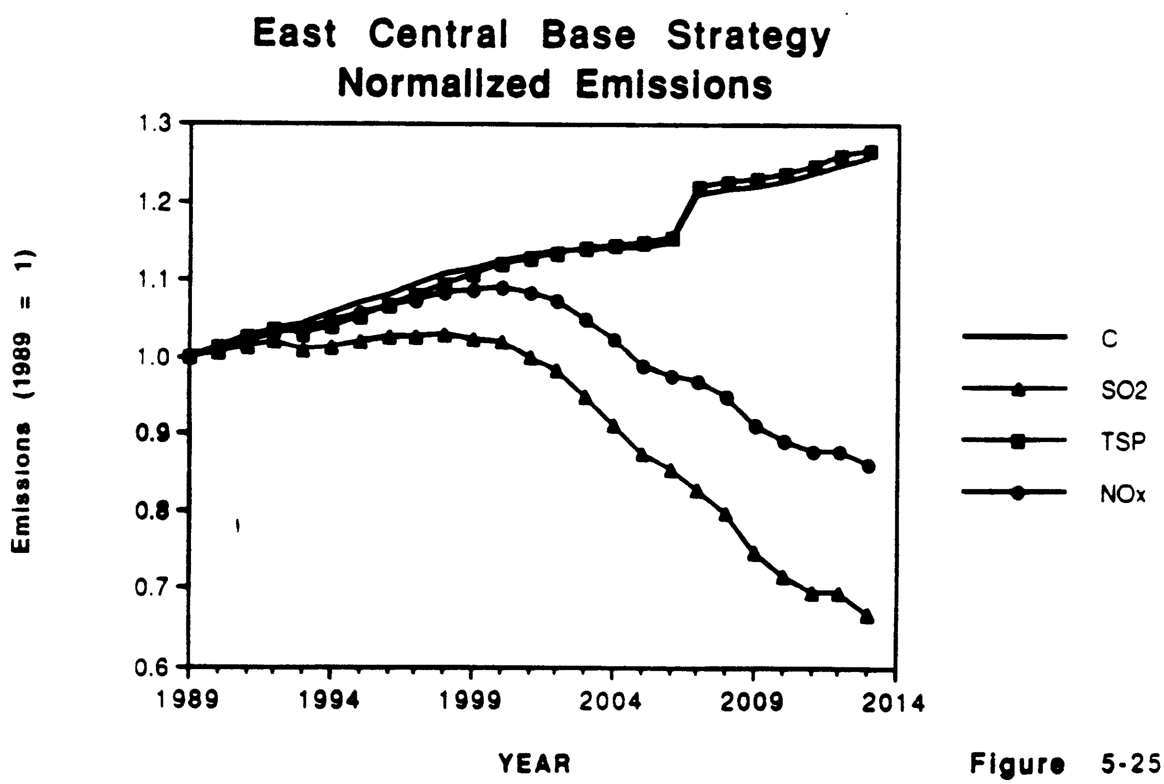

Figure 5-25

Results of the East Central region are similar. The emissions are shown in Figure 5-25. The lack of diversity in the capacity mix increases the dominant role of coal capacity, causing the tighter correlations seen here between carbon and TSP. Note that in both regions, carbon and TSP emissions are very closely correlated with total coal use, whereas SO_2 and NO_x are more closely tied to the amount of uncontrolled coal generation from old capacity, which decreases as new, efficient plants are brought on line.

Nuclear

Based on the assumptions of the study about the costs of nuclear power, the nuclear strategy is very attractive. While maintaining costs approximately at or below the level of the base case, the nuclear strategy results in decreases in all atmospheric emissions. Carbon emissions decrease — both relative to the base case and in absolute terms — while emissions of acid rain precursors are similar to those in the base case[117]. Nuclear is the only strategy which reduces all emissions in both regions regardless of the rate of demand growth. The emissions in the Northeast region base future are shown in Figure 5-26; East Central emissions are shown in Figure 5-27. The reductions are dramatic when compared to the base strategy levels (Figures 5-23 and 5-24).

Obviously, however, the issues of nuclear waste and nuclear safety were not taken into account in this formulation. While these issues are

[117] As discussed previously, the dominant effect in the emissions of acid rain precursors for a power system is the percentage of the system's energy which is generated by uncontrolled coal (and to a lesser extent oil) capacity. While the marginal SO_2 and NO_x emissions of nuclear power are well below those of IGCCs, both are orders of magnitude below the marginal emissions from existing uncontrolled capacity. Since each displaces a similar amount of generation from this older capacity, the overall acid rain emissions are similar between the two scenarios.

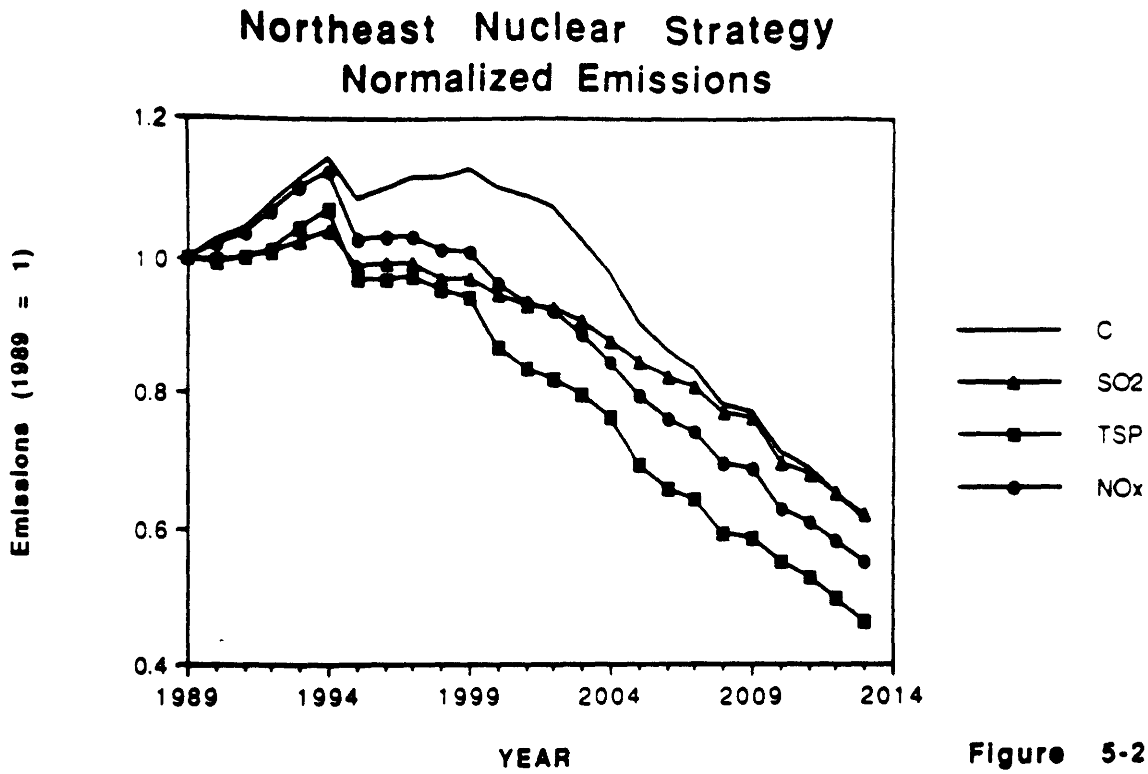

Figure 5-26

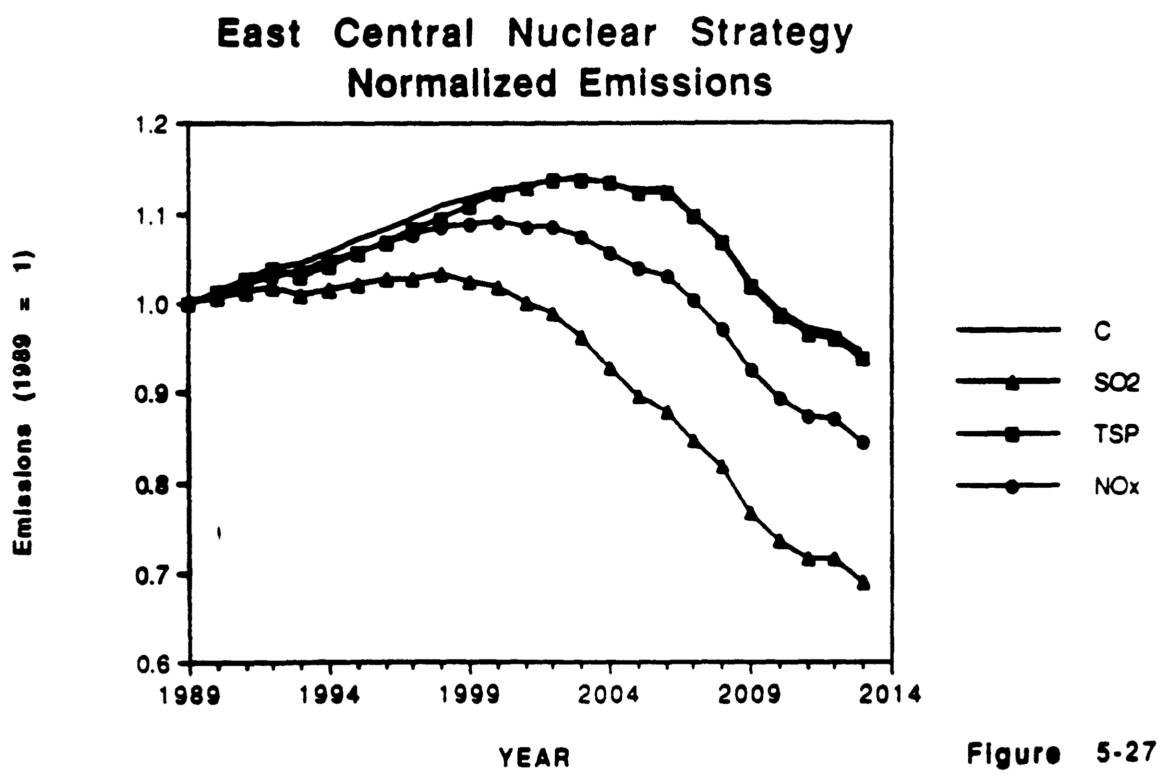

Figure 5-27

considered by many experts to be technologically controllable[118], recent experience has shown the general public to be highly skeptical — with substantial cause — of expert opinion in this area. Additionally, the capital cost estimates are probably optimistic, and certainly assume a more friendly regulatory environment. Due to the many other issues which surround nuclear power, the option is not as clearly optimal as this formulation may make it appear.

No Nuclear / No Coal

The no nuclear / no coal option was, somewhat counterintuitively, fairly ineffective at reducing emissions significantly below those of the base case. The emissions for the strategy are shown in Figure 5-28 (Northeast) and Figure 5-29 (East Central). The reason for this ineffectiveness is due to the nonlinear correlation between technology capacity and technology energy generation, discussed in Chapter 3. While the capacity for natural gas increases under this strategy, the energy generated is still small due to the high marginal costs of the technology. This high marginal cost forces two occurrences. First, the inefficient, high-emissions, baseload capacity is forced to generate more energy — and more environmental emissions — than required in the base strategy. Second, in later study years where the cost of gas is high, the system may actually to choose to let energy go unserved instead of operating a large amount of high cost generation, sacrificing system reliability in order to keep costs down. As a result, the costs of the no nuclear / no coal strategy are similar (in some cases even below) to those of the base case, but do not represent costs for similar

[118] Cohen, B.L., 1977; Lidsky, L.M., 1988.

Northeast No Nuclear / No Coal Strategy
Normalized Emissions

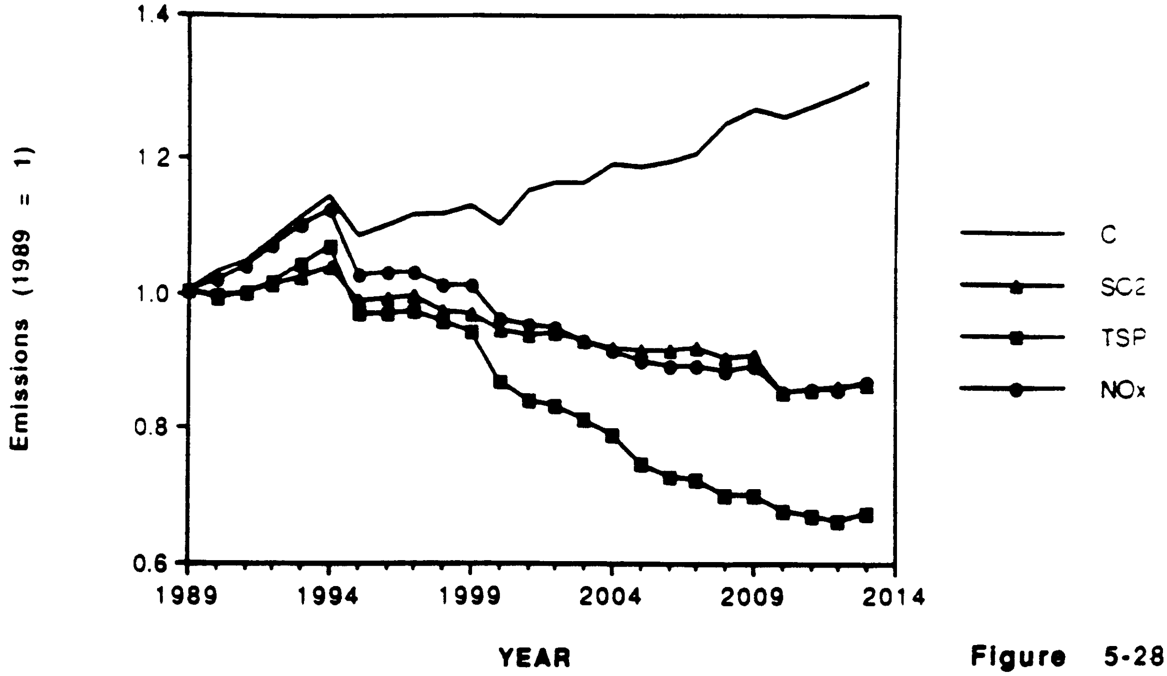

Figure 5-28

East Central No Nuclear / No Coal Strategy
Normalized Emissions

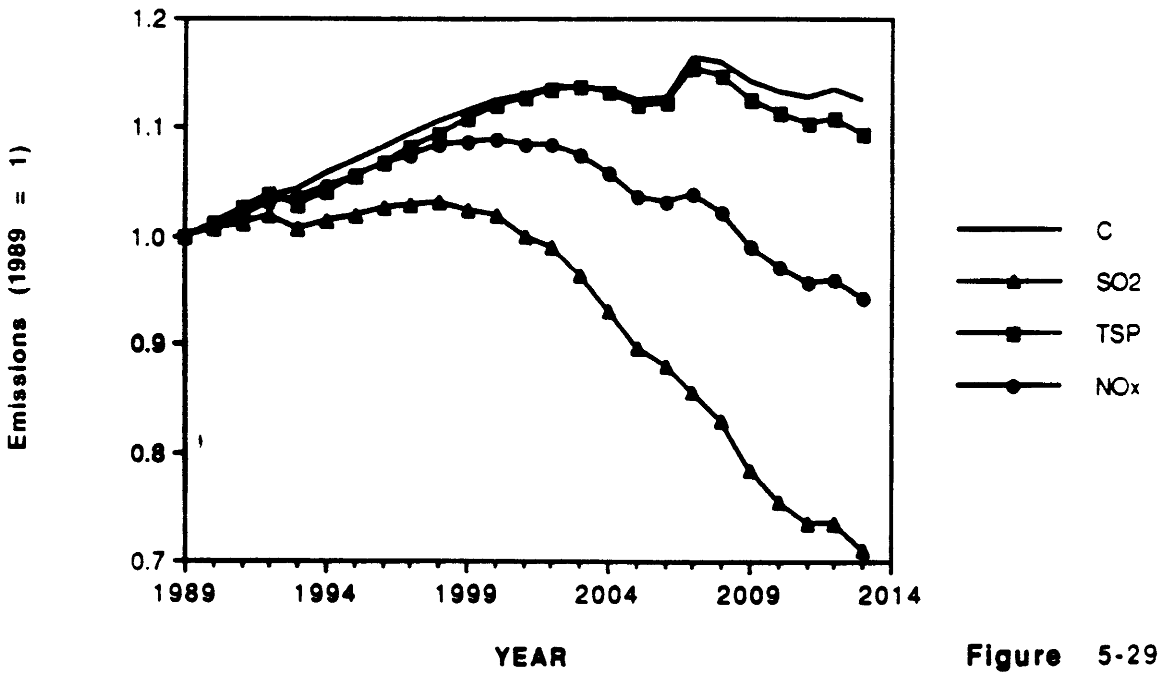

Figure 5-29

qualities of service. The impacts of natural gas — both on costs and on emissions — would be much greater if gas-fired capacity were forced to operate lower in the loading order[119].

This strategy is the first in which the availability of natural gas becomes an important question. In the East Central region, we saw that the final year natural gas use for the no nuclear / no coal strategy was approximately $100(10^9)$ cubic feet. If, for the purposes of an order-of-magnitude approximation, we assume the scale factor in the model is exactly four, and that the same amount of gas would be needed in the other five regions of the U.S., we arrive at an estimate of $2.4(10^{12})$ cubic feet needed for electricity in the final year. Natural gas consumption in the U.S was approximately $17(10^{12})$ cubic feet[120], implying — if consumption remains about the same in other sectors — an increase in nationwide demand for gas of approximately 15%. Whether this amount can be made available to electric utilities is unclear, although it does not seem unreasonably high.

Dispatch Modifier

The dispatch modifier approach, as modeled, is attractive for all emissions. The emissions for the Northeast base future are shown in Figure 5-30. Carbon reductions, relative to the base case are significant in all futures as would be expected. Additionally, the dispatch modifier approach is among the most effective in the reduction of SO_2 (see Figure

[119] Significantly lower gas prices or higher coal prices would have this effect naturally, as seen below in the carbon tax strategy.
[120] British Petroleum, 1988.

Northeast Dispatch Modifier Strategy
Normalized Emissions

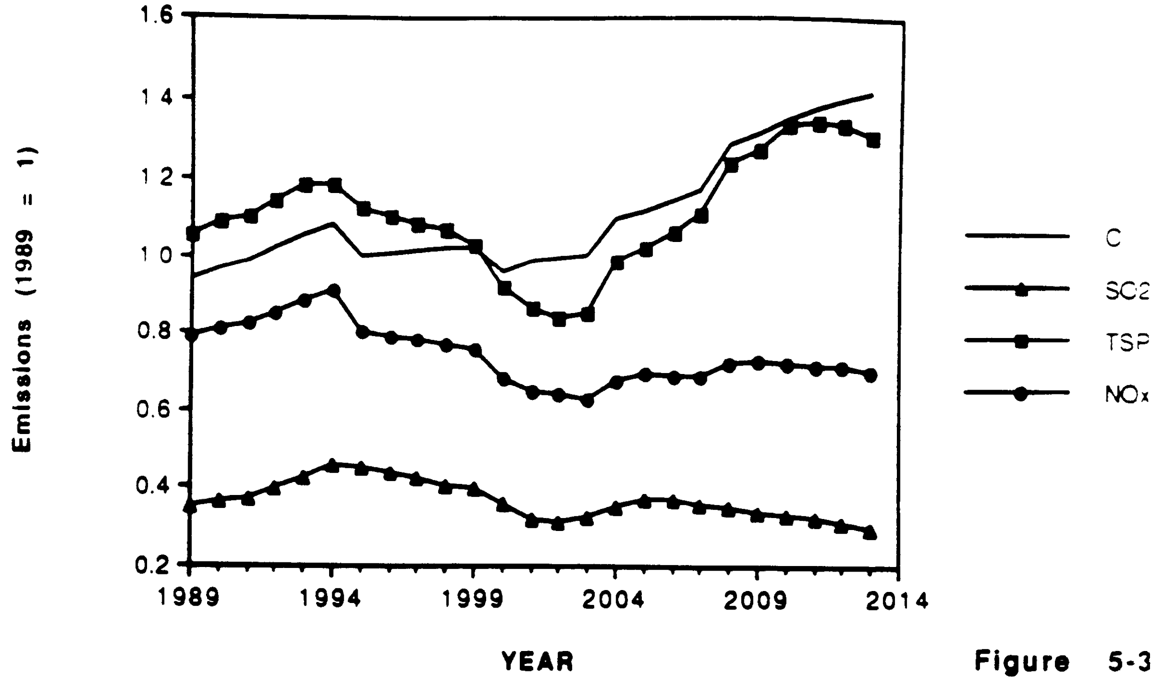

Figure 5-30

East Central Dispatch Modifier Strategy
Normalized Emissions

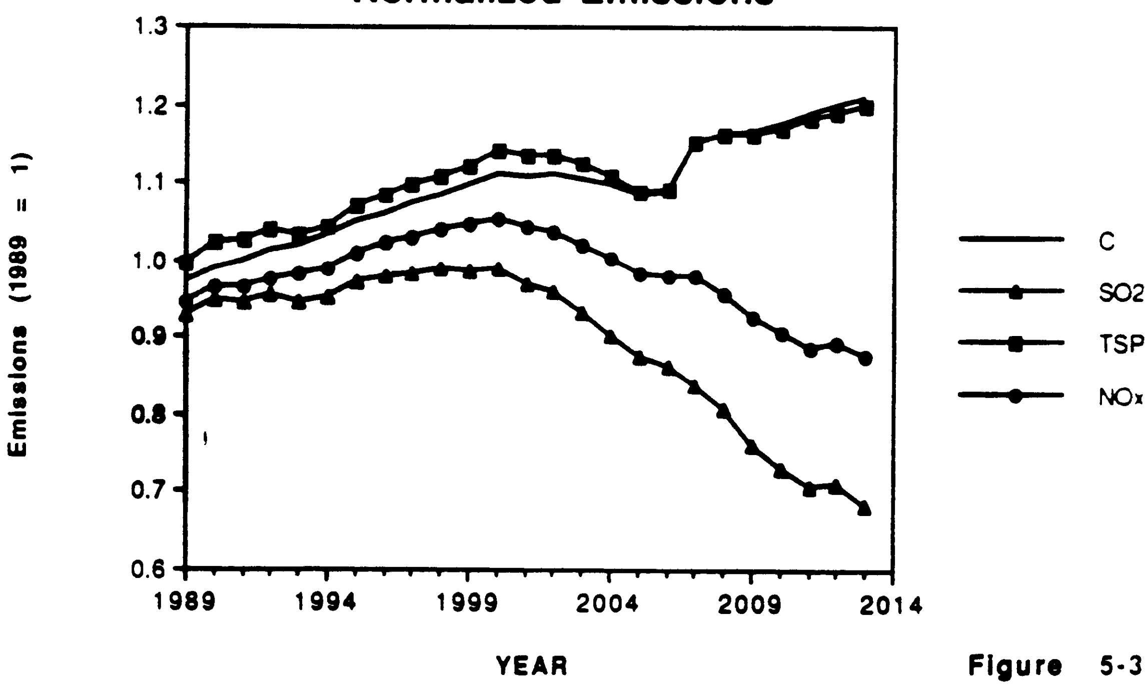

Figure 5-31

5-12, for example)[121]. As was seen in the tradeoff curves of Figures 5-1 and 5-2, these emissions gains come at significant cost in the Northeast.

The impacts of the dispatch modifier are not as great in the East Central region, as was seen in the tradeoffs of Figures 5-4, 5-5, and 5-6. Detailed emissions, very similar to the base strategy, are shown in Figure 5-31. Because coal is so dominant in the capacity mix, changes in the loading order have minimal impact on the overall pattern of energy generation. The natural gas and oil capacity which is available displaces some existing coal capacity. allowing for small reductions in overall emissions and small increases in cost. Clearly, the dispatch modifier has greater impact — both on costs and on emissions — when the capacity mix is more diverse. The natural gas demand of the dispatch modifier is of the same order as that for the no nuclear / no coal strategy — less in the East Central and more in the Northeast.

It must be reiterated that the dispatch modifier strategy is not optimized either against costs or carbon emissions, but is rather the cost-optimized base strategy expansion path dispatched with a least emissions criterion. For this strategy to be evaluated thoroughly, an emissions minimization algorithm must be substituted for the cost minimization algorithm. This would then create an environmentally optimal plan, as opposed to an economically optimal plan, as the starting point of the analysis for any given future. It should also be noted that while the strategy provides significant emissions reduction in the short run, it might be less ideal in the long term. Since the presence of high cost - low emissions capacity increases the costs of electricity generation, there is a

[121] Sulfur dioxide emissions would be even lower, and carbon emissions somewhat higher if an SO_2 dispatch were used.

strong economic incentive to minimize the amount of such capacity in the system. This could in turn actually increase emissions.

Early Retirement

The value of the early retirement option varies regionally and with the load growth of the system. Under all but the highest of the modeled growth scenarios in the Northeast, early retirement is the only option which dominates the base strategy in all attributes (See Figures 5-1, 5-2, and 5-3). That is, early retirement of old coal capacity leads to a reduction in emissions with a cost savings. The emissions gains are due to the replacement and displacement of inefficient, more polluting capacity with efficient, cleaner technologies. The gains are more significant in the early years of the study period than in the end. The emissions for the early retirement strategy in the Northeast base future are shown in Figure 5-32. In this particular future, the operating cost gains from efficiency outweigh the increased capital costs. We have seen, however, that this result does not hold for all futures (Figures 5-7, 5-8, and 5-9).

Because of the greater amount of coal capacity in the East Central region, the effects of the early retirement strategy are much greater than in the Northeast. The emissions are shown in Figure 5-33. These reductions are generally higher than seen for the same strategy in the Northeast. Costs, however, are also higher, as was observed in the tradeoffs. The sheer volume of the older coal capacity which must be retired in this strategy causes capital requirements which are too high to be completely offset by emissions improvements, even in relatively low growth futures.

Northeast Early Retirement Strategy
Normalized Emissions

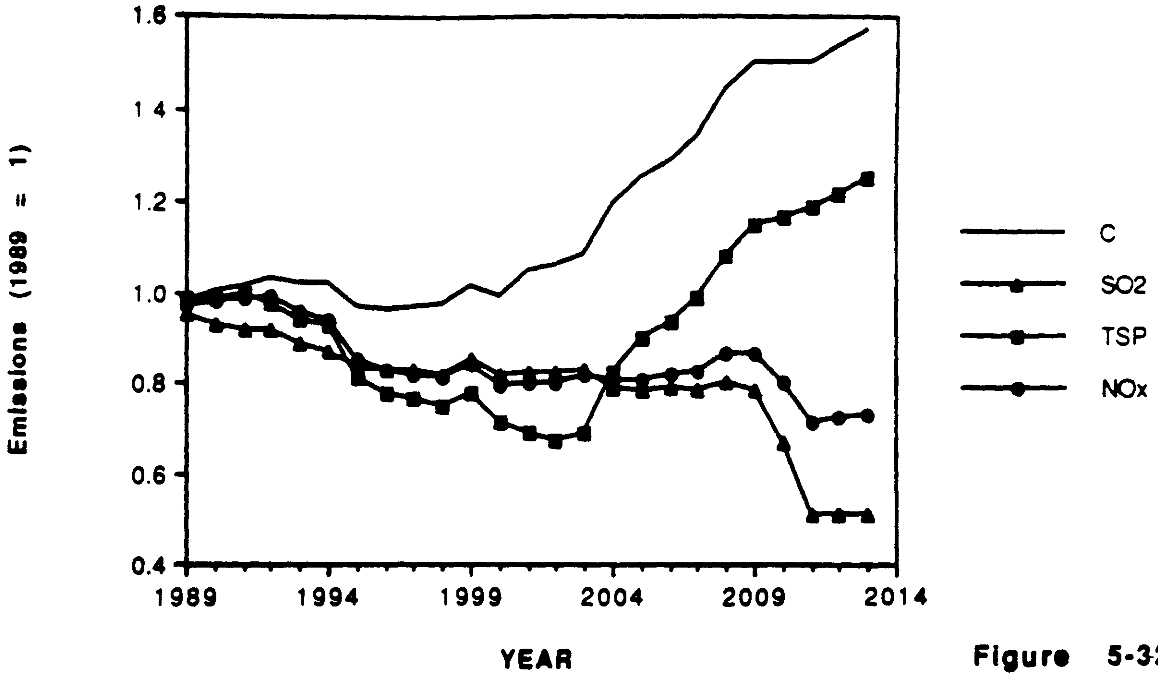

Figure 5-32

East Central Early Retirement Strategy
Normalized Emissions

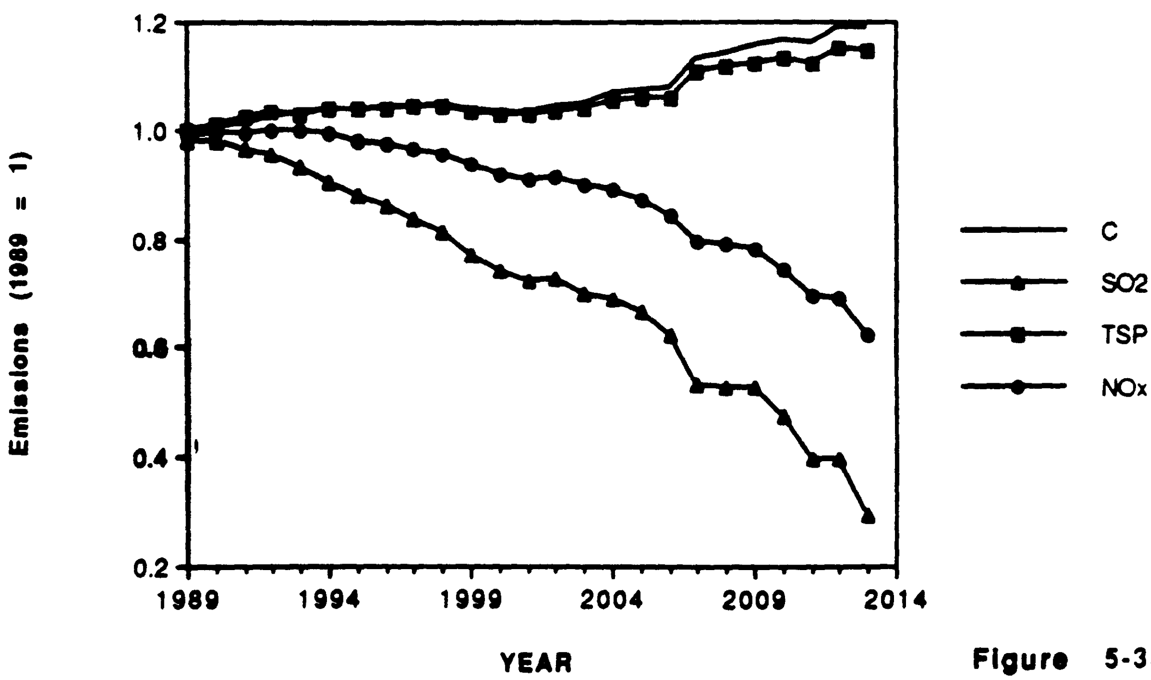

Figure 5-33

Carbon Tax

The carbon tax is consistently the highest cost alternative, as would be expected. It should be noted, however, that this is in reality a distributional effect, since significant revenues are generated which are available for other purposes or which might in some way be returned to customers. For instance, in the base future of the East Central region, the total net present value of the costs of electricity generation under the carbon tax strategy is $119 billion. Over this time period, however, a total tax revenue of $77 billion was created. The costs of the strategy *to society as a whole* are actually $42 billion, less than 10% more than the base case. Figure 5-34 illustrates the change in the original tradeoff curve which result if net costs to society are plotted instead of the costs of electricity generation. When viewed from this perspective, the carbon tax is much more attractive.

Additionally, the higher cost of electricity generation creates an incentive for demand reduction, an effect unaccounted for in this formulation. The price elasticity of demand is negative, meaning that demand will decrease with the increase in energy cost, but the current formulation is equivalent to an assumption that this elasticity is zero. This demand would certainly cause costs to be lower than stated and would probably lower emissions as well.

The environmental effects of the tax are substantial. The strategy allows for very high levels of sulfur dioxide reduction and for a stabilization of carbon emissions in many futures. It is the only non-nuclear case which is fairly robust in this regard. The emissions for the base future of both study regions are shown in Figures 5-35 and 5-36. Emissions reductions are primarily due to the strong incentive for the increased use

Carbon vs. Net Societal Cost (EC - Base Future)

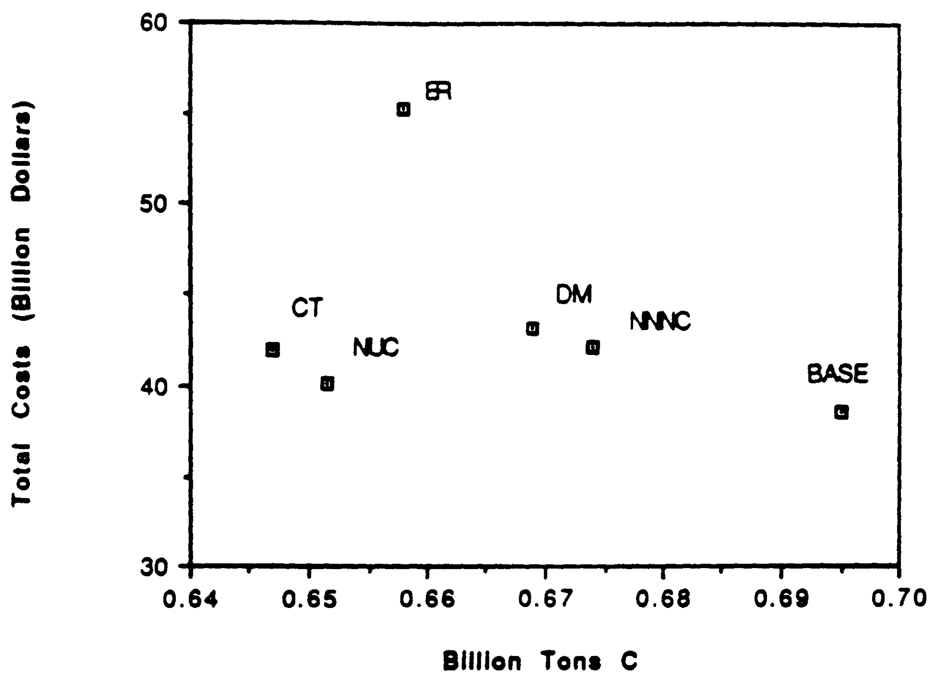

Figure 5-34

Northeast Carbon Tax Strategy
Normalized Emissions

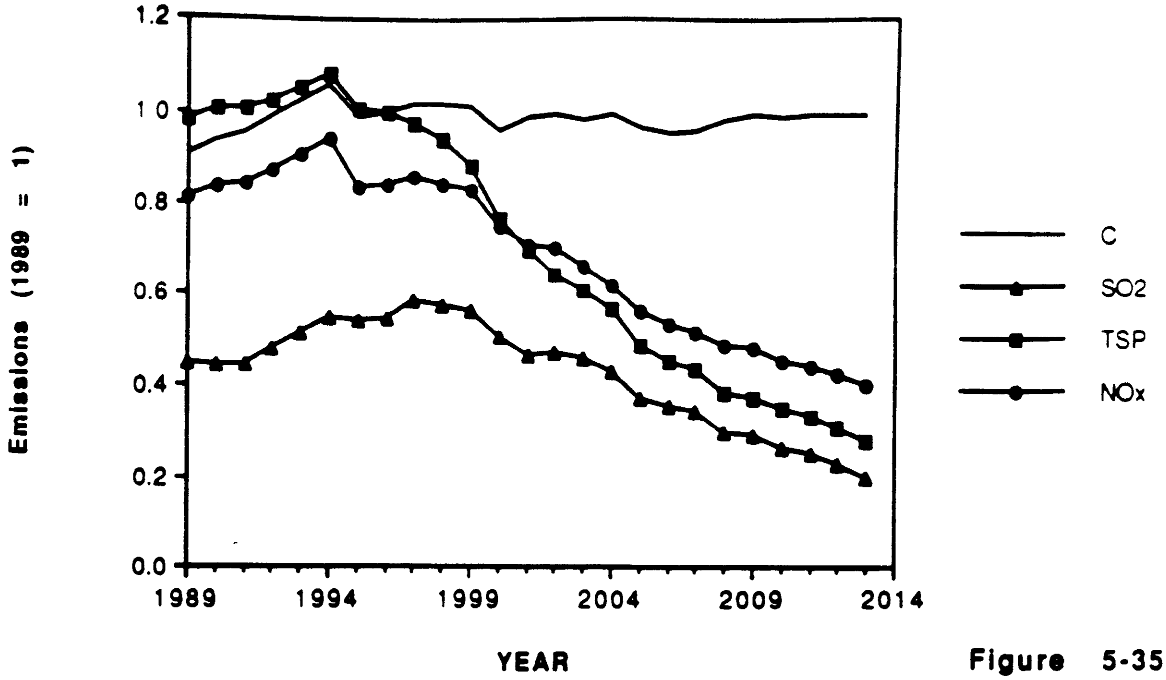

Figure 5-35

East Central Carbon Tax Strategy
Normalized Emissions

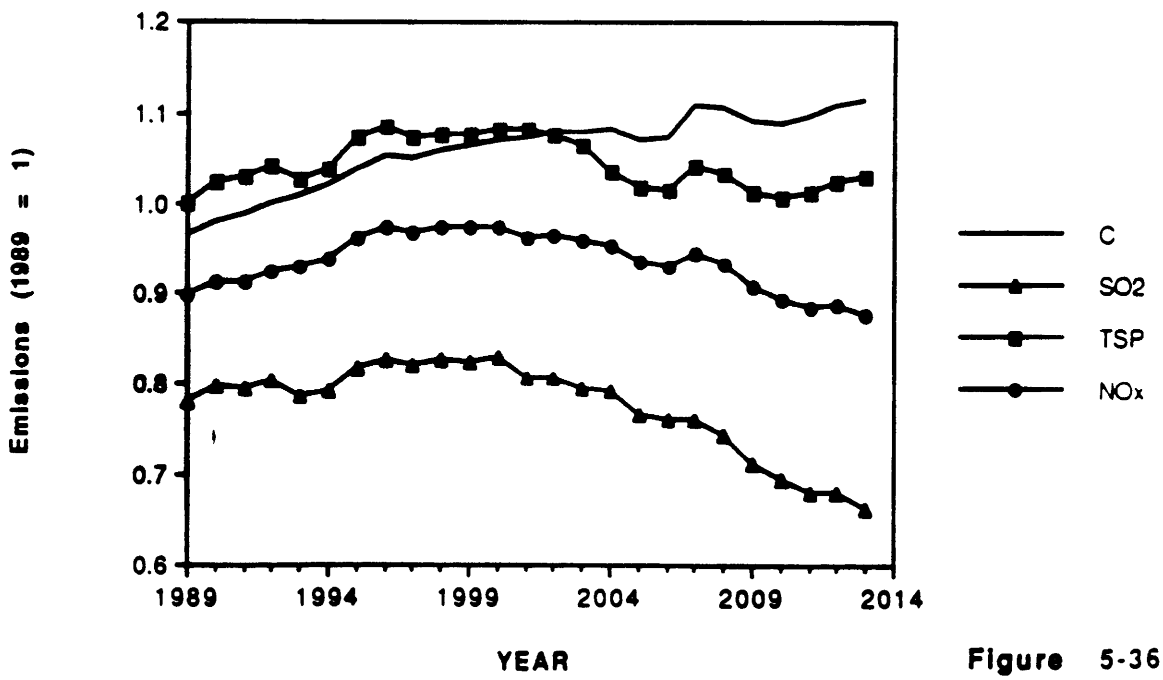

Figure 5-36

of natural gas which this strategy creates. The natural gas requirements of the carbon tax are the largest of all strategies. The implied effect on yearly national demand is an increase of approximately 20%, again large but not inconceivable. The strategy also creates strong incentives for the accelerated introduction of post-transition non-fossil alternatives. The primary disadvantage of the strategy lies in the unknown social impacts of such drastic economic measures as well as the likelihood of strong political resistance.

Effects of Load Growth

As suggested by the analysis of Chapter 3, the effects of load growth are not as straightforward as might be expected. Load growth increases the need for electricity generation, which, in isolation, leads to increased costs and emissions. Load growth also acts as a driver for new capacity additions, however. Since new capacity is generally more efficient than existing capacity, there are some countervailing reductions in costs and emissions. If the new capacity is an entirely different technology type — with significantly lower emissions — emissions might be reduced even further. The balance between these two effects differs according to strategy choice.

In the base strategy, load growth leads to the increased costs seen in the tradeoff curves. Carbon emissions increase steadily with higher load growth futures as seen in Figure 5-37. Because of the effect of IGCCs, however, SO_2 emissions are kept relatively stable in all but the very high growth future, in which emissions still decrease, as illustrated in Figure 5-38. In the nuclear strategy, the costs of electricity still rise with increased

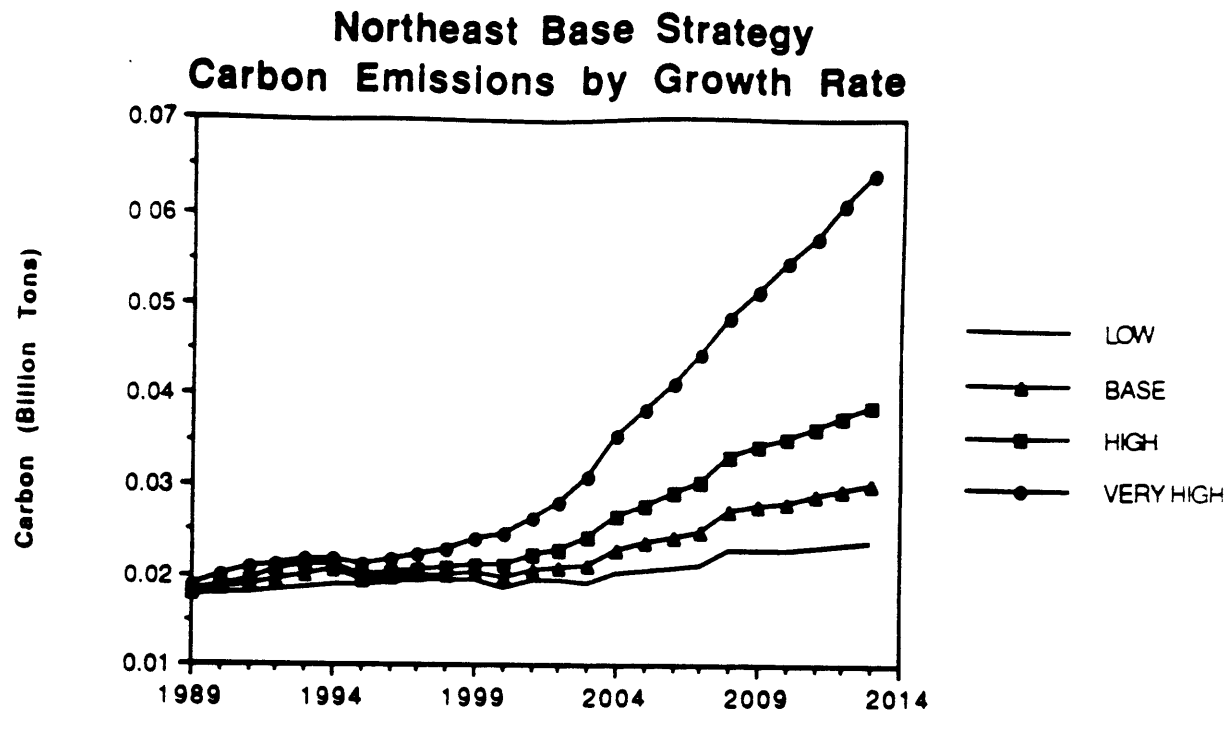

Figure 5-37

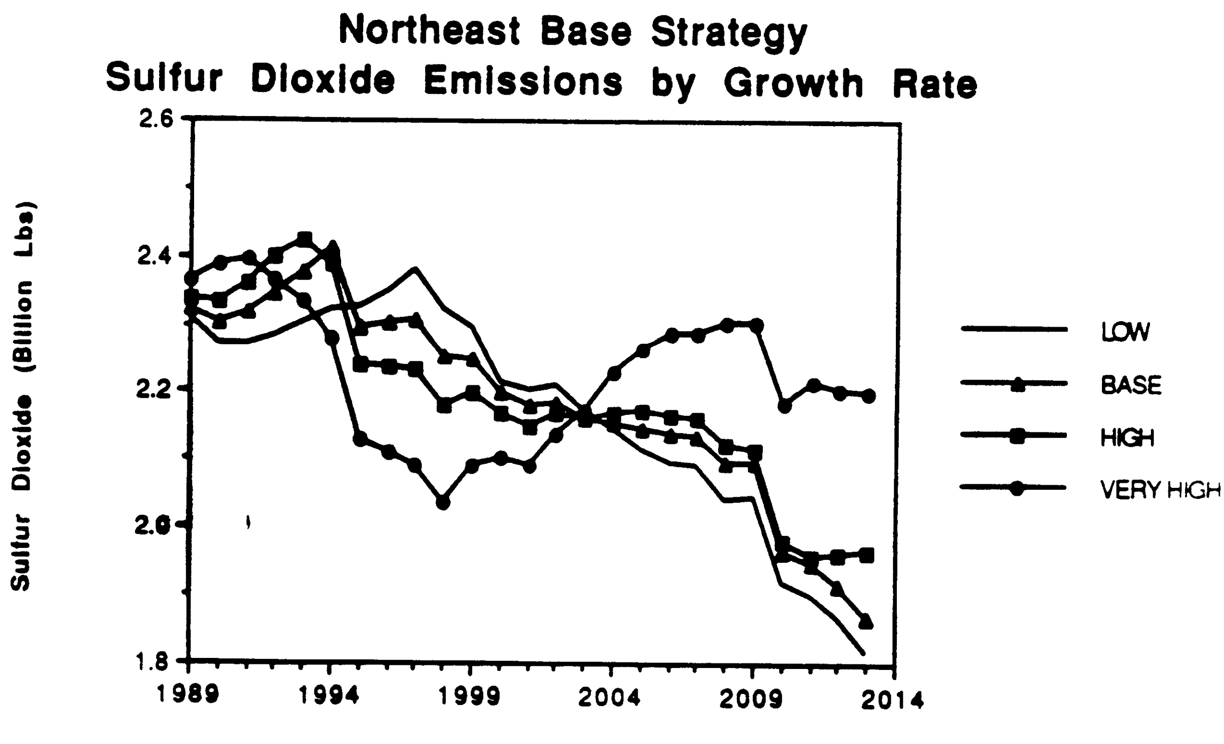

Figure 5-38

growth, but the effect on emissions is minimal, particularly in later study years. The carbon emissions are shown in Figure 5-39. The carbon tax shows somewhat mixed effects particularly in early study years (Figure 5-40). Carbon emissions increase with growth, but are still maintained approximately 50% below what would have been obtained with the base strategy in the highest growth case.

As expected, some strategies display a greater robustness with regard to load growth uncertainties. We can draw some conclusions about the effects of programmatic attempts to reduce load growth (conservation). First, the monetary benefits of conservation are substantial regardless of strategy. If the costs of programs to implement such reductions in load are less than these benefits, then conservation makes sense from a purely economic standpoint[122]. Environmentally, however, the benefits of conservation depend strongly on the supply-side strategy which is in place. There are cross-relations between supply-side and demand-side policies which can be synergistic if used properly or conflicting if misunderstood.

Effects of Fuel Price

The alternative fuel price uncertainty examined involved higher prices for both oil and natural gas than in in the base case. This naturally creates an incentive for greater use of other energy sources, particularly coal and, if available, nuclear. Since coal is used to a greater extent, carbon emissions are higher. This is seen in Figure 5-41, which compares the carbon emissions for the different fuel price futures for the base

122 This has been the case since 1973 and will probably continue to be the case at the margin, since the slack in this area is presently so great (Lovins, et.al., 1982; Goldemberg, et.al., 1987). Whether this holds true for very large amounts of conservation or for long periods of time remains to be seen.

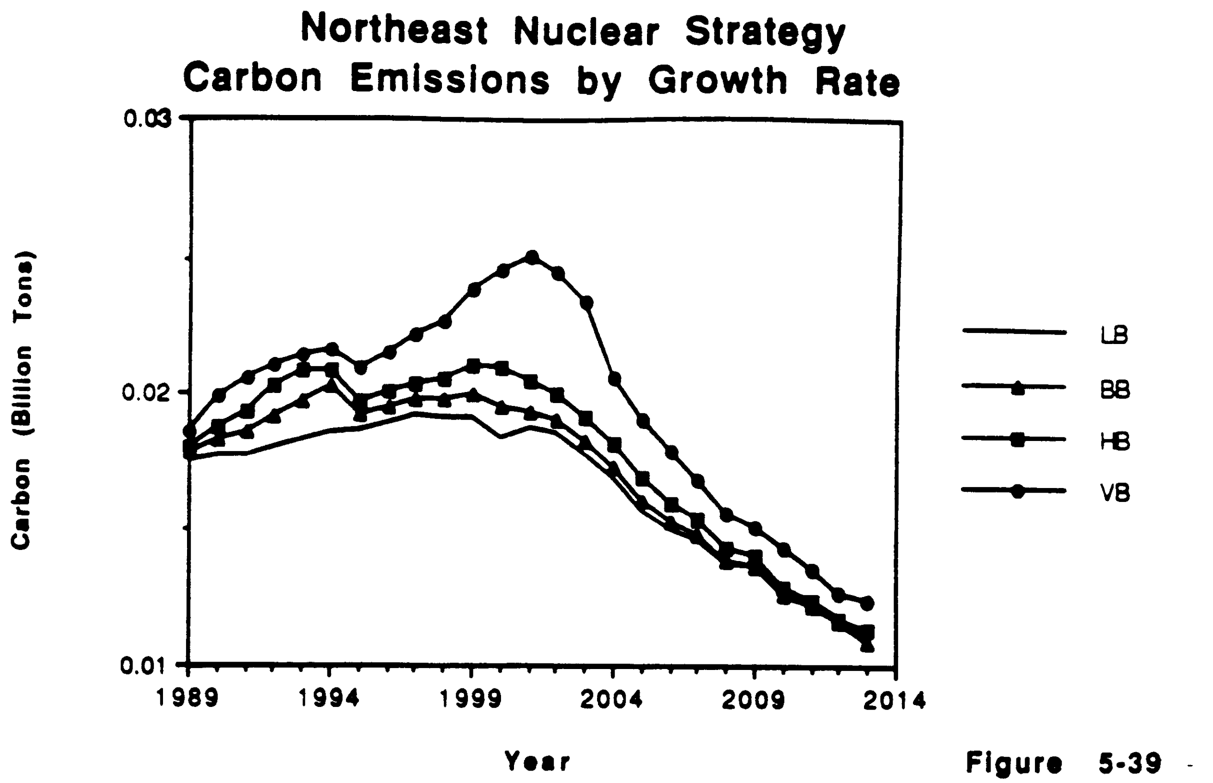

Figure 5-39

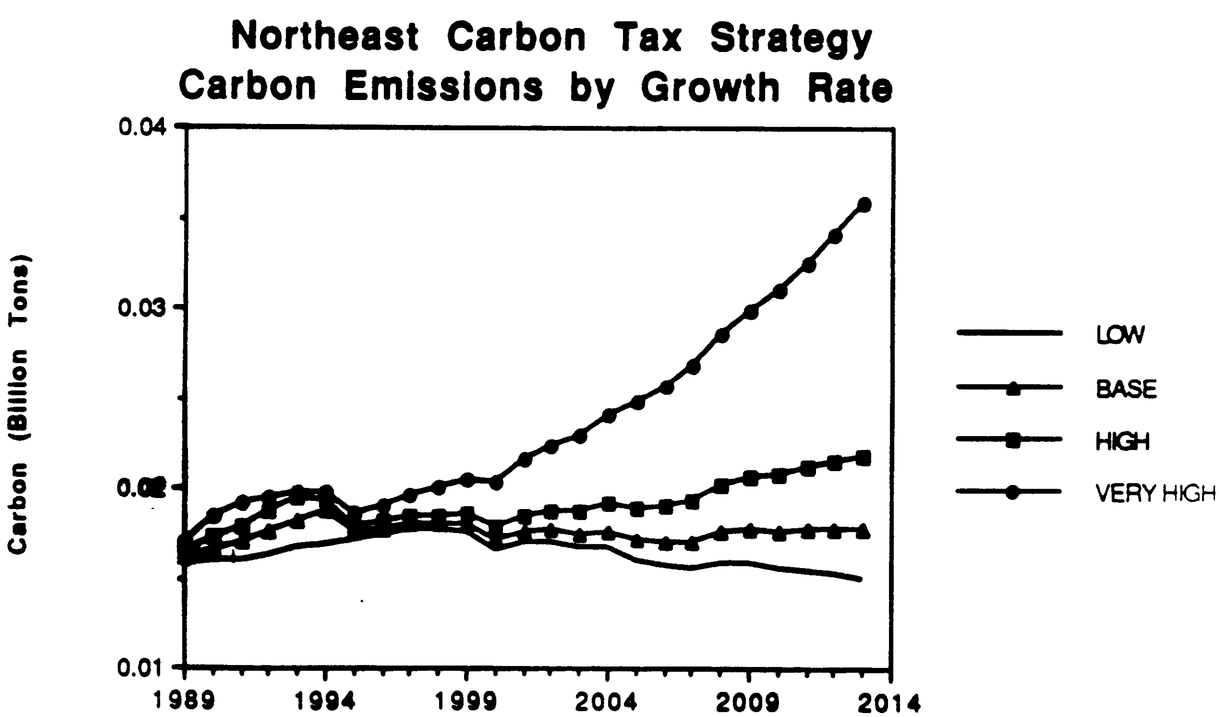

Figure 5-40

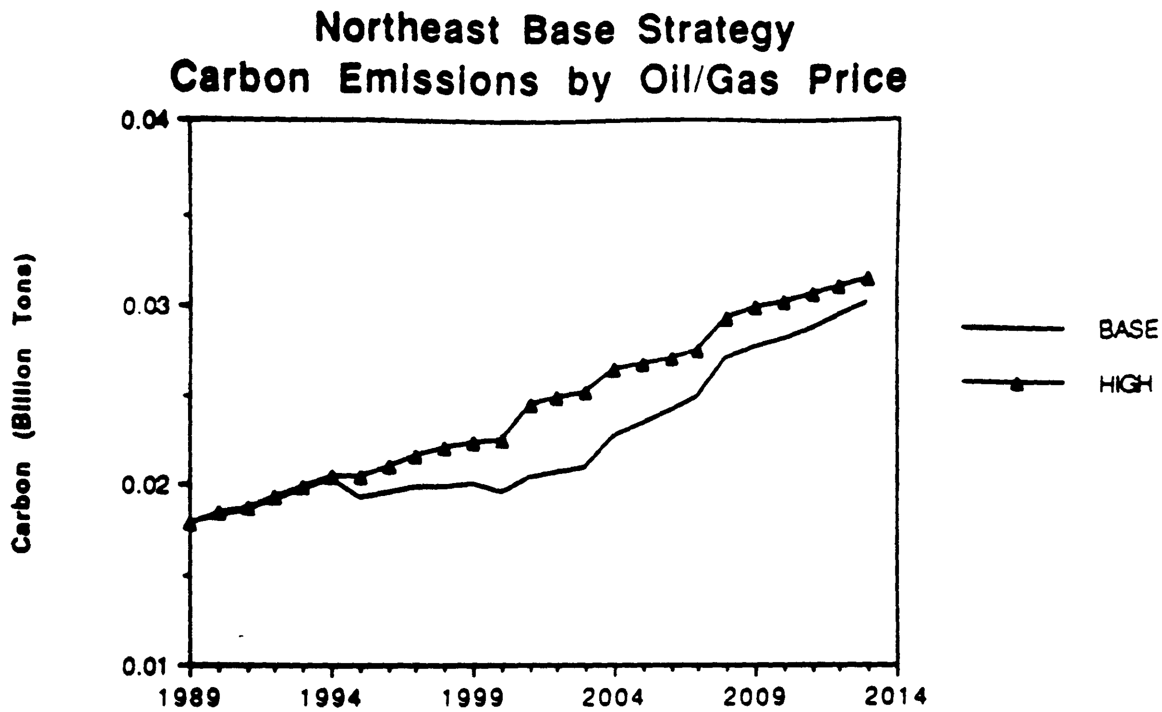

Figure 5-41

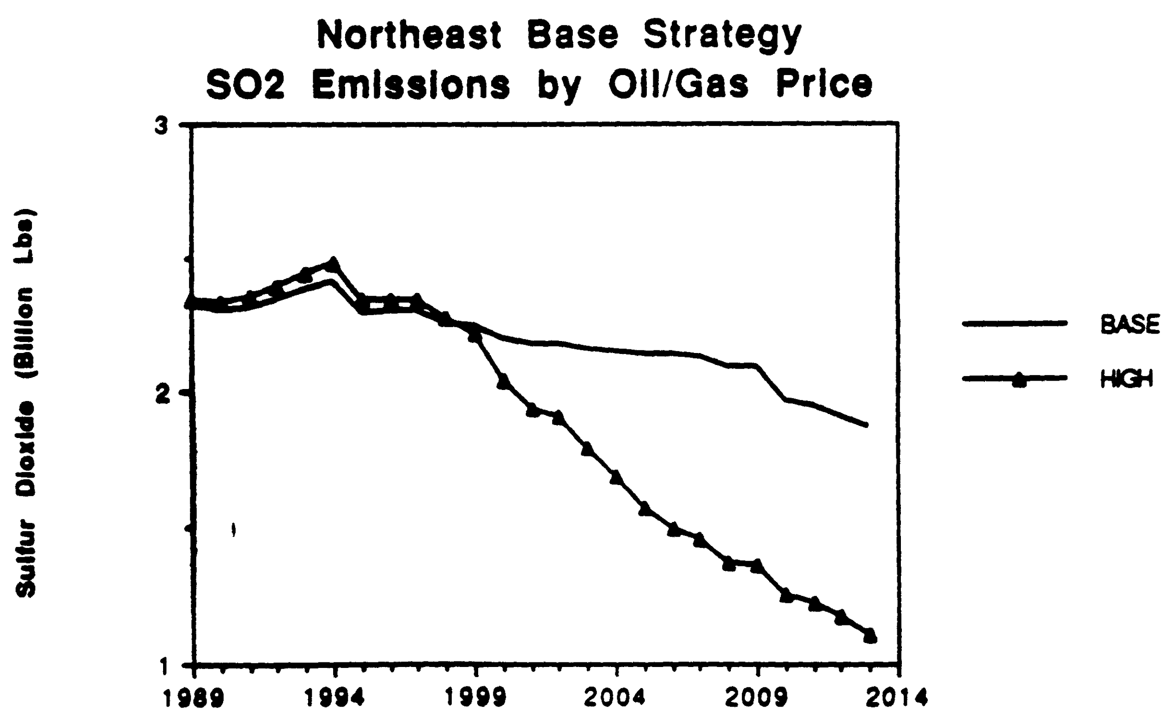

Figure 5-42

strategy, given base load growth. Since greater coal use is actually from IGCCs, which displace some higher emissions coal capacity, sulfur emissions are actually lower in the high fuel price future. This is shown in Figure 5-42.

Regional Differences

We have already seen many of the differing effects which can be caused by systemic differences in different regions. The primary differences between the Northeast and East Central region are caused by the differences in capacity mix, particularly the diversity of capacity mix[123]. The East Central dependence on coal makes immediate reductions in carbon emissions (such as those obtained from system-oriented policies like the dispatch modifier, early retirement, and carbon tax) more difficult and less cost effective than in the Northeast. On the other hand, technology-oriented strategies (such as the nuclear strategy), while slightly more costly than in the Northeast, have dramatic effects on carbon emissions when the technology begins to penetrate the capacity mix. Both regions show potential for large reductions in the emissions of acid rain precursors (at little or no cost) due to the presence of the IGCC and other "clean coal" options.

[123] This is driven by different levels of access to cheap coal and the different levels of public acceptance for the continued operation of coal-fired plants.

Chapter Six - Potential Strategies

Reasons for Strategy Success

Emissions reduction in the electric power sector can be accomplished through both demand and supply efforts. Demand side efforts are successful if they reduce the amount of electricity needed without overly suppressing the natural stimuli for supply side technological change. Supply side efforts are successful if large amounts of high emissions energy generation can be displaced by low emissions generation. Different policies will accomplish these goals to varying degrees, depending on the emissions which are of concern.

For the emission of primary focus here, CO_2, there are a few near-term supply-side technologies available for significant reduction: nuclear reactors, oil-fired GTCCs and gas-fired GTCCs. The nuclear alternative not only has zero emissions, but its ability to operate economically at baseload allows it to displace large amounts of the generation from older coal capacity. This brings about CO_2 reductions approximately equivalent to the percentage of base year coal generation which is no longer needed. The social and political problems with the option are substantial. The GTCC options have significantly lower emissions than typical existing coal capacity, but operation at baseload must be forced or induced through policy measures. The emissions reduction will be approximately one-third to two-thirds of the percentage of existing coal generation which is displaced. Increases in the usage of oil and gas will raise the cost of electricity generation, however. Additionally, there are likely to be limits to the availability of both of these fuels due to energy security concerns (oil) and possible resource scarcity (gas).

In the case of acid rain precursors, SO_2 and NO_x, the above technological options are augmented by three additional options: IGCCs pulverized coal with scrubbers, and fuel-switching to low-sulfur coal[124]. The IGCC is highly economical and displaces significant amounts of generation from existing coal capacity. This brings about reduction in SO_2 and NO_x emissions essentially equivalent to the percentage of original uncontrolled coal generation which has been displaced. Reductions in marginal CO_2 emissions of about 10% can be achieved, but are offset by any growth in overall generation from coal. The scrubber option is essentially effective in preventing a growth in the emissions of acid rain precursors, but not in displacing uncontrolled coal generation (due to higher costs). If scrubbers were installed on old coal plants as retrofits, SO_2 and NO_x emissions would be reduced approximately by the percentage of uncontrolled generation which was shifted to retrofits multiplied by the percentage effectiveness of the scrubbers (70%, 90%, etc.). Because of decreased efficiency, scrubbers will actually increase marginal CO_2 emissions by about 10%, with overall emissions again increasing with growth in overall coal-fired generation. Low-sulfur coal has similar effects. Oil- and gas-fired combined cycle generation and/or nuclear generation will reduce SO_2 emissions by a percentage virtuallv equivalent to the percentage of uncontrolled coal generation displaced, since the

124 AFBCs and PFBCs are not included here because they are unattractive when compared to the IGCC, which uses the same fuel feedstock at lower cost, higher efficiency, and lower emissions. Additionally, the IGCC is already being demonstrated commercially, whereas the AFBC lags several years in development.

marginal SO_2 emissions of these technologies are virtually zero relative to uncontrolled coal.

We can now define a general order of preference for technology choice, in the absence of cost or resource constraints. If our primary concern is the reduction of CO_2 emissions, the four classes of action we can take, in (approximate) descending order of effectiveness, are:

1) Increased use of zero-carbon baseload: This class of actions includes the use of nuclear, hydroelectric, and non-fossil renewable electricity generating technologies[125]. Some of these technologies do not naturally operate at baseload. Many also have severely limited resource bases in the regions studied (hydroelectric, solar, wind, etc.).

2) Increased use of low-carbon baseload: This class of actions consists primarily of the use of gas turbine combined cycle technologies, fired by oil or natural gas. These technologies do not normally operate at baseload. This class of actions would also include the use of CO_2 scrubbing technologies for coal-fired generation.

3) Reduced demand: The placement of demand reduction at this level in the list assumes that annual demand reduc-

[125] Biomass may be included in this category, since the lifetime net emissions of CO_2 into the atmosphere from biomass are zero. The CO_2 which is released from the burning of biomass is CO_2 which was removed from the atmosphere during the lifetime of the plants and would have been released upon the death and decay of the plant. Biomass generation does not "short-circuit" the natural carbon cycle as does the burning of fossil fuels.

tions are on the same order as natural annual growth in load (a few percent per year). In this case, the emissions reductions are at the margin and technology substitution is suppressed. If demand reduction were significantly more substantial, actually lowering the amount of baseload demand, this action could be higher in the list.

4) Increased use of low-carbon intermediate / peaking load or increased use of higher efficiency baseload: Low-carbon intermediate / peaking load is the natural position of oil- and natural gas-fired technologies. Higher efficiency baseload is the natural occurrence of new capacity construction — in this case, construction of IGCCs. Both of these effects are marginal and unlikely to offset any demand growth. The ranking of the two depends on numerous characteristics of the system.

Due to the technological differences outlined earlier, the ranking is essentially the same for the emissions of acid rain precursors, but the technologies which are included in each are somewhat different. For instance, if our concern is the reduction of SO_2, the actions we can take, in descending order of effectiveness (again in the absence of cost or resource constraints), are:

1) Use of zero-SO_2 or low-SO_2 baseload: The technologies which could be used in this class of action include nuclear, hydroelectric, renewables, oil- or gas-fired combined

cycles, IGCCs, FBCs, and scrubber-fitted coal plants. Essentially all technologies which can theoretically operate at baseload, except uncontrolled conventional coal-fired plants, may be used in this class of actions. Some of these technologies do not naturally operate at baseload, and many are resource-limited. Zero-SO_2 and low-SO_2 technologies are lumped here because the marginal emissions of these technologies are all significantly below those of uncontrolled coal (>90%). There is no equivalent here to the 30-70% reduction technologies available with carbon emissions[126].

2) Reduced demand: The same comments made for the CO_2 case apply here. It should be noted that due to the economical nature of many of the low-sulfur baseload options listed above, the tendency of demand reduction to stagnate technological substitution is a more important effect here than with the CO_2 case.

3) Increased use of low-sulfur intermediate and peaking load: This is the natural operating mode for oil- and gas-fired technologies, including conventional steam plants, combined cycles, and combustion turbines.

126 There are, in fact, several "clean coal" technologies, such as physical coal cleaning, which can provide reductions in this range. Due to the economic characteristics of these technologies, and the larger gains which can be reached through other technologies, these are not considered viable options.

The primary difference between approaches to the SO_2 problem and the CO_2 problem is the economics of reduced-emissions technologies. Several options are available for the economical accomplishment of the most important task: increased use of low-SO_2 baseload. With the exception of the nuclear case, which may not be politically viable, this is not the case with CO_2. Conservation then becomes increasingly important. Returning to the policy levers outlined in Chapter 3, it appears that economical supply-side options are likely to be more effective than demand-side options. In the absence of viable technologies for the implementation of these supply-side policies (which may be the case for CO_2 in the near term), demand-side options must then be pursued.

Strategy Evaluation

The various strategies which we have examined all accomplish these tasks to different degrees, and sometimes in unexpected ways. What, then, can be said about the "success" of the examined strategies, both overall and with reference to the above tasks? Additionally, what unevaluated attributes of these strategies will effect the ability to address these goals?

Base

There are two fundamental observations which can be made about emissions in the base strategy. First, in the case of CO_2, emissions should be expected to rise in the absence of policy attempts to minimize them, due primarily to the abundance of low-cost coal. It should be noted, however, that the standard modeling assumption of constant marginal CO_2 emissions (a constant value of carbon released per unit of energy obtained) does not apply, since conversion efficiency tends to increase over time. This effect occurs for economic reasons in the absence of regulatory policy, and is completely consistent with past experience[127]. This can be recognized as a minimally positive action, belonging to the least effective group listed above. The second observation concerns the emissions of acid rain precursors. Present legislation and economic incentives alone will cause SO_2 emissions to eventually decrease from present levels as old capacity retires and as new baseload demand is met by cleaner technology (an action belonging to the most effective SO_2-reduction group). It should be noted that this decrease will occur very gradually.

Even though the base strategy is unsuccessful in reducing CO_2 emissions and is slow in its successes with SO_2, the advantages are numerous. No political action is required, and utilities can continue to operate as they have in the past. Coal interests continue to be served, as coal continues to play a prominent, if not dominant, role in electricity generation. Since the U.S. is fairly self-sufficient in coal, there are few problems with excess reliance on foreign energy sources. The disadvantages are primarily environmental. If CO_2 is a real concern, this strategy is ineffective in addressing that concern. Emissions of particulates are also expected to rise. Finally, even the moderate growth rates of the study base cases indicate a need for substantial siting of new plants to begin in the next ten years. In the recent past, this has not been a trivial task, particular in high population density areas such as the Northeast. Finally, it should be noted that the

[127] Note that policies may inadvertently cause a decrease in efficiency. For instance, policies which mandate sulfur scrubbers can cause a discontinuity in the trend of efficiency improvements, although once implemented, the efficiency of the mandated technology can be expected to increase over time with operating experience.

costs for electricity generation in the next twenty-five years will be substantial, even in a cost-minimizing strategy such as this one.

Nuclear

The nuclear strategy is very attractive both economically and environmentally. While requiring expenditures essentially equivalent to the base strategy, the nuclear strategy significantly reduces CO_2 emissions, not only relative to the base, but relative to 1989 levels as well. The strategy's effectiveness is due to its ability to accomplish the most important emissions reduction task — increased use of zero-carbon baseload — relatively painlessly. That is, the economics of the nuclear option make extensive use, once constructed, automatic. Its technological characteristics lead to reduced emissions. Emissions of acid rain precursors are also reduced, although not significantly more than in the base case. This is due to the fact that the characteristics of IGCCs and nuclear reactors are essentially the same with regard to these emissions — low emissions and baseload operation capability.

Nuclear power has many other disadvantages, however. Nuclear waste disposal has never been adequately addressed. Feasible technical solutions, have been offered[128], but it is unclear that the political will exists to deal with this issue on a purely technical basis. Nuclear safety is a major concern. The reactors which were used in this study have advanced safety features, but are still based heavily on conventional light water reactor designs. While experts have often vociferously proclaimed the safety of nuclear power, particularly in comparison with other societal activities[129],

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128 Cohen, B.L., 1977.
129 Cohen, B.L., 1977; Sutton, C., 1988; Slovic, 1987.

the Three Mile Island and Chernobyl accidents may have forever soured the public's acceptance of these risk assessments. Additionally, it is unclear that the traditional formulation of risk[130] is truly as rational as it might appear in low probability - high consequence situations, such as those associated with nuclear power. Fear of nuclear proliferation is also a major concern, particularly if we begin to look at nuclear power as an option throughout the world. Since this issue is essentially beyond any feasible technical control, this is the issue which has even the "experts" worried[131]. It should finally be said that all of these issues will be barriers to any further use of nuclear power. The feasibility of a policy which calls for massive nuclearization instead of coal-fired capacity is even lower.

The public acceptance of nuclear power and a more consistent regulatory environment are essentially an assumption of the nuclear option in this study. Without these preexisting conditions, utilities are unlikely to invest further in nuclear power. With these conditions, the costs are likely to be very close to those assumed in the study. If the capital costs of nuclear power are more in line with recent experience (two to three times larger than assumed here) the nuclear option becomes less of a dominant one, but still within the set of attractive options. To illustrate this, Figure 7-1 shows the carbon-cost tradeoff curve of Figure 6-1 with a tripling of the nuclear power capital costs. The option is costly, but still within the optimal set.

Perhaps a more likely scenario for the future use of nuclear power involves one of the more advanced nuclear technologies with passive safety features. The advantages and disadvantages of these options have been

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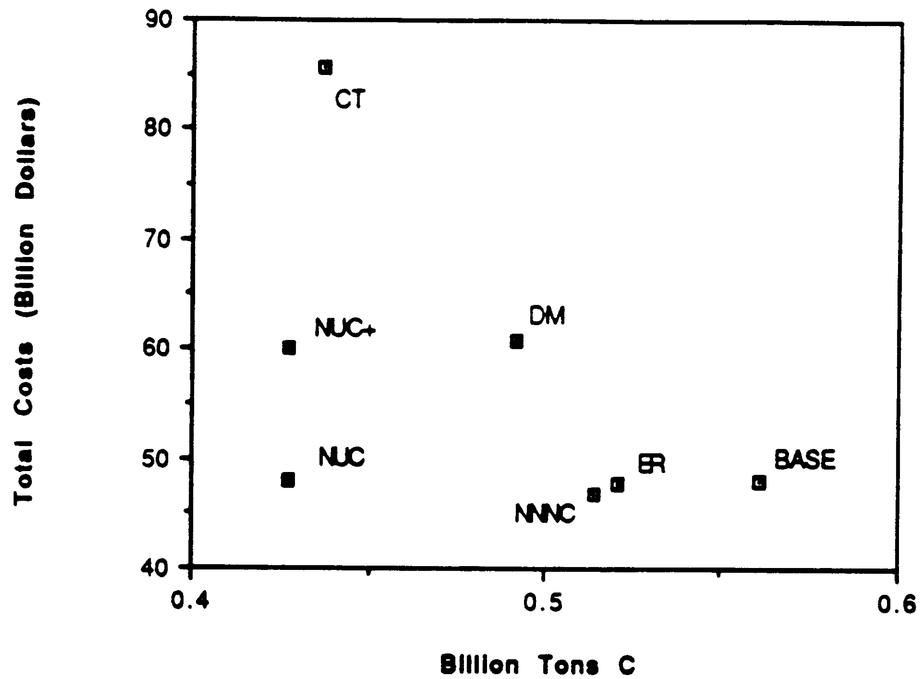
130 Risk = (Probability of outcome) x (Consequence of outcome)

131 Rose and Lester, 1978.

Carbon vs. Cost (NE - Base Future)



NUC+ indicates effect of increased nuclear capital costs

Figure 6-1

discussed at length elsewhere[132]. It will only be said here that these options are less economically attractive and, in the absence of policy initiatives, are unlikely to compete with coal on a one-to-one basis in the near term. While these options, particularly the modular high-temperature gas-cooled reactor (MHTGR), may indeed prove to be attractive options for emissions reduction in the long term, they have very little role to play in transitional strategies.

No Nuclear / No Coal

The no nuclear / no coal option, as modeled, was almost completely ineffective. This was for the simple reason that extensive construction of natural gas-fired capacity does not guarantee that any of it will be used. At present fuel prices, and in the absence of policy initiatives, natural gas capacity will not be lower in the system loading order than coal. Without displacing baseload, the option accomplishes only the least effective reduction task on all emissions — increased use of low emissions intermediate and peaking load. The dominant source of emissions continues to operate as before, and in fact may be forced to operate more because of the lack of efficient baseload replacements.

This policy has several distinct political disadvantages as well. While it is less successful at decreasing the use of coal than some of the other policy strategies outlined below, it might appear to be more so because of its direct nature and apparent favoritism. Implementation of the policy would require a regulatory mandate for the construction of natural gas and oil capacity and/or a moratorium on nuclear and coal. While not

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[132] Taylor, 1989; Lidsky, 1988; Golay and Todreas, 1990.

completely impossible, past experience has revealed just the opposite tendency. The oil shocks of the 1970s have created a skittishness about oil. Sectors which do not fundamentally need oil, such as electric utilities, have consciously tried to reduce their dependence. In the late 1970s, natural gas was considered a premium fuel which was "too good to burn"[133], and its use by utilities was limited. The other major disadvantage of this strategy is that system reliability, as measured by the amount of unserved energy, tends to decrease under this policy. While, this reduction is at a level calculated to be economically optimal given the present costs associated with unserved energy, these costs are likely to be much greater when the amount is very large, as is the case in the study.

Dispatch Modifier

The dispatch modifier is a fairly effective strategy, with costs increasing proportionally with emissions reduction. The carbon dispatch is particularly effective because it successfully forces low emissions capacity, particularly natural gas, into baseload operation. In fact, for a given capacity mix and demand, carbon dispatch releases the minimum amount of emissions possible. The modifier is most effective, and most costly, when the capacity mix is diverse, since there is a greater amount of low emissions capacity available for baseload displacement.

There are several disadvantages, however. The first is the high level of cost increase which this strategy entails, as we saw in Chapter 5. The second is the large amount of natural gas required by the strategy. It is not apparent that this amount of fuel use will be sustainable, given the limited

[133] Lee, Ball, and Tabors, 1990.

resource base, or even available to the utility industry. A third disadvantage is the requirement for the reprogramming of power dispatch centers. The dispatch modifier would require a fundamental change in the way power systems operate. While this is not infeasible (or even undesirable, perhaps) it would undoubtedly be costly and time-consuming, an effect which was not accounted for in this study.

Finally, the dispatch modifier, while highly effective for reducing emissions from a given system, does not in any way reduce emissions through capacity mix changes. In fact, since the construction of low emissions capacity will actually increase the costs of electricity generation, the carbon dispatch rules encourage the exclusive construction of low-cost (and probably high-emissions) supply. Utility planners seeking to minimize costs under the constraints of carbon dispatch rules might actually face an incentive to build higher emissions capacity than they would have otherwise. To counter this effect, some method by which capacity construction could be planned to minimize emissions — similar to the methods of minimizing cost used generally by businesses — would have to be used. How such a modification to the dispatch modifier policy would be implemented is unclear.

Early Retirement

The early retirement strategy is an option with several attractive features. In low and moderate growth futures of the Northeast region, the early retirement option is the only one which dominates the base strategy on all attributes. That is, early retirement is the only strategy which not only reduces all emissions relative to the base strategy, but reduces costs as well. The reason for the strategy's emissions reduction success is that it accomplishes high emissions generation is not only displaced, but replaced by newer more efficient technologies. In higher growth futures, however, the early retirement is the only strategy which is itself dominated by the base strategy. Also, the strategy in the East Central region, while leading to even larger emissions reductions, does increase costs substantially.

The implication of these results is that there is some optimal level of win-win improvement — that is simultaneous improvement in both costs and emissions — which can be made if utilities are willing to abandon some inefficient plants for new ones. At this optimal level, the efficiency improvements are sufficient to offset the capital costs of new construction. If the need for new construction becomes higher than this optimal level, the capital costs will be too high to be offset by efficiency improvements. This will be the case if growth is too high (observed in the higher growth cases of both regions) or if the level of capacity retirement relative to the entire system is too high (seen even at moderate growth in the East Central region where the capacity of older coal plants is much higher than in the Northeast).

Clearly in the absence of efforts to keep growth down, the early retirement strategy can only be of limited usefulness. In conjunction with conservation efforts, however, the strategy appears to have a common-sense appeal. The strategy would likely be met with enthusiasm by environmentalists who would like to see the most polluting plants shut down. If utilities are convinced that money can be saved (much more likely when it is their own models and data which indicate this to be the case) the strategy might provide some no-regrets options for expansion planning. It should finally be noted that this strategy need not be as direct (or even intentional) as implied in this formulation. Regulatory policies which make the operation of inefficient plants too uneconomic — by requiring scrubber retrofits, for instance — may indirectly lead to the early retirement of older coal capacity.

Carbon Tax

The carbon tax strategy is particularly appealing to those who prefer market-based strategies. In theory, if the environmental costs of carbon emissions (or any other pollutant) are internalized into the costs of electricity generation, the same profit incentives which lead utilities to seek cost-optimal solutions for electricity generation will lead utilities to solutions which are an optimal balance between costs and emissions. The problem with the carbon tax is not in the theory, but rather in the implementation. Defining the "costs" of any environmental pollutant are difficult enough, a problem which expands geometrically as new externalities (SO_2, solid waste, land use, etc.) are considered. This cost definition is even more difficult with a substance such as CO_2 whose environmental effects are not fully understood and, indeed, not even guaranteed. Traditionally, the effects of pollution are external to the polluter, but internal to some policy-making authority (i.e., a local or national government). With CO_2, the effects are not only likely to be across many sovereign authorities, but delayed by several generations. Traditional economics, which drives the choice of the carbon tax as the most efficient strategy, is essentially useless in providing the tools for the proper implementation of the strategy. Finally, of course, even if an optimal taxing level could be defined, public acceptance is hardly a foregone conclusion, as recent political experience has shown.

At the somewhat arbitrary, although purposely substantial, level of carbon tax examined in this study, the environmental effects are significant. The carbon tax accomplishes all of the supply-side tasks outlined for emissions reduction, increasing the level of low emissions technology used at all levels of operation from baseload through peak by rearranging the loading order in a dynamic fashion[134]. If we assume that the tax is at the correct level and exactly internalizes the social costs of carbon, this reordering is done in a socially optimal manner, and is accomplished without explicit regulation of utility actions. Once the prices are set, the utility merely acts to minimize costs. We can additionally assume, that if price-oriented feedback were allowed into the demand side, the carbon tax would induce conservation which would lower costs and further lower emissions. We have seen that, as modeled, the tax creates substantial new cost burdens for the utility industry, although much of the additional cost is in the form of tax revenues, which would then be available for different purposes.

Conservation

Conservation was not explicitly modeled as a strategy option, but its effects were observed through the modeling of various load growth uncertainties. As discussed in Chapters 3 and 5, the environmental effects of conservation are mixed. When conservation does not interfere with the most important task of displacing high emissions baseload by overly stagnating the natural construction of new capacity (usually technologies with high efficiency and low emissions), the environmental improvements

[134] The effectiveness of the strategy is based on the assumed availability of a low emissions alternative — in this case, natural gas, the resources of which may be limited.

are substantial. The primary implication is that interactions between supply side and demand side policies must be recognized and accounted for in the development of emissions reduction strategies.

The main difficulty with conservation strategies concerns implementation. Even when conservation is clearly of economic benefit, beyond any environmental considerations, implementation is not at all straightforward. First, under the regulations which many utilities face, prices are set per kilowatt-hour. The only way for utilities to increase profits under these sorts of regulations is to increase sales — a strong disincentive against conservation. One viable solution to this dilemma is least-cost planning, an approach presently being adopted in limited areas of the country[135]. For consumers, the economic benefits of conservation are realized through lower electric bills. To obtain these benefits, however, requires initial investment in higher efficiency items, such as light bulbs, refrigerators, and so on. While the payback period is usually very small for such items, on the order of six months to two years for many items, many barriers exist which prevent typical consumers from making these investments[136]. Many creative plans are being developed by utilities to encourage or assist in least-cost investments, but the extent of success which these programs will achieve remains to be seen[137].

Most Promising Strategies

The objective of this study has not been to develop projections of energy futures or to develop highly specific policy recommendations for

135 Moskovitz, 1989; Cavanaugh, 1989; Joskow, 1990.
136 Lovins, et.al., 1982; Goldemberg, et.al., 1987; Williams, 1989b.
137 Cicchetti and Hogan, 1990; Cohen and Townsley, 1990; Geller, 1989; Williams, 1989b.

greenhouse gas abatement. The focus has instead been on illustrating that a range of options exists, that useful policy options may be suggested by a deeper understanding of the systems involved, and that with an understanding of the involved systems, we can choose those policies which best meet diverse social goals, discarding those which are less effective.

Clearly, the few options which have been examined in this study do not constitute a complete menu. They do, however, provide some insight into what characteristics a successful strategy might have. The most striking point illustrated by the study is that, in the absence of conservation, the only option which is useful for reducing CO_2 emissions involves the single short-term alternative for cheap, low-emissions, baseload capacity: nuclear power. In the absence of nuclear power — a strong possibility even in the face of climate change — or the sudden emergence of another low-emissions alternative as economical, electricity demand must be kept down in order to actually reduce emissions below present levels.

This apparent need for conservation recalls another major theme of this study: demand-side management, in the absence of complimentary supply-side policies, is not the environmental panacea which it appears to be. If conservation is actively pursued (a complex, though probably economically beneficial, strategy), the accompanying supply side-policies can take several forms, depending on the time frame of desired emissions reductions and the level of reduction desired. Small reductions can be made quickly, at little or no cost, by retiring inefficient capacity. This also encourages the accelerated construction of higher efficiency capacity, which may or may not have significantly lower emissions. Large reductions can be made quickly through modifications in the system dispatch rules, but these reductions come at large cost and provide no long-term incentives for emissions reduction. Finally, large reductions can be obtained in both the short and long term through carbon-based taxes, with accompanying large distributional effects on the cost of electricity generation. Outright bans on the construction of new coal capacity will do little for emissions reduction unless either the nuclear (or some similar) option is viable or there are policies which favor the construction and use of low emissions capacity, even if the costs are high (i.e., with natural gas). This appears less efficient, but may have the advantage (or disadvantage, depending on one's point of view) of direct implementation. The optimum combinations of such policies (and modifications thereof), and the processes by which such combinations can be agreed upon and implemented, is the focus of Chapter 7.

Chapter Seven - Emissions Reduction in Context

The Politics of Carbon Dioxide

The development of policies for the mitigation of (or adaptation to) climate change will undoubtedly be a very complex process. Perhaps only with the threat of nuclear war has the world ever been faced with a problem of such potentially far-reaching consequences; perhaps never before has the world been faced with a problem with such far-reaching and diverse causes. The previous chapters have provided some tools for addressing a well-defined segment of the problem and partially evaluated some of the suggested solutions. We will now turn our attention to the processes by which coherent and specific policies might be developed and implemented, with the focus still on the electric power sector, but given the broader context of the climate change issue as well as socio-economic realities. With this goal in mind, we will examine the various actors and institutions involved in the climate change issue, the processes by which change occurs in the involved systems, and the mechanisms through which appropriate changes might be encouraged.

Actors

The list of actors with a stake in climate change and climate change policy could not be more comprehensive. All people are in some way linked to the causes of climate change, through their use of energy, agricultural products, and so on; all people will be affected by climate change policy since it must seek to alter these activities in some way; all people, or their children, will be affected in some way if large-scale climate change becomes a reality. The effects of climate change will even reach beyond humanity, fundamentally altering ecosystems and possibly causing mass extinctions. Beyond these observations, which imply a need for some level of social consensus on the climate change issue, there are a few individuals and groups with very specific roles to play in this process.

The first of these are the governmental actors who will have to play a role in the development, encouragement, and enforcement of any climate change policy. Even these are nearly too numerous to mention, as they span from individuals in local governments to diplomats in the highest international context. At the local and regional level, governmental actors will include executives (mayors, governors, etc.), legislators, and regulatory agencies. Regulatory agencies of interest might include environmental protection bureaus, economic development bureaus, and public utility commissions. The list can be directly extrapolated to the national level, where in the U.S., the agencies with a stake include groups as diverse as the EPA, DOE, NASA, and the State Department. The international context of the issue extends the playing field to officials and groups in foreign governments, as well as quasi-governmental international organizations such as the U.N. and the OECD. Not all of these foreign governments see climate change as undesirable (the USSR might have more land for agriculture, for instance) and some see climate change policies as directly in opposition with other national goals (i.e., China, which intends to exploit its massive coal resources).

The second group of actors are the industrial groups which will probably bear much of the responsibility for behavioral change. The most obvious of these are the industries whose processes or products are most directly responsible for greenhouse gas emissions: electric utilities, primary energy producers, automobile manufacturers, energy-intensive manufacturing firms, agriculture, and so on. Many other industries use the products of these firms (electricity, primary fuels, cars, etc.) and will be fundamentally affected by any limits or price changes associated with these products. Finally, there are those companies which might benefit (or be created) in the face of strong climate change policies. Among these might be photovoltaic firms, natural gas utilities, or manufacturers of high-efficiency appliances.

A third group which has been and will be fundamentally involved with the development of climate change policies is the scientific and technical community. Much of climate change policy will depend on the opinions of scientists about the causes, extent, and timing of climate change. Likewise, technology and the opinions of experts about technological potential are likely to play an important role in solutions to climate change.

For the sake of brevity, the remaining actors will be grouped in the overly aggregated category of special interests. Foremost in this category are the environmental groups who are most likely to press for climate change policies. We have already noted that this is no longer a specialized group — approximately 15.9 million people worldwide are members of one or more environmental groups, up from 13.3 million only one year before[138]. We may also include in this group such diverse special interests as unions, for whom jobs may be gained or lost due to climate change or climate change policy, or consumer groups, which might be opposed (or in favor) of fuel efficiency standards or energy taxes.

[138] Time, "The Fight to Save the Planet", 12/18/89.

Institutions

The institutions through which climate change policy might be shaped and enacted closely parallel the actors outlined above, so the list will not be repeated here. The additional institutions which will play a role in the climate change issue are primarily those created specifically because of this issue. Included among these are the scientific institutions created for study of the scientific aspects of this and related issues, such as MIT's Center for Global Change Science or the International Institute of Applied Systems Analysis (IIASA) in Vienna, as well as those designed to assist in policy formulation and implementation, such as the International Panel on Climate Change (IPCC). There are many international agencies designed to deal with other environmental (United Nations Environmental Program - UNEP) or economic (European Economic Community - EEC) issues, which have taken up climate change policy in some form as well.

Drivers of Change

Many processes have acted or may act as drivers to change the systems involved in the climate change issue. The primary processes of importance to the climate change issue are economic and population growth. As the number of people has grown, and their demand for higher standards of living has grown, so have grown the activities which contribute to climate change. In the past, the only limits to this growth have been caused by technological innovation and independent concerns such as those over other environmental problems. All of these fundamental processes will continue to have broad effects. Several other processes may now lead to limitations on greenhouse-forcing activities. First, increased scientific discovery and enhanced measurement have led to an awareness about potential problems. Second, political pressure has been brought to bear by environmental interest groups and those who perceive potential loss due to climate change. Third, media coverage of this and other transnational environmental issues, such as acid rain and ozone depletion, has accelerated a common perception of great environmental danger, which has in turn intensified the environmental movement and increased political pressure. All of this, of course, is still in tension with ever present demands for high standards of living.

Points of Intervention

With this broader context in mind, we will now return our focus to the electric power sector, outlining those places where climate change policies might be directed in order to effect change. Similar outlines could be developed for other sectors. The intervention points which might be used to affect the electric power sector include the following:

1) Production of Primary Energy: Policies could be developed which limit in some way the amount of coal or oil is produces, or change the price of producing primary energy. This would affect sectors other than electric power as well.

2) Consumption of Primary Energy: Prices or quantities could again be altered, as was modeled with the carbon tax strategy, or primary energy distribution systems (such as natural gas pipelines) could be limited or encouraged. Again, such strategies might also affect other sectors.

3) Production of Non-Electric Intermediate Energy: Policies could be directed at encouraging (or discouraging) the production and use of non-electric intermediate energy (such as natural gas for home heating) in order to alter electricity demand or increase overall energy efficiency.

4) Production of Electricity: Climate change policies could seek to alter the capacity mix (as with the early retirement strategy) or the way in which the capacity mix is used (as with the dispatch modifier). Policies may be directed at individual power plants or at any aggregation thereof.

5) Transmission and Distribution: Policies could alter the transmission and distribution of electric power. Goals of such policies might be to limit access to electricity or to minimize electricity losses in transmission lines in an effort to reduce total energy generation requirements. Policies directed at this area might also alter the way in which interconnected power grids transfer electricity. Greater transfer can increase total generation efficiency and smooth peak demands[139].

6) End Use of Electricity: All of the demand side policies listed in Chapter 3 would be included in this category.

139 The load factor for a system which spans several time zones is higher because peak demand is spread over more hours. This is a prime motivation behind proposals for greater interconnection between European power systems.

7) End Effects of Electric Power: Policies might be targeted directly at atmospheric CO_2 levels, for instance. Such policies are appealing in that they attack the concern directly, but suffer from a lack of connection to the root causes, which in this case are highly diverse and decentralized.

8) Planning of Electric Power Systems: Policies could attempt to directly alter planning decisions, through mandates or subsidies of particular technologies, for example, or they could in some way alter the planning process itself. Several of the studied strategies use this approach.

9) Technological Innovation: Policies could be directed at the research, development, and/or demonstration of alternative technologies for use in the electric power sector.

Mechanisms for Change

As suggested by the examples given above, policies directed at any particular point of intervention may take a variety of forms. These various policy mechanisms are generic to all areas of regulation, although some obviously will have more applicability in the electric power sector than others[140]. The two primary categories of such mechanisms may be classified as direct regulation and incentive-based regulation. More indirect informational mechanisms, such as advertising campaigns or educational

140 A more comprehensive list can be found in the DOE report A Compendium of Options for Government Policy to Encourage Private Sector Responses to Potential Climate Change (1989), which also lists numerous examples of what form such policies might take in various sectors, including electric power.

programs, and innovation-based mechanisms, such as support for demonstrations of new technologies, have important roles to play but will not be examined exhaustively here.

Direct regulation includes two broad categories of mechanisms: command-and-control regulation and standards. Command-and-control regulation can take the form of limits, quotas, or outright bans on particular materials, transactions, or activities. Among these might be fuel use, fuel production, technology use, or environmental emissions. Command-and-control regulation might also be directed directly at price or profit levels. This is, in fact, a large part of present utility regulation already, with electricity prices and rates of return mandated by regulatory agencies. The second set of direct mechanisms — standards — could detail technological specifications which must be met by power plants. Regulations which establish maximum heat rates or which specify particular technologies for use, such as sulfur scrubbers or particulate removal systems, would be included in this category.

The main advantage of command-and-control legislation is its direct nature, which makes it relatively easy to implement and enforce if correctly designed. This direct nature also tends to be politically more acceptable to pro-regulation interests (i.e., environmentalists) and less so to those who are regulated. The primary disadvantage of such mechanisms is economic inefficiency. If quotas, levels, or technologies are not chosen correctly, emissions reductions may come at greater cost than was necessary, or not at all, and incentives to seek new methods or technologies may be stifled. This is likely to be the case, particularly when such choices are made by regulators or legislators unfamiliar with the system or the technological possibilities[141].

The second broad category, incentive-based regulations, are based on free market principles which assert that once prices are "right" (that is, once all external social costs such as environmental damages are included), the same mechanisms which lead individuals and firms to maximize profits will lead individuals and firms to maximize social benefits. Incentive-based regulation can take many forms, the foremost of which are taxes and subsidies. These taxes and subsidies may be applied at almost any of the intervention points above. For instance, an attempt to internalize the cost of SO_2 emissions might place taxes on the production of high-sulfur fuels, the purchase of these fuels, sulfur emissions, or the price of electricity itself. Likewise, subsidies might be given for the production or purchase of low-emissions fuels or technologies, the removal of SO_2 from stack gases, or for conservation programs. Combinations of such systems are also possible[142]. Another incentive-based system, included in several of the most recent U.S. Clean Air proposals, involves the use of tradeable emissions permits. Under such a system, each utility, for instance, is permitted to emit a certain level of pollution. If it can reduce pollution below those levels, it can sell its extra permits to those companies to whom such a purchase is cheaper than emissions reductions. This allows for

141 Ackerman and Hassler (1981) discuss how the choice of scrubbers as the mandated technology for sulfur removal, and the poor design of the accompanying legislation, has actually led to increases in SO_2 emissions, at great cost.

142 DOE (1989) refers to such a system as "deposit-refund" and suggests an innovative approach to carbon emissions, wherein taxes are placed on the purchase of carbon-based fuels, but then subsidies are awarded based on carbon removal, such as through scrubbing or the planting of biological offsets (afforestation). Such a system would act similarly to the carbon tax of the study in the short term, but would provide a long-term incentive for the innovation of carbon removal strategies.

economically efficient emissions reduction, since emissions are reduced first by those most capable of doing so[143].

The primary advantage of incentive-based regulation is its theoretical economic efficiency and its flexibility. Its indirect nature is often a political liability. For instance, may environmental groups have criticized the recent Clean Air proposals because they give industry "the right to pollute", even though this total amount of pollution may be less than otherwise possible. The second problem with this type of regulation is that the transaction costs and informational requirements for such systems to operate may be very high. There are few reliable estimates, for instance, about what the costs of pollution permit markets and brokers will be, and whether this will counteract the theoretical efficiency of the system.

Policy Objectives and Barriers to Change

The many diverse, and often conflicting, objectives which any climate change policy must pursue, or at least consider, have already been mentioned and will only be outlined here. The primary ones are those considered quantitatively in this study: minimized costs of electricity generation and reduced CO_2 emissions[144]. Also of unarguable importance are positive effects on other environmental objectives, reliable electricity supply, safe supply, and maximized energy security. Other objectives which might be added, are robustness to uncertainty (flexibility), distributional equity (across present society and possibly intergenerational), and

143 Another special type of incentive might also be included in this category, the potential of which is driven by the vastness of government itself. The mechanism is the direct purchase (or end of purchasing) by the government of some item or technology for which it wishes to create (or eliminate) markets. For instance, a mandate for all government buildings to be equipped with energy efficient light bulbs and equipment would instantly create a larger market for such items.

144 Or perhaps reduced climatic effects of CO_2 emissions.

sustainability (political, economic, and environmental). Many others, of course, are possible, particularly at a more specific level.

The criteria by which we can judge the success or failure of any particular climate change policy are parallel to the objectives we have outlined for the policy above. For any particular individual or interest, the weighting of these objectives might be very different (emissions are more important than costs to an environmentalist) as might be the degree of perceived accomplishment of any particular objective (costs, if distributed unevenly, will be perceived differently by different parties). Individuals have their own individual criteria for policy success based on their personal values. Perhaps the best criterion for measuring success then becomes acceptability. If enough of a society's members accept a certain policy as meeting their own personal objectives, then the policy may be deemed a success.

Given this general statement, what conditions must be met to ensure that the criterion is met? First, the policy must have legitimacy. In order for members of a society to accept a policy as striving toward their own objective, they must feel as if they have some control over the choice of that policy. Methods for increasing the participation in policy-making are discussed at greater length below. Second, appropriate and acceptable tools must be made available to those making policy decisions and evaluating policy success. For instance, controversy over the accuracy of the climate models which have driven concerns over climate change is likely to continue to be a barrier to the policy-making process. This reality is a primary motivator for the choice of data and models in this study. If the basic assumptions of an analysis are suspect to the utility industry, the conclusions and recommendations of such an analysis will be meaningless.

Similarly, interested parties must be satisfied with the tools used to measure success (avoided costs or emissions data, for instance), or the policy will suffer from lack of acceptability.

The constraints which may prevent any policy from meeting the general criterion for success are particularly substantial in the case of climate change policy. Just meeting the first conditions is a non-trivial task. The diversity and number of actors involved in this issue makes the problem of participation and legitimacy very difficult. Even if full participation could be obtained, it is not clear that any particular policy would be acceptable to enough of the actors, given the diversity of their interests. The acceptability of tools may also be difficult to achieve. There will never be a 100% accurate and reliable climate model, nor will there be a completely reliable model of the socio-economic impacts of climate change or policies to prevent it. Whether any model can be made reliable enough to gain broad acceptance (or is so already) is not clear. Similarly, the objectives we have listed as most important — costs and climatic effects — are nearly impossible to measure, particularly relative to those which might have occurred in the absence of any given policy. Gaining acceptability for those measurements which can be made will be difficult.

There are, of course, many other constraints, some of which are generic and some of which are due to the peculiarities of the climate change issue. The foremost of these is the tension (and perceived incompatibility) between the objectives of economic growth and environmental protection. This might even be generalized to the strong societal tension in the U.S. between those who advocate *laissez-faire* policies, to allow market forces to control such societal concerns as environmental protection, and those who advocate interventionist policies to correct what are perceived as failures in the market. Other constraints are a reflection of these tensions. Recent experience with regulation of other environmental residuals has shown the utility industry to be sluggish to respond to calls for environmental protection measures. In fact, the industry has dug in its heels in costly efforts to prevent such measures. Similarly, environmental interests have been so distrustful of industry and government, that they tend to fight any measures which are perceived as "sell-outs", often delaying what might be productive actions. The third point of this triangle, government, has poorly balanced these competing interests and often enacted inefficient legislation and regulation[145].

Other constraints are reflective of the long-term nature of the climate change issue. People already have an aversion to anything perceived to be a tax, as reflected in the U.S. election campaigns in recent years. This is even more likely to be so when the costs of a policy are clear and in the present, such as would be the case with higher electricity bills, and the benefits are vague and in the future, as is the case with avoided climate change. This is exacerbated by a pervasive "technological-fix" mentality. Many people advocate a wait-and-see policy, in which it is assumed that if disastrous climate change becomes a reality, society will have had time to develop technologies which will counteract climate changes. The various proposals have included suggestions to inject SO_2 or dust into the upper atmosphere in order to simulate the cooling effect of volcanoes or nuclear winter, as well as suggestions to cover the ocean with styrofoam chips to increase the reflectivity of the earth's surface[146]. These proposals are made with varying degrees of seriousness, but all with the

[145] Ackerman and Hassler, 1981.
[146] Broecker, 1985; Bach, 1984; New York Times, 8/16/88.

underlying point that we will be able to think of something if the problem is bad enough, and it will not cost money until that time comes. While there is historical precedent to support the assumption that technology will progress well beyond what we can presently imagine, there is also precedent for the assumption that incremental technological-fixes in complex systems can lead to irreversible, unexpected, and unavoidable consequences[147].

Overcoming the Constraints / Pursuing the Objectives

Obviously, the challenges to the policy process will be formidable. There is reason to believe, however, that climate change initiatives may not only be possible but may, to some extent, be inevitable. As was discussed in Chapter 1, environmental issues have begun to affect political agendas at all levels, and the public support for environmental initiatives appears to be growing. The challenge is to make policies which are sensible, sustainable, and acceptable.

All of the actors which were outlined earlier in this chapter will have an important role to play. Foremost among these are the scientists providing the warnings about climate change (or refutations thereof). Scientists must recognize that their role in this issue will be long-lived and iterative. They must seek to be completely accurate and honest in their assessments of the evidence at hand. Any attempt to overstate claims or selectively ignore evidence in order to justify policies which reflect personal values will only create distrust of science and subsequent backlash.

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147 The series of decisions which led to the explosion of the U.S. space shuttle Challenger, or the nuclear accidents at Three Mile Island and Chernobyl, provide examples of how large systems can get beyond the control of technology if the systems are not properly controlled from the outset. The energy / climate system is, of course, infinitely more complex than these.

A similar comment can be made about the mass media, whose role in this issue will also be fundamental for a long period of time. Many adults in the U.S. get all or most of the knowledge they obtain after high school from television. This gives the members of the media a very important informational and educational role, whether they want it or not. The role of the media can be very positive in this regard, but if reporting is too biased or too inattentive of evidence which does not fit into preconceived notions, credibility is eventually lost. If this powerful communication tool is lost, then the building of national (or international) consensus will be all the more difficult.

The role perceived here for government is fairly simple in concept, although undoubtedly more difficult to implement. The first of the tasks is merely educational. This can be general, through support of general environmental awareness programs or through sponsorship of scientific and political conferences on the issue, or specific, through the support of research on technological and political options. Such activities are already underway within agencies such as DOE, EPA, OTA, and others. The second task involves the setting of general goals. Foremost among such goals might be national implementation of least-cost planning and the inclusion of environmental concerns in the planning process. Goals might even be as specific as the setting of national targets for emissions reduction (such as the 20% reduction by 2005 suggested by the Schneider and Wirth bills[148]).

The final task would then be the establishment of processes through which consensus policies might be built, followed by action based on

[148] The National Energy Policy Act of 1989 (Timothy Wirth [D-Colorado] S. 324); The Global Warming Prevention Act of 1989 (Claudine Schneider [R-Rhode Island] H.R. 1078).

consensus decisions. One model for such consensus-building processes is that used by the Analysis Group for Regional Electricity Alternatives (AGREA) in New England[149], in which a wide variety of parties (environmentalists, utilities, regulators, citizen groups, etc.) are brought together to outline possible policy options for meeting their various goals. Technical analysts then use a set of agreed upon tools to generate data about the effectiveness of the options (similar to the data presented in Chapter 5). The parties can then use the data to eliminate those options which are clearly inferior and determine what tradeoffs might make sense. In this way, the different values of the parties are made clear, and consensus can begin to build around common goals. Final action, by government, utilities, or others, can then be taken according to decisions which are legitimized by their wide participation.

Reasonable Approaches to Emissions Reduction

Although any specific recommendations given here for emissions reduction would be incompatible with the above recommendations for consensus building, some outlining of those general options which appear most reasonable for the U.S. electric power industry, based on the analysis of this study, is in order. Again, the model analysis has provided only a limited window for viewing a complete option set. Final policy decisions, of course, would have to be based on more detailed analysis of combinations and modifications of the most promising options.

Ideal strategies are likely to contain the following options:

149 Connors, et.al., 1989.

1) Conservation: Conservation appears to be a fairly robust strategy, both for cost and CO_2 emissions reduction, providing a strong win-win situation when used appropriately. Exceptions to the robustness occur when a technology is available for cheap, low-emissions baseload generation, the adoption of which is stifled by conservation. For CO_2, the only present alternative in the regions studied is nuclear power, the use of which is in direct opposition to many other societal goals and may not be feasible[150]. Any conservation policies must be joined with sensible and complementary supply-side policies, as outlined below.

2) Short-term adjustment of present capacity mix: Within the study's option set, this would indicate the early retirement option. The analysis indicates that early retirement at low levels, and in conjunction with conservation, is also another win-win situation. Retirement could be forced by standards or encouraged by incentives. Other similar options might also be available, such as encouraging repowering (which increases efficiency) over life extension (which decreases efficiency).

3) Near-term alteration of capacity use: Of those options included in the study, this goal can be approached by

[150] Many baseload technologies are available with low SO_2 emissions, making conservation less attractive if SO_2 is the main concern. The conflicting nature of some CO_2 and SO_2 reduction policies must be explicitly defined when examining tradeoffs and choosing policies.

either the dispatch modifier or the carbon tax. Given the likely high transaction costs and the contradictory long-term signals of the dispatch modifier, the carbon tax is probably the better of these two choices. Other alternatives would be the forced construction and use of natural gas (economically less efficient and subject to price shocks, but low transaction costs for implementation and enforcement) or system-wide carbon caps enforced through tradeable permits (economically efficient, but very high transaction costs).

4) Long-term alteration of capacity planning: Of the options examined in the study, the carbon tax is the most effective long term option for this goal. Bans on the construction of coal capacity are ineffective in the absence of cheap baseload alternatives (such as nuclear). Other options might include the deposit-refund modification to the carbon tax, or the tradeable permits scheme with gradual reductions in permitted levels.

If nuclear power (or some other inexpensive zero-emissions baseload technology) becomes available and acceptable for widespread use, the natural spread in the use of the technology could conceivably achieve all emissions goals without complex interventionist policies. In fact, when such an alternative becomes available — as is likely to be the case sometime in the 21st century — this will mark the end of the "transitional" period of this study and the beginning of a new transition. Such an occurrence, however, is not perceived to be likely, or a wise assumption, for electric power planning in the intermediate term.

Chapter Eight - Lessons

What Have We Learned?

Clearly, a specialized study of the electric power sector in two regions of the United States can not be extrapolated to drive policy for other sectors or regions. This study was not intended to serve that purpose. There are, however, some general lessons which this study provides which can be of use for climate change policy formulation beyond its limited focus.

Lessons for Electric Power in Other Regions and Nations

This study focussed primarily on two regions of the U.S. electric power industry. Utilities within both of these systems operate under the same national laws, have access to generally similar technologies, and attempt to maximize profits given similar constraints. Yet, in spite of these similarities, the two regions are substantially different, both in their current contribution to total carbon dioxide emissions and in the policies which will effectively reduce those emissions. This indicates the most general lesson to be learned from this study: the formulation of climate change policies must be regionally sensitive despite the global nature of the problem. Policies will have varying effectiveness and acceptability within different regions which, if not recognized, can render the policies overly costly or even useless. The study also illustrates that regional differences apply not only to broadly defined regions, such as the industrialized world and the developing countries, but can be significant within different regions of the same country as well.

These regional differences, in combination with some of the counterintuitive results of this study, indicate a need for system-oriented analysis to complement the large-scale long-term models which presently dominate the literature. In addition to regional differences, many of the complexities involved with dispatch, technological change, fuel switching, and interactions between supply and demand side policies are not captured by large scale models. This study has shown that these factors can be fundamental to policy effectiveness. That this lesson is already understood by utilities (they are distrustful of models which do not reflect systemic realities) makes its understanding all the more important for policy analysts hoping to influence utility behavior.

Several of the findings of the analysis suggest pitfalls to avoid and objectives to pursue in the formulation of policies for other electric power systems. First, the interactions between the supply and demand side are complex, particularly over the long term. Neither conservation or nuclear power, for instance, is the environmental or economic panacea which many advocates claim. Second, environmental emissions are driven by the use of a limited number of high-emissions technologies. The use of a technology is driven by many competing factors. The construction of low emissions capacity, for instance, does not guarantee that the technology will be used, and may, in fact, cause emissions to rise. Third, for both of the regions studied, there were several win-win alternatives — alternatives which reduced emissions and lowered costs. Although the total impact of such alternatives may be small, they provide a significant launching point for the suggested consensus-building process.

For the U.S. and many industrialized countries, the consensus-building process will be an effective approach to climate change policy formulation. The process will also be useful for the extrapolation to the international context, since the focus is not on centralized policy implementation and enforcement (the common barrier to international agreements). For many centrally planned countries, the consensus-building procedure will be inappropriate. These countries may, however, be better equipped to implement and enforce those climate change policies which are deemed appropriate. We also have seen that in much of the developing world, climate change policy might best be assisted by successful demonstration in the industrialized world in conjunction with mechanisms for technology and information transfer as the dominance of the issue begins to shift to these nations.

Lessons for Other Sectors

This study makes no attempt to evaluate specific climate change policy strategies for sectors beyond electric power. Some of the more general lessons, however, may have application in other sectors, particularly those which are part of the energy / CO_2 interaction: transportation, industry, and commercial / residential buildings. Many of the same social constraints apply and the institutional settings for other sectors are similar.

In transportation, for instance, the primary points of intervention are similar. Fuel production or consumption can be regulated directly. Automobile manufacturers, like utilities, are limited in number. Although the industry is not heavily regulated, there is precedent for regulatory action (on fuel efficiency standards, for instance), and a record of sluggishness with regard to these regulation which is similar to that of the utility industry. Finally, the use of automobiles is widespread and decentralized, as is the use of electricity.

Many of the lessons for electric power would would seem to also apply here. For instance, the transportation infrastructure and needs of different regions can be very different. There seems to be little reason to expect that some climate change policies would not have counterintuitive effects here as they did with electric power. Finally, it seems that the consensus-building procedure could be effective here as well. Similar observations can be made for general industry and the buildings sector.

Lessons for Global Change Policy

Some of the recommendations made within this study may seem, at the surface, contradictory. The fundamental basis of this study has been the belief that detailed sectoral studies are necessary for the formulation of sensible global climate change policies. Yet within the sector studied, the dangers of selective inattention (inattention to supply side by demand-side policy proponents, for instance) have been highlighted. If extrapolated to the general problem, it would seem that this indicates a need for comprehensive studies, to avoid the same pitfalls. These are indeed conflicting, although not mutually exclusive, ideas. The implication of this study is merely that the need for policy initiatives varies tremendously across sectors and regions and that similar policy initiatives in different sectors or regions may have very different outcomes. These differences must be well understood in order for policy initiatives, whether sector-specific or comprehensive, to be effective. The first lesson is that only sector-specific analyses can highlight these differences. The second is that these sector-specific studies will be of no use if interactions with other sectors are ignored. The complementary nature of sector-specific and comprehensive studies is then apparent.

Methodology aside, it seems clear that the potential outcomes from climate change policy are scattered over a very large range. Many of these outcomes probably include reductions in greenhouse gas emissions at minimal cost in conjunction with many other economic benefits, as appears to be the case with the U.S. electric power sector. It is hoped that the limited window provided by this analysis helps to highlight those strategies which are likely to be successful in the electric power sector and thus worthy of further investigation; it is also hoped that the lessons of this study can be applied outside this sector to assist in the formulation of sensible climate change policies.

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