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Report to the Congress of the United States

Limiting Net Greenhouse Gas Emissions in the United States

Volume II

Energy Responses

Editors:
Richard A. Bradley
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September 1991

U.S. Department of Energy
Office of Environmental Analysis
Deputy Under Secretary for Policy,
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PREFACE

Over the past decade, global climate change has been a subject of growing concern. The United States government in general, and the U.S. Department of Energy (DOE) in particular, have increased their level of activity in this area in recent years; since the 1970s, the DOE has sponsored scientific research programs in global climate change. Coordinated by the Committee on Earth and Environmental Sciences, these programs have sought to define the issues, reduce uncertainties, and quantify the interaction of global human and natural systems. Understanding the relationship between the production and use of energy and the accumulation of radiatively active gases in the atmosphere, as well as the consequences of this relationship for global climate systems, has been of particular interest, because constructive policy cannot be formulated without a firm scientific grasp of these issues.

Initial scientific concern about global climate change was transmitted to the larger policymaking community and the general public through a series of non-governmental conferences beginning in 1985 in Villach, Austria. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established to assess the state of scientific research into global climate change, the potential impacts of such change, and the possible response strategies. In 1990, the panel produced an initial report indicating that there is considerable uncertainty in our knowledge of the underlying processes and the physical and socioeconomic impacts of climate change, as well as of the effectiveness and costs of many of the proposed options for reducing greenhouse gas emissions and mitigating the effects of climate change.

The *National Energy Strategy* (NES) was developed to address all of the nation's energy concerns, taking into account related environmental issues such as global climate change. Actions included in the National Energy Strategy are projected to hold U.S. energy-related emissions of greenhouse important gases, weighted by IPCC-estimated global warming potential (GWP) coefficients, at or below 1990 levels through the year 2030. In the same economic and energy price scenario, GWP-weighted energy-related emissions of greenhouse gases are projected to rise by as much as 50% in the same period without the National Energy Strategy.

In 1988, in a Senate Report (S. Rep 100-381) accompanying the Energy and Water Appropriations Act, 1989 (P.L. 100-371), the Congress of the United States requested that the DOE produce four studies on climate change:

1. *Alternative Energy Research and Development*: To assess the state and direction of federal research and development of alternative energy sources, including conservation.

2. *Greenhouse Gas Data Collection*: To assess how greenhouse gas emissions and climate trends data are coordinated, archived, and made available to scientists, both within and outside of government.

3. *Options to Mobilize the Private Sector*: To assess policy options for encouraging the private sector to cooperate in mitigating, adapting to, and preventing global climate change.

4. *Carbon Dioxide Inventory and Policy*: To provide an inventory of emissions sources and to analyze policies to achieve a 20% reduction in carbon dioxide emissions in 5 to 10 years and a 50% reduction in 15 to 20 years.

This report, *Limiting Net Greenhouse Gas Emissions in the United States*, presents the results of the fourth study. The study was conducted by the Office of Environmental Analysis, Office of Policy, Planning and Analysis, Department of Energy, with assistance from staff throughout the Department of Energy and from other agencies and organizations. It is presented in two volumes:

Volume I: Energy Technologies
Volume II: Energy Responses

This document is Volume II. Note that, due to their size, Appendixes A through I are not included with this volume. They may be obtained from the Department of Energy in Washington, D.C.

EXECUTIVE SUMMARY

OBJECTIVES AND STRATEGY FOR THE REPORT

The Congress of the United States requested that the Secretary of Energy:

> ***Prepare a report for the Congress that comprehensively inventories the sources of carbon dioxide (CO_2) in the United States and analyzes the policy options to be formulated in cooperation with the Environmental Protection Agency (including, but not limited to, energy pricing, energy efficiency requirements, alternative fuels, alternative end use, and supply technology) which would lead to a 20-percent reduction in domestic CO_2 emissions in the short run (5 to 10 years) and a 50-percent emissions reduction in the long run (15 to 20 years).***

Limiting Net Greenhouse Gas Emissions in the United States responds to the congressional request. It also builds on the first National Energy Strategy (NES) of the U.S. Department of Energy (DOE) (DOE 1991). Energy and environmental technology data were analyzed using computational analysis models. This information was then evaluated, drawing on current scientific understanding of global climate change, the possible consequences of anthropogenic climate change (change caused by human activity), and the relationship between energy production and use and the emission of radiatively important gases.

Limiting Net Greenhouse Gas Emissions in the United States evaluates policy options for reducing U.S. emissions of carbon dioxide and other greenhouse gases. The analysis undertaken to implement this strategy is reported in the two volumes:

- *Volume I: Energy Technologies*: The principal performance and cost characteristics for energy and environmental technologies that were expected to play a role during the period of time studied were identified and described. Some technologies expected to be capable of penetrating the market shortly after 2030 (the end of the study's time frame) were also included because of the importance of understanding the effects of technology beyond the study's horizons.

- *Volume II: Energy Responses*: A national-level policy analysis was conducted to determine the effectiveness and costs of various federal policy instruments in reducing projected U.S. emissions. This analysis combined much of the technology data from Volume I with computer models to project energy use, emissions, and economic variables.

SCOPE OF THE REPORT

This study covers the principal greenhouse-related gases with significant anthropogenic emissions sources. These are the same gases addressed in the National Energy Strategy (DOE 1991): carbon dioxide, carbon monoxide, methane, nitrous oxide, chlorofluorocarbons,[a] CCl_4, CH_3CCl_3, hydrogenated chlorofluorocarbons,[b] hydrogenated fluorocarbons,[c] and Halon-1301. Nitrogen oxides and volatile organic compounds were excluded from the analysis because they are not themselves important radiatively active gases and because the measure of their indirect effects is subject to even greater uncertainty than is that of the gases studied.

To make possible a direct comparison between the emissions of various greenhouse gases, we have used the IPCC global warming potential (GWP) coefficients (100-year integration period). The use of these coefficients allows the computation of carbon dioxide equivalent emissions for all gases. The

(a) CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115.
(b) HCFC-123, HCFC-124, HCFC-141b, and HCFC-142b.
(c) HFC-125, HFC-134a, HFC-143a, and HFC-152a.

present study inventories the sources of emissions for these gases and investigates the feasibility and economic costs of emissions reductions beyond those achieved by the NES Actions. The development of GWP coefficients has made it possible to broaden the analysis requested by Congress from an assessment of carbon dioxide only to a full assessment of the carbon dioxide equivalent emissions of all energy-related radiatively important gases. While we still report analysis results for carbon dioxide explicitly, we are now able to look at total GWP-weighted emissions in terms of carbon dioxide equivalence. (Note, however, that the GWP coefficients for the gases studied are subject to significant uncertainty and are being reevaluated through the IPCC process, which could result in substantial changes in reported values.)

The use of GWP coefficients is important, as it allows a generalization to be made from the original congressional charge. Whereas the original congressional charge was to examine carbon emissions from fossil fuels, we can now examine carbon equivalent or carbon dioxide equivalent emissions from all energy related greenhouse gas emissions. When we examine fossil fuel carbon emissions, we will measure those emissions in units of **carbon emissions**, for example metric tonnes of carbon per year (mtC/yr). When we use the comprehensive approach to examining energy-related greenhouse gas emissions, we will use units of **carbon equivalent emissions**, for example metric tonnes of carbon equivalent emissions per year (mtC_e/yr) or metric tonnes of carbon dioxide equivalent per year ($mtCO_2e/yr$). Carbon equivalent or carbon dioxide equivalent emissions express the emissions of all emitted gases in terms of the amount of carbon or carbon dioxide that would have to be emitted to achieve the same greenhouse effect as the bundle of gases actually emitted.

This study focuses on energy-related emissions of radiatively important gases. No attempt has been made to forecast agriculture-related emissions. Emissions from rice production, ruminant livestock, and nitrogen fertilizers, and emissions due to land-use changes have not been assessed over the period 1990 to 2030. The one exception is the analysis of emissions carbon sequestration potential that would result from increasing the density and extent of forests (reforestation). This analysis is based on work by the U.S. Forest Service, which we consider to be the best available analysis at present. It is important to stress that work in this area is just beginning and that further improvements in our present understanding of reforestation potential and the implications of large-scale efforts to tap it are needed.

Finally, it is important to note that this study does not attempt to assess the benefits of emissions reductions or sink enhancement due to policies that go beyond the NES Actions. An assessment of such benefits, which would depend directly on the effectiveness of policies in changing global emissions and, consequently, the magnitude and timing of any climate change attribution of those emissions, was beyond the scope of this report.

OVERALL CONTEXT OF RESULTS

In reviewing the results, one must bear in mind that significant uncertainties surround every aspect of this analysis: the rate and timing of global climate change, the linkage between human activities and global change, and the consequences of climate change for human and natural systems. These uncertainties manifest themselves in numerous areas, including the values of GWP coefficients used to compare greenhouse-related emissions and the size and nature of the anticipated economic and environmental "benefits" and/or "damage" that might be expected to accompany a given array of future ***global*** greenhouse gas emissions. For this study, the GWP coefficients used are the IPCC estimates of the 1990 Scientific Assessment (IPCC 1990). The IPCC is continuing its research on GWP coefficients in order to refine its estimates of these values.

In addition to the uncertainties noted above, significant uncertainties also surround the forecasting of future greenhouse gas emissions from the United States and from other members of the world

community. The uncertainties associated with prediction are compounded the further into the future one attempts to look. For this reason, we have adopted the NES analysis as a point of departure. While any effort that makes projections as far into the future as 2030 will certainly be wrong in ways that we cannot yet foresee, examining possible future energy system trajectories within the context of an aggregate analysis structure can yield numerous useful insights, help point the way toward promising options, and help identify potential problems. For this and any other future-oriented analysis, it is not the forecast, *per se*, but rather, the qualitative analytical results that matter. The computation of cost is similarly fraught with difficulties, particularly insofar as explicit computations are involved.

In addition to its research and monitoring programs, the U.S. has developed a strategy for addressing the greenhouse issue that simultaneously reduces projected future emissions and meets other national needs. This approach is sometimes referred to as a "No Regrets" strategy. The NES, which serves as the basis of the analysis reported here, meets the "No Regrets" test.

The NES is projected to hold the energy-related GWP-weighted emissions of greenhouse-related gases at or below their 1990 values through the year 2030. The cost of further reductions may be great; the total annual cost to achieve the carbon emissions reductions specified by Congress, using only a carbon tax, was estimated to be $95 billion in the year 2000 and would require a tax rate of $500 per metric tonne of carbon (mtC), or $136 per metric tonne of carbon dioxide equivalent ($mtCO_2e$). (A tonne of carbon dioxide can be converted to an equivalent carbon value by multiplying mass by the ratio 12/44.) A carbon tax rate of $100/mtC would add $55 (240%) to the cost of a short ton of coal at the minemouth and $0.26 (27%) to the cost of a gallon of gasoline. The 20% and 50% reductions in emissions were achieved (with a tax of $500 per metric tonne of carbon) when emissions were expressed in terms of GWP-weighted emissions; no carbon tax, regardless of the amount, was able to reduce carbon emissions by 50% in the year 2010, the target set by Congress, or even in the year 2030.

It is important to recognize that any projection spanning a 40-year horizon is necessarily quite speculative. The baseline trajectory and the impact of particular actions to change it could differ significantly from those outlined in this report, which is based on a specific set of assumptions. For this reason, it is critical to recognize that, because the NES Actions Case is itself a policy scenario, the actual jumping-off point from which the additional policy options studied here have their effect cannot be known with certainty in advance. Therefore, even if we knew the actual effectiveness of individual policies studied here, attainment of an absolute emissions or energy-use target through a specified set of policies cannot be guaranteed. For this reason, commitment to any such targets implies a level of precision that is not captured in the analysis of scenarios in this report.

The results of this study and others lead to the conclusion that not enough is known to be able to achieve the dramatic reductions in carbon emissions proposed in the congressional request without an extremely detrimental effect on the U.S. economy.

REPORT FINDINGS - VOLUME I

Greenhouse gas emissions arise from many sources, including both natural and human. Activities related to the production and use of energy are the major contributors of anthropogenic carbon emissions, which most often take the form of carbon dioxide. Changes in the way energy is used in the U.S. economy, along with changes in land use, can significantly affect the growth rate of net U.S. emissions. Development and use of low-emission energy and environmental technologies are essential to provide the mechanisms for such changes. The purpose of Volume I of *Limiting Net Greenhouse Gas Emissions in the United States* is to characterize energy and environmental

technologies that show promise for reducing emissions from greenhouse gases. The volume does not address the potential of these technologies to penetrate energy markets; such an evaluation would include the issues of whether consumers will accept the technologies, what patterns of technology investments are likely, and how technologies compete to attract these investments.

A wide range of currently available, emerging, and long-term technologies was reviewed for this study to illustrate the variety of technical options that could help reduce greenhouse gas emissions during the next 20 to 30 years. An overview of the major technologies and their roles in emissions reduction strategies is provided in Chapter 1 of Volume I. Technical performance and cost characteristics for these technologies are presented in the remaining chapters. Some of these data were used in the Volume II analysis of major public policy instruments that are candidates for promoting development and use of new technologies.

As a result of the numerous contributions by a variety of authors and a substantial literature review conducted for this volume, four general findings can be noted:

1. Although most greenhouse gas emissions occur from combustion of fossil fuels to produce energy, multiple stages of the energy production-use cycle may have important emission contributions.[a] For instance, coal-fired combustion for electric power generation produces carbon dioxide emissions, but methane is also released during the coal mining stage. New technology can achieve potentially significant emission reductions in each stage of the energy cycle. Emissions can be reduced either directly (e.g., by converting to nuclear energy) or indirectly (e.g., by conserving secondary energy forms such as electricity).

(a) The energy cycle includes primary fuel extraction and preparation, conversion and processing to intermediate energy forms, transmission and distribution, and final end uses.

2. Advanced technologies are essential for the four main strategies available to cut energy-related emissions:
   - *fuel substitution* (substituting low-carbon for high-carbon fuels)
   - *carbon removal* (extracting carbon from fuel or waste streams either before or after fossil fuel combustion)
   - *energy efficiency improvement* (increasing the efficiency of energy supply, conversion and use)
   - *energy service demand modifications* (a shift in the level or type of end-use energy service demand, resulting in use of lower-emission energy).

   However, the role of advanced technologies is affected substantially by behavioral and structural changes in the economy that are not currently well understood. A high degree of interdependence exists between the strategies, and efforts to implement one strategy will often have secondary impacts on others.

3. Many advanced technologies with the potential to have major impacts on energy use and carbon emissions are available now or are under development, although the time periods needed to achieve results vary. For many technologies, substantial research and development efforts will still be necessary before advanced systems will be ready for the marketplace. Even technologies available today may require a significant period of time to achieve any appreciable emissions reductions. The factors influencing the degree to which these technologies will eventually be used include stage of technological development, the rate of capital stock turnover, the availability and competitiveness of alternatives, and public acceptance.

4. Important uncertainties remain regarding technical performance and costs for technologies that have not achieved commercial use. The knowledge base is weakest for certain carbon removal and demand modification technologies, as

well as for long-range technologies such as nuclear fusion and hydrogen. Moreover, interactions between technology options in practice make the overall impacts of any one technology difficult to predict. Comprehensive evaluation of emission-reduction technologies requires a full energy cycle analysis, including provisions for handling both the uncertainty in technology performance and costs and the behavioral and structural factors affecting technology use.

REPORT FINDINGS - VOLUME II

The results of the substantial research effort undertaken for this report appear to support eight major conclusions:

1. Taking a comprehensive approach to the analysis of U.S. contributions to global warming potential seems preferable to focusing on either a single greenhouse gas, such as carbon dioxide, or a single human activity, such as energy production and use. Global warming potential (GWP) coefficients (IPCC 1990) were used to provide a measure of the relative importance of various radiatively significant emissions.

2. **The National Energy Strategy (NES) Actions are projected to hold GWP-weighted energy-related emissions of greenhouse gases at or below 1990 levels throughout the period to 2030. This represents a reduction of more than 40% by the year 2030, relative to the Current Policies Case. Because the NES Actions are a comprehensive package of measures designed to meet the full array of national energy concerns, these emissions reductions were obtained in the context of an overall policy whose benefits exceeded costs. All policy instruments examined that went beyond the NES Actions achieved further projected reductions in emissions, but did so at a cost.**

3. The goals of reducing future greenhouse gas emissions 20% by the year 2000 and 50% by the year 2010 are technically feasible, but have high costs and require actions that go beyond those of the NES. Such reductions are also subject to diminishing marginal returns; that is, while the first reductions in emissions can be obtained at lower cost, costs rise steeply with increasingly stringent reductions, relative to a reference case that includes the NES Actions. The costs of achieving emissions reductions are also subject to uncertainty.

4. The most effective combination of strategies (lowest cost) for meeting the congressional emissions objectives encompassed a wide array of actions, including **NES Actions** such as emissions reductions of chlorofluorocarbons and hydrogenated chlorofluorocarbons, the planting of large areas of new forests, and a broad energy-related emissions reduction program. **It is important to emphasize the critical role NES Actions, particularly those that increase energy efficiency and energy production from nuclear and renewable sources that produce no direct greenhouse gas emissions, play in minimizing costs.**

5. Starting from the NES Actions policy scenario, achieving a 20% reduction in GWP-weighted emissions, relative to 1990, by the year 2000 using a comprehensive approach of GWP-weighted taxes on energy-related emissions with credits for reforestation would require a tax rate of between \$25/mtC_e and \$40/mtC_e and would cost between \$2 billion and \$10 billion per year in the year 2000. A 50% reduction in GWP-weighted emissions, relative to 1990 emissions, achieved by the year 2010 using a comprehensive approach would require a tax rate of between \$100/mtC_e and \$500/mtC_e and would cost between \$30 billion and \$205 billion per year in 2010. Achieving a 20% reduction in carbon emissions from fossil fuels alone, relative to 1990 levels, in the year 2000 required a tax of almost \$500/mtC_e, at a total cost of approximately \$95 billion per year in the year 2000. Taxes of up to \$750/mtC_e were insufficient to reduce carbon emissions from fossil fuels alone by 50%, relative to 1990 levels, in the year 2010.

6. To explicitly address the fact that the NES Actions represent a policy scenario subject to uncertainty, a sensitivity analysis case was constructed, using the NES Actions Case without its nuclear power component as an alternative starting point. This sensitivity analysis projects little difference in the marginal costs required and total costs incurred in meeting emissions reductions targets through the year 2010. However, this alternative starting point has a major impact in the later years of the study period. For example, the projected total cost in 2030 of maintaining a 50% reduction in GWP-weighted emissions with a comprehensive approach increases by almost $25 billion per year in the sensitivity case, as compared with the NES Actions Case.

7. The energy system required time to fully implement long-term adjustments in low emissions cases. There was a general tendency in all cases examined for the cost of achieving any specific emissions reduction objective relative to 1990 levels to rise between the years 2000 and 2015 and to fall thereafter. The tendency for costs to rise was driven by the long-term rate of population and economic growth, which led to expanding demands for energy services. Energy conservation and fossil fuel substitution were important tools in keeping the near-term costs of achieving emissions reduction objectives low. In the long-term, costs rose until new energy supply technologies such as renewable and nuclear sources were able to make a significant contribution to total energy service demands.

8. The United States acting alone cannot hold global greenhouse gas or carbon emissions constant. Even the most extraordinary efforts of the entire OECD acting alone could not hold global fossil fuel carbon emissions constant beyond the year 2020. By the year 2020, non-OECD fossil fuel carbon emissions are expected to exceed present global emissions.

A Greenhouse Gas Inventory

In the last few years, the terms "greenhouse effect" and "greenhouse gases" have moved from scientific research literature to the general consciousness. The greenhouse gases are a suite of gases, including water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3), that are essentially transparent to incoming solar radiation, but that absorb and reradiate energy in the infrared spectrum. The presence in the atmosphere of these radiatively important gases, which originate primarily from natural sources, is responsible for raising the mean global surface temperature of the Earth from an uninhabitable temperature of -19°C to the relatively comfortable temperature of +15°C that we observe today.

While researching this report, we reviewed natural science data regarding global climate change (Chapter 1), surveyed the knowledge base on potential consequences of climate change (Chapter 2), and evaluated the present state of understanding of naturally occurring and anthropogenic emissions of gases that can affect the Earth's energy balance and climate (Chapter 3).

We have observed, as have others, that the concentrations of some radiatively active (greenhouse) gases have been increasing throughout the industrial era (Chapter 1). Greenhouse gases whose concentrations have been observed to be increasing include those occurring naturally, such as CO_2, CH_4, and N_2O, as well as anthropogenic compounds such as the chlorofluorocarbons (CFCs), hydrogenated chlorofluorocarbons (HCFCs), and hydrogenated fluorocarbons (HFCs). The latter gases also tend to warm the Earth's surface in the absence of feedback effects. Abundance in the atmosphere, rates of increase, and the relative role human activities play in gas cycles vary substantially among various gas species. The links between the emissions of radiatively important trace gases and their concentrations in the atmosphere are complex and not yet fully understood (Chapter 1).

A significant band of uncertainty surrounds the best current understanding of the implications of the "doubling" of the preindustrial concentration of CO_2, which was approximately 275 parts per million volume in the atmosphere in the year 1720. Estimates of the increase in mean global surface temperature that would result from an equivalent doubling of atmospheric CO_2 concentrations range from 1.0°C to 5.0°C, with more recent research results tending toward the lower end of the range.[a] The link between equilibrium climate response and transient response has not been defined well yet, making it difficult to assess whether the observed changes in global climate variables are the result of changes in atmospheric composition or simply part of a "noisy" natural record. The best available climate models are currently unable to predict reliably whether a region will become wetter or drier, despite a general consensus that an overall increase in precipitation will occur globally.

Most of the radiatively important trace gases, such as H_2O, CO_2, CH_4, N_2O, and O_3, have natural sources in addition to releases attributable to human activities (Chapter 3); others, such as CFCs, HCFCs, and HFCs, are of strictly human origin. Human activities release greenhouse gases into the atmosphere in quantities that are known to be significant relative to the global system. While the qualitative relationship between emissions of greenhouse gases [and gases that influence concentrations of greenhouse gases, such as carbon monoxide (CO) and nitrogen oxides (NO_x)] and concentrations of greenhouse gases in the atmosphere is well-known, significant work remains to be done before precise relationships between potential future emissions and atmospheric concentrations can be established.

Because the global climate system depends on the composition of the atmosphere, all emissions matter in determining the overall effect on atmosphere and climate, as do changes in factors such as albedo, solar radiation, clouds, and other changes in the climate system. The relative contribution of the United States to global anthropogenic emissions varies from gas to gas (Chapter 3). It is lowest for methane (CH_4), approximately 12% of the global total, but higher for fossil fuel CO_2, approximately 23%. Emissions of greenhouse gases by individual states also vary greatly and are principally dependent on population, agricultural activities, and rates of industrial production. For example, carbon emissions associated with the states of Texas, California, Pennsylvania, Ohio, and New York were significantly greater than those associated with New Hampshire, Idaho, South Dakota, Rhode Island, and Vermont.

For the purposes of policy formulation, it is useful to compare the warming effect of the various gases, which differ in their direct and indirect contributions to radiative forcing. These effects include the temperature change that would be expected if there were no feedback effects such as increased evaporation, changes in albedo from decreased ice and snow cover, and changes in the time profiles of atmospheric removal processes, as well as the direct influence on atmospheric composition. A set of weighting coefficients was developed by the IPCC (1990) to make such comparisons. These are referred to as global warming potential (GWP) coefficients. GWPs are defined as the change in radiative forcing for the release of a kilogram of a gas, relative to the release of a kilogram of CO_2, summed over a specific period of time (20, 100, or 500 years). The GWP of a gas is expressed in kilograms of CO_2 equivalent ($kgCO_2e$). Use of GWP coefficients makes possible direct comparisons between different policy instruments that affect both the magnitude and timing of all greenhouse gas emissions (Chapter 3).

Throughout this analysis, we have computed energy-related emissions of CO_2, CO, CH_4, and N_2O, as well as those of CFCs, HCFCs and HFCs. These emissions have been weighted by GWP coefficients (using the 100-year integration period values developed through the IPCC in 1990) to calculate a total impact of all U.S. emissions on potential radiative forcing. The use of GWP weights

(a) The IPCC (1990) gives its best guess as 2.5°C.

makes possible the analysis of the cumulative impact of all greenhouse gas emissions and is referred to as being within the "comprehensive approach" for addressing potential climate change. Throughout our analysis, we have adopted a comprehensive approach in which we consider energy-related greenhouse gas emissions as well as carbon sinks from reforestation. It is important to note that, while the IPCC GWP coefficients embody the best current information regarding the relative impacts of a one-kilogram release of various greenhouse gases, this information base is uncertain. The exact values of these coefficients are likely to change over time, both as the result of continued scientific research and because the atmospheric composition against which these values are developed will change. Research scientists supporting the DOE are presently refining these values.

We have noted that developing an understanding of the consequences of climate change is important in the formation of a fully informed public policy (Chapter 2). However, while the numerous studies examined in this report provide considerable knowledge about the impacts of global climate change, the comprehensive models and data required to assess such changes in terms of the full consequences to society do not yet exist.[a] This problem is compounded by the fact that critical issues still exist in predicting and assessing the nature and timing of global climate change on local and regional scales, as well as at the global level. However, even if the general circulation models of climate were capable of accurately forecasting future patterns of local and regional climate change for alternative emissions scenarios, we would still be faced with problems in predicting and depicting local and regional physical and human impacts and responses. These problems include lack of appropriate data and problems in describing the linkages between regions. Furthermore, climate change can result in regional and sectoral benefits as well as damages: for example, the CO_2 fertilization effect enhances plant productivity and water use efficiency for a wide range of crop species. Thus, while it is possible to describe the type of effects that can be expected from global climate change and, in some cases, to provide preliminary estimates of the scale of those effects, any comprehensive net impact assessments remain a goal for the future. Whatever the impacts of possible climate change might be, the benefit of policies to slow the emission of greenhouse gases is directly dependent on the effectiveness of such policies in changing **global** emissions. In this regard, it is important to recognize that without global cooperation, the effect of policies discussed in this report on the global rate of greenhouse gas emissions will be relatively small.

(a) Several recent efforts have attempted to bring together information to create preliminary measures of the net cost and benefits of atmosphere/climate change. These are sometimes referred to as "damage functions." These include Nordhaus (1990), Peck and Teisberg (1991), and Cline (1991). Such efforts are seminal, but remain preliminary and subject to substantial revision as future research proceeds.

Approach

One contribution of this report will be to improve the present understanding of the cost and effectiveness of potential policy instruments that could go beyond the NES Actions. To explore the consequences of such instruments, we have used several models of the relationship between energy and the economy (Chapter 4).

The principal model used to examine the relationship between energy and the U.S. economy is Fossil2. This model was also used in the analysis underpinning the development of the NES. Fossil2 is a dynamic simulation model of U.S. energy supply and demand designed to project long-term (30- or 40-year) behavior. The analytical framework of Fossil2 was used to incorporate the set of technology and policy assumptions generated for the NES. These assumptions combined to establish the projection of U.S. energy supply, demand, and prices to the year 2030. Fossil2 estimates energy supply for oil and gas production, coal production, and renewable energy production. The Fossil2 energy demand sectors estimate residential, commercial, industrial, and transportation energy demand.

It is worth noting that the Fossil2 Model may tend to underestimate the responsiveness of the energy system in extreme cases. This is because the model has no mechanism for prematurely retiring existing capital stocks, even when they are no longer economically viable. The model simply continues to operate them throughout their useful lifetimes. This behavior is reasonable when, for example, carbon taxes are low, but when carbon taxes rise above $100/mtC, this behavior may not reflect the full extent of economic response and may therefore tend to underestimate the impact of the modeled policies. The assumption that only fossil fuel carbon emissions are taxed is also limiting. A more general analysis would consider taxation of carbon from other potential net sources including, for example, cement manufacture and forest practices, as well as the effect of taxes on other activities that produce greenhouse gas emissions.

The output from Fossil2 provided inputs to two other modeling systems used for analyzing the impacts of policies to mitigate greenhouse gas emissions. The first of these models is the Edmonds-Reilly Model of long-term, global energy-economy interactions. This model is an energy market equilibrium model, with supply and demand equated only for the energy sector. The Edmonds-Reilly Model calculates base Gross National Product (GNP) directly as a product of labor force and labor productivity. This model was used to assess the global energy and greenhouse gas emission implications of U.S. actions that go beyond those implemented by the NES (Chapter 10).

The Data Resources, Inc. (DRI) Quarterly Macroeconomic Model was used to estimate the impact of greenhouse gas emission mitigation policies on investment, GNP growth, and other aspects of the U.S. economy. Two examples of policy instruments were selected for detailed examination (Chapter 9). The DRI Model uses energy demand as an input to generate estimates of economic growth. When the DRI Model is used in this study, the energy component is represented by estimates of total demand at full employment, obtained through Fossil2 simulations.

In the analysis of costs, we have sought to calculate estimates of reductions in the dollar value of new, final goods and services produced in a given year (GNP). We have used the tools of economic analysis to construct these estimates. Reductions relative to the NES Actions Case are reported in the year in which they occur. There are obvious differences in the burden of costs incurred in the present and in the future. The discount rate is a tool frequently used to enable a comparison between costs incurred at different points in time. But great uncertainty exists as to the proper rate of comparison. Problems in determining the correct rate occur for a variety of reasons, including the fact that the beneficiaries of possible changes in the rate of emissions of greenhouse gases will be, to a large extent, future generations, while costs may be incurred to a greater extent by those currently alive (see, for example, NAS 1991). Rather than attempt to deal with uncertainties associated with comparing costs across time, we have chosen to report costs in the year in which they occur only. We provide perspective by comparing these costs to the then-current GNP. In addition, we have made no attempt to assess the demographic, geographic, or sectoral distribution of the costs of emissions reductions policies. While important, these issues are beyond the scope of the present study and remain to be addressed in future research.

Analysis of Current Policies

Three sets of policies were examined with regard to their impact on greenhouse gas emissions: Current Policies, NES Actions, and Policy Instruments Beyond the NES Actions.

The first set consists of the Current Policies Base Case. This is also the reference case used in the NES analysis. It is examined in Chapter 5. Three general assumptions guide the development of this case, modeled in Fossil2: that there are no major changes in current laws and energy policies

after September 1990, that there are no major changes in the structure of the U.S. economy and world energy markets, and that new technologies currently under research or development are allowed to penetrate the market based on current technology and cost estimates (Volume I). This case is thought of as a "continuation of current trends" case.

In the Current Policies Case, energy prices are driven by the world oil price. The world oil price increases about 160% during the simulation period, 1987 through 2030. The wellhead price of natural gas peaks in 2030 at 360% above its 1987 level. The minemouth price of coal remains relatively stable over the entire period, rising slightly more than 50% between 1990 and 2030. The path of electricity prices over time is even more stable than that of coal, increasing 16% between 1990 and 2030.

Energy consumption rises 80% between the years 1987 and 2030. Domestic oil consumption increases slowly over the entire simulation period, by about 60%. Natural gas consumption peaks and falls, with a net increase of 37% by 2030. Coal consumption increases 206%, due primarily to its use in electric power generation.

U.S. GWP-weighted greenhouse gas emissions increase approximately 50% between 1987 and 2030, due to an increase in fossil fuel emissions and to growth in electricity demand. Carbon dioxide emissions almost double between 1987 and 2030. There is little change in either the CO_2-to-fossil-fuel ratio or the fossil-fuel-to-energy ratio. The only factor in the Current Policies Base Case acting to reduce the emission of carbon per dollar of GNP is an assumed overall decrease of about 30% in the energy intensiveness of the economy. This is counterbalanced by reductions in GWP-weighted emissions associated with the phaseout of CFCs under the 1990 London Agreement, as implemented in the Clean Air Act Amendments of 1990.

Impacts of NES Actions

The second set of policies examined was the NES Actions Case, as defined in DOE (1991) and discussed in Chapter 5. The NES Actions Case combines a wide variety of policies to address the broad array of energy issues associated with the short-term and long-term provision of adequate supplies of energy at reasonable cost in an environmentally safe manner. It therefore meets the Presidential Directive of July 1989.

The implementation of the NES has a profound effect on future projections of U.S. greenhouse gas emissions. GWP-weighted emissions decrease 5% from 1990 to 2030 and never rise above 1990 levels. This is about 33% lower than the terminal level of GWP-weighted emissions anticipated under the Current Policies Case. While GWP-weighted emissions through 2030 never rise above 1990 levels, they are not constant. They decline between the years 1990 and 2000 in response to near-term NES Actions, but rise between 2000 and 2015 because economic growth spurs increased demands for energy services and because most of the benefits of phasing out CFCs have been captured. After 2015, GWP-weighted emissions decline again as the effects of long-term NES Actions, which, for example, encourage the introduction of nuclear and renewable energy technologies, reach the scale necessary to more than compensate for continued economic expansion.

Carbon emissions from fossil fuel combustion increase by 33% over the period between 1990 and 2030, compared to the roughly 100% growth projected for the Current Policies Base Case over the same time period. Of this reduction, 31% is due to reduced emissions associated with oil, and 69% is due to reductions associated with coal. Most of the difference between the two scenarios in 2030 is due to decreases in CO_2 emissions. The highest level of fossil fuel carbon emissions occurs in the years 2020 and 2025, but these emissions levels are lower in the year 2030.

The importance of various policy instruments within the NES Actions package in reducing potential future U.S. GWP-weighted emissions varies with time. Over the course of the next decade, integrated resource planning, coupled with changes such as energy efficiency actions that reduce electricity demand, greater use of alternative-fueled vehicles, natural gas reforms, and the expanded use of waste-to-energy technology are important. By the year 2030, increased transportation fuel efficiency and expanded use of alternative fuels and alternative vehicles, expanded use of nuclear energy, energy efficiency and integrated resource planning efforts, and industrial energy efficiency improvements become more important. (With the NES Actions implemented, the Clean Air Act Amendments of 1990 are projected to have only a minor incremental impact on greenhouse gas emissions, although this legislation is important in that it implements the United States' participation in the Montreal Protocol and the subsequent London Agreement.)

The most dramatic change in energy production and use in the Current Policies Case as compared to the NES Actions Case is in coal production and use. In the NES Actions Case, coal consumption still increases, but the rate of growth over the entire simulation period falls from about 200% to 80%. Total primary energy consumption grows only 55% in the NES Actions Case, as opposed to 80% in the Current Policies Base Case. Oil consumption increases 9% by 2030, as opposed to a 50% increase in the Current Policies Case. Natural gas follows a peaking pattern similar to that of the Current Policies Case, decreasing in 2030 by 17% from the 1987 level. Renewable energy use rises approximately 150% by 2030 in the NES, and nuclear power generation increases from 0.4 quads in 2030 under current policies to 12.5 quads under NES actions.

Policy Options Beyond the NES

Additional policy options that go beyond the NES Actions Case in reducing energy-related greenhouse gas emissions were analyzed using the Fossil2 Model of U.S. energy-economy interactions. There were three basic kinds of policies: fiscal (taxes) (Chapter 6), regulatory intervention (Chapter 7), and a combination of fiscal and regulatory strategies (Chapter 8).

Individual policy instruments examined in this volume were selected from a much larger list developed in DOE (1989). Five broad strategy groupings are identified in DOE (1989): fiscal incentives; regulation; information; research, development and demonstration; and combined strategies. These instruments provide specific policy tools capable of inducing all sectors of the economy to alter behavior. Information and research, development and demonstration policy instruments are included within the set of NES Actions. This volume focuses on fiscal incentives, regulation, and combined strategies that go beyond the NES Actions. Within the latter three policy categories, a limited set of policy instruments was chosen, instruments which were representative of these classes of actions and which, on theoretical and empirical grounds, appeared to hold promise of effectiveness in reducing greenhouse gas emissions.

In evaluating the results, it is important to recognize that any projection spanning a 40-year horizon is necessarily quite speculative. The baseline trajectory, and the impact of particular actions to change it, could differ significantly from those outlined in this report, which is based on a specific set of assumptions. It must be recognized that the actual jumping-off point from which policies have their effect cannot be known with certainty in advance. Therefore, even if we knew the actual effectiveness of individual policies, attainment of an absolute emissions or energy-use targets with a specified set of policies cannot be guaranteed. For this reason, commitment to such targets implies an inherently open-ended exposure that is not captured in the analysis of scenarios in this report.

To emphasize that the NES Actions Case is itself a policy scenario and thus subject to uncertainty, we have conducted a limited sensitivity analysis on the costs of policies under a modified baseline. In the sensitivity cases, we use the results

of the NES Actions Case as the baseline except with respect to nuclear power, where results from the Current Policies Case are used (that is, no new nuclear plants are ordered and existing plants continue to operate until reaching retirement). For the purposes of a sensitivity analysis, the modified nuclear power assumption was chosen because it provides a useful illustration of the potential consequences of the uncertainty involved in defining a baseline from which additional policies are measured.

Figures ES.1 through ES.9 (shown at the end of the Executive Summary) show the total, marginal, and average cost of implementing each of nine of the greenhouse gas emissions control strategies that go beyond the NES costs for the years 2000, 2010, and 2030. These figures plot the cost and emissions reductions associated with individual policies and should be used as a quantitative point of reference for the following discussions of individual policy instruments.

Fiscal Policies, Chapter 6

Two of the fiscal instruments examined were forms of financial incentives. The first policy calculates fuel-specific tax rates based on carbon emissions from the combustion of fossil fuels (carbon taxes). The second fiscal policy uses the concept of GWP as an alternative metric for development of tax rates (GWP taxes). GWP-weighted energy taxes take account of the release of all greenhouse gases (not simply carbon) from combustion of fossil fuels, as well as the release of greenhouse gases from extraction and distribution of these fuels.

Both the carbon and GWP taxes are powerful individual policy instruments for reducing potential future GWP emissions beyond the reductions achieved by the NES Actions. Carbon taxes are particularly cost-effective in reducing future fossil fuel carbon emissions because the incentive to reduce carbon emissions is equal in all applications; that is, an incentive to reduce emissions through either energy conservation or fuel switching exists as long as the cost of reducing emissions is lower than the carbon tax. The GWP tax was slightly more effective in reducing potential future GWP-weighted emissions of greenhouse gases than was the carbon tax. The appropriate weights to employ for different fuels are open to debate, and it is not clear that non-combustion emissions could not be more effectively addressed with emission-specific taxes or controls.

It is important to note that the present analysis is restricted to energy sector activities, where gases other than CO_2 play a relatively minor role. The advantage of a GWP tax over a carbon tax would be greater if allowance was made for the role of non-carbon greenhouse emissions from other economic sectors.

A carbon tax or GWP tax does not affect all fuels equally. Biomass, nuclear, and renewable energy technologies, as well as energy conservation, are not taxed. Fossil fuels are taxed unequally with regard to energy content. For a $100/mtC fuel tax, the cost of minemouth coal would increase by almost 250% (up $55 per short ton of coal), and crude oil prices would jump over 70% ($12.19 per barrel), while the cost of gasoline would increase about 25% ($0.26 per gallon), and the wellhead price of natural gas would rise about 82% ($1.49 per trillion cubic feet). (See Table ES.1.)

The tax rate necessary to hold carbon emissions roughly constant between 1990 and 2000 is approximately $100/mtC. While emissions would be expected to increase between the years 2000 and 2015 at this tax rate, by the year 2030, a tax rate of $100/mtC would be expected to reduce U.S. carbon emissions to 1990 levels. The tax necessary to reduce carbon emissions by 20% in the years 2000 and 2010 rises sharply to approximately $500/mtC. Reductions of carbon emissions by 50%, relative to 1990 levels, in the year 2010 were not achieved.

That the cost of any specific emission reduction relative to 1990 levels is greater around the year 2015 is the result of two factors that work in opposite directions: the scale effect and the time-to-adjust effect. The interplay of these two factors

Table ES.1. Fuel Price Changes per $100 Carbon Tax

Fuel	Base Cost($)	Added Cost($)	Added Cost(%)
Crude Oil ($/bbl)	16.01	12.19	73
Gasoline ($/gal)	0.98	0.26	27
Heating Oil, distillate ($/gal)	0.89	0.29	33
Wellhead Natural Gas ($/tcf)	1.81	1.49	82
Residential Natural Gas ($/tcf)	5.87	1.50	25
Minemouth Coal ($/short T)	23.02	55.33	240
Utility Coal ($/short T)	33.51	55.33	165
Electricity (c/kwh)	6.5c	1.76c	27

Notes: 1989 constant dollars. Base year 1990.

determines whether costs of meeting emissions reduction objectives rise or fall over time. The scale effect reflects the fact that, as population and economic growth continue, there are increasing demands for energy services. The time-to-adjust effect refers to the fact that the further into the future a change needs to be made, the less costly that change is likely to be, since a more orderly transition can be made. As a result of NES Actions, it is projected that GWP-weighted emissions will peak in the year 2015 and decline thereafter. The decline in emissions is predicated on the success of DOE research programs in developing new and improved energy technologies that have had sufficient time to attain significant market share, so the time-to-adjust effect overtakes the scale effect. Costs rise prior to that date because growing demand for energy services can only be met with a limited set of shorter term response tools, including energy conservation and fuel switching, which do not include major increases in energy production capacity for non-carbon energy technologies--the scale effect overwhelms the time-to-adjust effect. Beyond the year 2015, these technologies join energy conservation and fuel switching, making it possible to achieve emissions reductions at lower costs.

These tax rates are associated with greater reductions in GWP-weighted emissions, as they build on the accomplishments of the NES Actions. A carbon tax of $100/mtC would be associated with a reduction of between 10% and 15% in GWP-weighted emissions relative to 1990 levels over the course of the next two decades and would effect a more than 25% reduction by the year 2030.

Total energy consumption decreases between 1990 and 1995 for the $100/mtC carbon tax case as the taxes are being phased in. After 2000, total energy consumption grows at a roughly equivalent average annual rate of 1%/yr for all cases. In 2015, total oil consumption peaks in all cases, including the NES Actions Case. The importance of oil as a form of energy consumption decreases after 2015. Natural gas consumption is lower in all tax cases than in the NES up to 2000, but exceeds NES consumption in all cases from 2010 onward. All carbon taxes reduce coal consumption relative to the NES, with more stringent tax cases yielding greater reductions.

The total cost of carbon emissions reductions relative to U.S. GNP is less than 1% for tax rates of

$100/mtC or less. These losses rise to more than 1% at a tax rate of $500/mtC and escalate rapidly thereafter. As defined here, however, these total costs do not reflect transfers or adjustment costs.

Carbon and GWP taxes also raise a great deal of tax revenue. At the rate of $100/mtC, more than $130 billion/yr is raised. Such high rates of tax revenue generation would necessitate a reappraisal of overall national tax strategies.

A sensitivity analysis was conducted on the carbon and GWP taxes against the NES Actions scenario results with the assumption that no new or life-extended nuclear capacity comes into operation. The results differ little from those of the tax cases with the full NES Actions until after the year 2010. The results diverge after this point, as the growth in nuclear power assumed in the NES Actions Case has its impact. With the NES Actions Case results as the baseline, the carbon tax required for a 20% reduction in carbon emissions, relative to 1990, in the year 2030 is approximately $300/mtC and results in a total cost in 2030 of $97 billion. In the case without new nuclear power, however, a carbon tax of about $430/mtC is required to maintain this 20% reduction and results in a total cost in 2030 of $172 billion.

It is important to point out that, other than the use of forests to sequester carbon, no technologies that capture and dispose of carbon have been examined in this report. Such technologies exist, but have never been deployed on a wide scale. (See Volume I of this report.) Significant uncertainties about disposal exist for those technologies that capture carbon either before or after fuel combustion in the form of CO_2. Abandoned gas wells, salt domes, and deep ocean have been suggested as repositories for captured CO_2. The implementation of technologies that use coal as a carbon feedstock for the production of hydrogen also produce carbon in solid form as a byproduct; disposal is therefore not an issue with such technologies. They would, however, require the development of an infrastructure to transport and use the hydrogen. The successful development of such technologies could radically alter the role of fossil fuels, coal in particular, in future reduced emissions cases.

Regulatory Instruments, Chapter 7

Four individual policies were examined:

1. *Reforestation*: New trees are planted to an extent sufficient to sequester carbon equivalent to the amount released by new utility powerplants over the lifetime of their operations.

2. *Powerplant Energy Efficiency Standards*: An energy efficiency standard for new electricity generating capacity is created based on the most energy-efficient generating technology available. New capacity installed by utilities must meet this standard or the utilities will be penalized based on the degree to which the efficiency of actual new capacity falls short of the standard.

3. *Buildings Energy Efficiency Standards*: A wide range of standards is established for buildings and their energy-using devices. Standards are set so that the additional cost of a kilogram of carbon emissions reductions is equal in all applications.

4. *Transportation Energy Efficiency Standards*: Energy efficiency standards are set for new gasoline-powered passenger vehicles.

Two of the four regulatory policy instruments studied were directed at electricity-generating facilities. The first policy, Reforestation, mandated the planting of trees to offset the incremental lifetime carbon emissions of all newly constructed and life-extended fossil fuel-fired power plants. The Reforestation policy reduces carbon emissions in two ways: first, it encourages non-fossil electricity-generating technologies, more efficient (clean) fossil generating technologies, and electricity conservation; and second, the trees planted for the new fossil fuel plants sequester the emitted carbon. Reforestation provided the greatest GWP-weighted

emissions reduction of any single regulatory policy instrument examined, and it did so at economic costs only slightly greater than those observed for a combined strategy of carbon taxes and a reforestation rebate.

Because reforestation appears to be the most powerful and cost-effective option among the regulatory strategies considered, we have also analyzed this option under the NES Actions Case without new and life-extended nuclear power assumptions. The results here are similar to those for sensitivity analysis of the carbon and GWP tax cases; that is, the effect of the nuclear power assumptions is small over the first half of the study period, but raises the costs of emissions reductions in the years 2015 through 2030. In 2030, the total cost of the Reforestation Case with the sensitivity analysis assumptions is $51 billion, compared to $33 billion when the full NES Actions Case results are used as the baseline.

There are several unaddressed issues and uncertainties associated with implementation and maintenance of the Reforestation Policy. One major issue is the institutional mechanism for monitoring and enforcing such a policy. New institutions likely would be required and could have implications for all land use in the United States.

A further problem is the long-term disposition of the trees. The carbon uptake of the trees will not continue indefinitely. Beyond the year 2030, the "new" trees planted in this case eventually mature and cease their carbon uptake. If the trees are left in place, they continue to occupy land resources. In the analysis presented in Chapter 7, slightly less than 340 million acres of the United States, including marginal crop lands, is involved in the program, sequestering at a maximum rate of between 350 TgC/yr and 700 TgC/yr by the year 2030, based on an average sequestration rate measured over a 40-year lifetime and depending upon the sensitivity chosen. The program would increase total forest lands by up to half again their present size and would account for up to one-fifth of all agriculture-related lands, potentially requiring as much as half of those lands currently used as croplands. If the trees were used as a biomass fuel, they would release carbon back into the atmosphere with an emission coefficient approximately the same as that of coal. If the trees were harvested and used in wood products that do not oxidize for long periods, they would have no net carbon release to the atmosphere, but could substantially affect the market for forest products. Expectations of such effects could in turn reduce reforestation activities within the traditional foresting sector, lessening the net effect of the program.

In light of the uncertainties associated with a major reforestation program, our approach was to study specific scenarios assuming an unspecified mechanism that induced reforestation with carbon sequestration potential equivalent to new plant emissions without addressing any of the problems discussed in the preceding paragraphs. Two scenarios were studied. The first scenario takes the carbon sequestration supply schedule given by Moulton and Richards (1990). The second uses the arbitrary assumption that only half of the carbon sequestration will be available at any cost, and its associated cost schedule is derived on the assumption that land prices will be three times greater than at present. We do not specify whether the reduced availability of land comes from the fact that productivity is lower than anticipated by Moulton and Richards or that there is less land to be had; either is possible. To the extent that land is less available, the price of land is implicitly more than three times greater than at present. These scenarios were constructed to serve as sensitivities indicating that the potential effectiveness of reforestation is uncertain.

The second policy aimed at electricity generating plants was the Powerplant Efficiency Standards. These standards were designed as cost penalties for the construction of new fossil fuel plants that did not employ the most efficient generating technology available. These standards were not as effective as Reforestation in reducing GWP-weighted emissions, both because they did not take advantage of the carbon sequestration potential of reforestation and because they allowed some types of fossil fuel

powerplants, although only the most efficient, to come into operation and emit carbon without suffering any penalties.

The two remaining regulatory instruments studied were standards imposed on energy end-use sectors. The first set of end-use standards was the Buildings Standards. These standards produced relatively small reductions in greenhouse gas emissions beyond the levels achieved in the NES Actions Case, when compared to the fiscal and utility regulation policies examined in this study. This does not mean that there are few opportunities for energy conservation in the buildings sector; the potential for cost-effective energy conservation in this sector is great. Rather, this result is indicative of the success the NES Actions will have in affecting energy conservation. In general, there are only marginal additional gains to be obtained beyond NES Actions unless measures can be found that have the effect of reducing the apparent internal rate of return of end-use energy consumers.

The second set of end-use standards was the Transportation Energy Efficiency Standards on gasoline-powered passenger vehicle fuel efficiency. The Transportation Energy Efficiency Standards had only a marginal effect on greenhouse gas emissions, relative to the NES Actions Case, due in part to the low share of vehicle miles accounted for by gasoline-powered passenger vehicles in the NES Actions Case and the correspondingly high market share of non-conventional vehicles. In 1990, the share of non-conventionally-fueled passenger vehicles in the NES Actions Case is zero. By 2010, this share has grown to 30%, and by the year 2030, just over 56% of total passenger vehicles in service are non-gasoline-driven. Indeed, in 2030, methanol-powered vehicles constitute exactly the same percentage of the total as do gasoline-powered vehicles, about 43%.

In general, end-use energy efficiency standards that go beyond the NES Actions appear to be relatively expensive as strategies for reducing potential future greenhouse gas emissions. Their high reported cost is due both to the fact that NES Actions induce the introduction of many energy conservation and efficiency technologies and to the fact that the analysis in this report explicitly accounts for "take back"[a] costs. Other benefits and costs of the regulatory approach, which include the possible benefits or costs of substituting expert engineering judgment for private choice made by individual consumers, are not explicitly calculated. For example, both information costs and the availability of products suited to a particular taste or application will be reduced by regulation. However, an analysis of the cost reductions associated with a reduction of the apparent consumer discount rate is provided to define an extreme upper bound on the overall potential benefit from regulations, standards, and institutional change. Narrowing this range further remains a research task for the future.

In addition, we conducted an analysis to explore an upper bound on the maximum potential of energy-efficient technologies in the residential, commercial, and industrial sectors of the economy to further reduce the cost of greenhouse gas emissions reductions. The analysis is similar in approach to a "bottom-up" technology analysis, but incorporates economic feedback effects. These estimates indicate that, in the year 2000, the total cost of achieving the 20% reduction in GWP-weighted emissions relative to 1990 levels could be substantially reduced if all energy efficiency technologies having a positive present value using a 5% discount rate were installed when new investments were made, and if an aggressive tree planting program were implemented in addition to a carbon tax and the continued phase out of CFCs. The cost of achieving a 50% reduction in GWP-weighted emissions relative to 1990 levels would also be significantly reduced.

(a) This term refers to the fact that, when standards mandate the introduction of more efficient technologies than would be purchased by consumers, the cost of the energy service provided by the technology falls. Consumers respond to the lower cost of energy services by increasing their use of the service. The observed reduction in demands for fuels is therefore less than might be expected because consumers "take back" some of the energy demand reductions in the form of increased use of the energy service.

This sensitivity provides an upper bound on the maximum market potential of currently available technology. In this regard, three caveats are especially important. First, market potential may be overstated (and costs understated) because consumer decisions regarding the technologies may actually reflect heterogeneity in applications or in other product attributes that are not incorporated in the modeling framework, rather than failures in capital markets. Second, there may not be any policies that can capture the technological potential. Finally, even if policies are available, they may present other problems, by failing to account for heterogeneity or other attributes or by diverting investment resources from alternative opportunities that offer internal rates of return higher than 5%.

Combined Strategies, Chapter 8

Three sets of combined strategies were considered. The first strategies are either carbon taxes or GWP taxes on energy combustion gases applied in combination with a tax refund for the sequestration of carbon through the planting of trees. The second pairing of policies was to combine reforestation with efficient building standards equivalent to a $250/mtC carbon tax level. The final combination strategy was to impose a series of carbon or GWP caps with tradeable permits.

The combination of carbon or GWP taxes with a refund for reforestation showed the greatest reductions for a given cost. Due to the uncertainty of the cost of such a large tree planting program, the analysis was bounded through the inclusion of three alternative sensitivity cases for the supply schedule of carbon sequestration. The energy impacts are the same as those derived in the fiscal policies, given the same level and type of tax. This is a result of the assumption that the energy and forest sectors are independent. However, the impact on net U.S. GWP-weighted greenhouse gas emissions is improved by the addition of a sink enhancement (trees) for the sequestration of carbon. The result is that while GWP-weighted energy-related emissions are reduced 20% in the year 2000 (as compared with 1990) with approximately $150/mtC$_e$ GWP tax, the addition of a reforestation program could reduce the tax rate to between $15 and $30/mtC$_e$, depending on whether low- or high-cost trees more truly reflect the cost of the reforestation program and achieve this same level of reduction. The total cost of this reduction would likewise fall from about $17 billion per year in the year 2000 (no reforestation program beyond the President's tree initiative) to between $4 billion and $6 billion per year for low- and high-cost trees, respectively.[a]

Looking at the combined strategies, the results of a sensitivity analysis using as the baseline the NES Actions without new and life-extended nuclear power are similar to those for the tax cases and the Reforestation Case in the previous chapters. The growth in nuclear power expected to occur in the NES Actions Case has little effect on the cost of reducing carbon and greenhouse gas emissions in the short term, but has a larger impact on costs after the year 2010. In the sensitivity case with the modified nuclear power results, the total cost of reducing GWP-weighted emissions by 50% of 1990 levels in 2030, with the comprehensive approach of GWP taxes and reforestation with high-cost trees is $63 billion in 2030, compared to $40 billion under the full NES Actions Case assumptions.

It appears that, without a very large reforestation program,[b] a 50% reduction in GWP-weighted emissions is not achievable in 2010, and although

(a) The terms "high-cost trees," and "low-cost trees" refer to two separate carbon sequestration cost schedules. Low-cost trees employ the "best guess" cost schedule in Moulton and Richards (1990). High-cost trees employ a sensitivity to the low-cost trees case in which the land costs were assumed to be triple those in the "best guess" case. The same cautions and uncertainties raised with regard to the forestry component of the Reforestation Case apply equally to the GWP Taxes with a Refund for Reforestation Case. These include the issue of long-term disposition of the trees and land-use policy, as well as uncertainties associated with cost.

(b) As with the Reforestation Case examined in Chapter 7, a program with maximum potential to sequester 725 TgC/yr and using 340,000,000 acres of land is assessed. The maximum program could increase forested lands by 50% and account for one-fifth of total agriculture-related land area, or 15% of total U.S. land, and require as much as half of all lands currently used as croplands.

such a reduction can be achieved by 2030, it requires a $710/mtC$_e$ GWP tax. However, even in the High-Cost Trees Case, an approximately 50% reduction could be achieved in 2010 at a GWP tax rate of approximately $150/mtC$_e$ and at a total cost of about $56 billion in that year. With low-cost trees, a reduction of this magnitude would require a similar GWP tax, but the total cost would fall to about $32 billion in 2010, due to the differing costs of the reforestation program.

The pairing of a reforestation program with building standards has little impact on overall energy consumption or GWP-weighted emissions beyond what was achieved with the reforestation program alone. The costs and removal results of the carbon and GWP caps analyses are nearly identical to those for the carbon and GWP taxes, if an interpolation is made for those levels of caps.

We must recognize here, as we did in discussing the Reforestation Case developed in Chapter 7, the special issues associated with using tree planting as a net sink for carbon. Trees typically absorb carbon at a relatively constant rate for a limited period of time. This period of time depends on the particular tree species under consideration. For the species considered in this analysis, at least 40 years of carbon uptake appears typical. After that, a tree reaches its mature state, and annual carbon uptake decreases steadily. Because the period of analysis that we have chosen is 40 years, the use of trees appears to be a relatively cheap method for controlling carbon emissions. It is important not to be misled by the boundary conditions of the study. Beginning in the year 2030, the uptake of trees planted in the year 1990 diminishes. This results in a problem: the carbon sink begins to fill. At this point, several options appear. The trees could be left in their present locations as a standing stock of carbon, but with a diminishing carbon uptake. Alternatively, they could be cut down and transported to some storage site where their carbon would not be released to the atmosphere; the sites would then be replanted. No obvious way exists to continue to obtain a constant rate of uptake of carbon by trees in the long term. Trees are therefore an option that can only be used for a relatively limited time to reduce net carbon emissions to the atmosphere.

Because of these uncertainties, a sensitivity analysis has also been conducted for the GWP Tax with Refund Case, in which it is assumed that the potential carbon sequestration from reforestation is reduced to 50% of the original estimate. Under this Reduced Sequestration Case, the total cost of achieving a 20% reduction in GWP-weighted emissions levels in 2000 was $13 billion per year, while the total cost of achieving a 50% reduction in 2010 rose to $204 billion per year.

It is also important to note that crucial institutional questions arise if a major program to use "new" trees to sequester carbon is contemplated. The definition of "new trees" and development of a set of accounts for these trees are non-trivial problems.

Comparison of Relative Costs

Overall, the combined policy of GWP taxes on energy combustion gases with credit for reforestation using low-cost trees yields the greatest reduction in GWP-weighted emissions at lowest total cost for all years. This is shown in Figures ES.1 through ES.9, which plot the total, marginal, and average costs of implementing greenhouse gas emissions control strategies beyond the NES Actions for the years 2000, 2010, and 2030.[a] For instance, at a 20% reduction level in the year 2000, the combined strategy of GWP taxes and trees would cost between $3 billion and $9 billion per year in that year, depending on assumed reforestation potential and costs; achieving this same level of reduction through a program of GWP taxes without trees would cost well over $17 billion per year in the year 2000. Point estimates are provided for the other control strategies, none of which is more

(a) We note here the duality between a GWP-weighted energy-related emissions cap with a tradeable permit and credit for reforestation and the tax case above.

effective than the GWP taxes and trees. In considering any of the results involving reforestation, the difficulty in identifying a specific regulatory mechanism that could implement the modeled scenario, as outlined in the discussion of Chapter 7, should be kept in mind. The reforestation option alone showed substantial emissions reductions at costs close to the combined GWP taxes and trees. It should be noted that, at lower levels of reduction (around 10%), the cost of the alternative strategies is relatively close. Also, costs and emissions reductions associated with the two sets of Transportation Energy Efficiency Standards are so close as to be indistinguishable from each other in the year 2000.

As with total costs, the marginal cost curves for the GWP taxes with low-cost trees are farthest to the right; that is, for the same level of marginal cost, this policy produces the greatest reduction in GWP-weighted energy-related emissions. This is shown in Figures ES.4 through ES.6, which plot the marginal costs ($/mtC$_e$) of reducing GWP-weighted energy-related emissions.

The average costs of GWP-weighted emissions reductions are universally lower than the marginal costs. In many cases, average costs are significantly lower than marginal costs. This fact is the direct result of the modeling approach used, which always chooses lowest cost emissions reduction options first. We report both marginal and average costs to avoid the great potential for confusion associated with these two reporting modes. Figures ES.7 through ES.9 show the average cost in dollars per tonne of carbon dioxide equivalent ($/mtCO$_2$e) of reductions from all nine scenarios that go beyond the NES Actions. (Note the change in units of measure from mtC$_e$ to mtCO$_2$e. Recall that a tonne of carbon dioxide can be converted to an equivalent carbon value by multiplying mass by the ratio 12/44.) As with total and marginal costs, the average costs of reductions are lowest with the GWP taxes and low-cost trees.

There is a general tendency at any given emissions level for costs to increase between the years 2000 and 2015 and then decrease thereafter. This is due to the time required to bring new energy supp options on-line, particularly new renewable ene technologies and a second generation of nucl facilities. The first new reactors, for example, be coming on line in the year 2015. The effect of this additional electric power generating technology is important; it allows utilities to expand electric power without directly producing greenhouse gas emissions.

Macroeconomic Impacts, Chapter 9

A policy's indirect macroeconomic effects can propagate through the many markets and sectors of the economy. Most potential greenhouse gas control policies would increase expenditures on end-use energy consumption and/or energy conservation. Other policies such as reforestation would also require added expenditures, but those would not be primarily related to the energy sector.

The levels of tax revenue generated by either the carbon tax or the GWP-weighted taxes needed to stabilize or reduce carbon emissions or achieve substantial reductions in GWP-weighted emissions relative to 1990 levels are so large compared to the scale of the economy that they would cause a general reassessment of national tax policy.

A $100/mtC carbon tax generates over $130 billion per year. If such a tax were enacted and revenues were used to reduce the federal deficit, overall output would be depressed relative to the baseline forecast for a decade or longer. The models studied suggest that the imposition of a $100 carbon tax would create a loss of GNP in 2000 ranging between 1% and 3% of the GNP without the tax. Over the longer term, such a tax could actually cause GNP to be greater than under the no-tax NES Actions Case. This result occurs because, when the tax is used to retire debt, it acts as an increase in national savings, which makes more funds available for private investment, leading to more rapid accumulation of capital in the economy and eventually to greater GNP. It is important to note, however, that while GNP may be significantly higher in the year 2030 than it would have been

without a carbon tax, our analysis shows that personal consumption is lower in all years than it would have been without a carbon tax. Use of the carbon tax to reduce the deficit also acts as a mechanism to force national savings.

Two additional points are worth noting. First, these are model results and not forecasts. It is also possible that even when taxes are used to retire debt there may be long-term reductions in GNP. Second, the ability of the government to raise taxes and, indirectly, national savings does not depend on revenue from greenhouse-related taxes. The government always has this fiscal policy option.

If the revenues from the tax were returned to individuals by the government in some fashion, the pattern of effects would be quite different. In the short run, up to 3 years, the rebating of tax revenues by reducing either the personal income tax or the payroll tax rate would lead to a short-term expansion in economic activity. By 1993, GNP is estimated to be from 1% to 4% higher than it would be otherwise. The high end of this range would give pause to policymakers seeking to avoid inflationary pressures. After this immediate boost, however, the models all show long-term detrimental effects on economic growth from this policy. By the year 2000, real GNP might be reduced by 1% to 2%, with further reductions in subsequent years.

The estimated macroeconomic impacts from the combined reforestation/building standards policy are considerably less than those from the tax. By 2000, the range of GNP losses is from 0.2% to 1.0%. In the long term, there is more uncertainty about the direction and magnitude, as the results in this study are sensitive to choice of assumptions and selection of model.

The principal point to be made regarding the results of Chapter 9 is that the revenues generated by carbon taxes of a magnitude considered in this study are so great that if actually raised, they would necessitate a national fiscal policy reassessment.

International Implications, Chapter 10

The United States produces only part of the global total emissions of greenhouse gases. For example, it accounts for approximately 23% of present fossil fuel carbon emissions to the atmosphere, a fraction that has declined steadily from approximately 40% in 1950. This share is expected to continue to decline throughout the remainder of this century and into the next (IPCC 1989). It is clear that the United States acting alone cannot control the composition of the Earth's atmosphere; the expected increase in carbon emissions from nations other than the United States over the next twenty years exceeds total U.S. emissions in 1990. Similarly, the OECD as a whole could not stabilize emissions at present levels beyond the year 2020. Here, too, expected growth in non-OECD emissions exceeds present total OECD emissions.

The imposition of policies to directly control greenhouse gas emissions must be crafted with some care in an open economy. For example, the imposition of carbon taxes at the point of emission results only in a significant decrease in the direct emission of carbon to the atmosphere by the United States. However, there is great incentive for energy-producing industries to expand exports of fossil fuels to the rest of the world. Greenhouse gas emissions reduction policies reduce net imports of oil, but their effect on greenhouse gas emissions is far greater than their effect on oil imports. A carbon tax applied as a severance tax on the production of fossil fuels (without a concurrent tariff on carbon-based fuel imports) has the result of extinguishing domestic oil and gas production and radically curtailing coal production, while only reducing net United States emissions marginally.

Comparison to Other Studies, Chapter 11

A great deal of confusion appears in the literature on greenhouse gas emissions reduction strategies, due to the way in which results are reported. Some carbon emissions are reported in

short tons, while others use metric tonnes (1 metric tonne = 1.102 short tons). Some emissions are reported in terms of carbon weight emissions, while others assume complete oxidation of the carbon content of the fuel and report emissions as CO_2 emissions (1 kilogram carbon = 12/44 kilograms CO_2). Some studies report only fossil fuel carbon emissions, while other studies consider GWP-weighted emissions from all sources. Some studies report the tax rate or marginal cost of achieving a fixed level of emissions reduction, while others use the average cost (average cost is always less than marginal cost). Some studies report total cost of emissions for a particular year, while others report the discounted sum of total costs over varying lengths of time. A significant increase in the level of agreement between studies might be achieved if reporting results were standardized.

Some of the differences in findings between studies with regard to the cost of potential greenhouse gas emissions reductions can be reconciled by simply standardizing the form in which results are reported, but other differences are more fundamental. One body of literature that has emerged is frequently referred to as the "bottom-up" approach, as it attempts to build energy-economic scenarios from a technology basis. This literature frequently finds that significant reductions in potential future greenhouse gas emissions could be obtained if technologies that are either currently available or expected to be available in the near future were widely deployed. Such a deployment is generally found to result in both reduced potential future greenhouse gas emissions and reduced energy costs. These studies usually recommend a policy of energy efficiency standards to accomplish this deployment. This result contrasts sharply with the traditional economic approach, sometimes referred to as the "top-down" approach, which assumes, as a first approximation, that a market economy operates efficiently and that deviations from the market equilibrium have economic costs.

The approach to cost employed in this volume is economic in nature and assumes that correctable market imperfections that remain after the implementation of the NES Actions are relatively minor. While we feel that this volume makes some progress in identifying the issues necessary to reconcile the bottom-up and top-down approaches, we have not attempted such a reconciliation; we have simply recognized the results of the bottom-up literature. We have not reconciled the two approaches in part because we have not developed a full set of tools for doing so.

A review of the rapidly expanding literature on the cost and effectiveness of measures to reduce potential future greenhouse gas emissions reveals that the cost of emissions reductions obtained by this study is well within the range of estimates obtained elsewhere, when results are reported in common format. We note that the range of reference case energy-related carbon emissions developed by various studies encompasses both the Current Policies and NES Actions Cases. While there is a large and growing literature on the topic of greenhouse gas emissions reductions, this study is one of the few that examines the costs of strategies beyond the NES for reducing the combined effects of multiple energy-related greenhouse gases. To do this, we have employed the comprehensive approach discussed earlier.

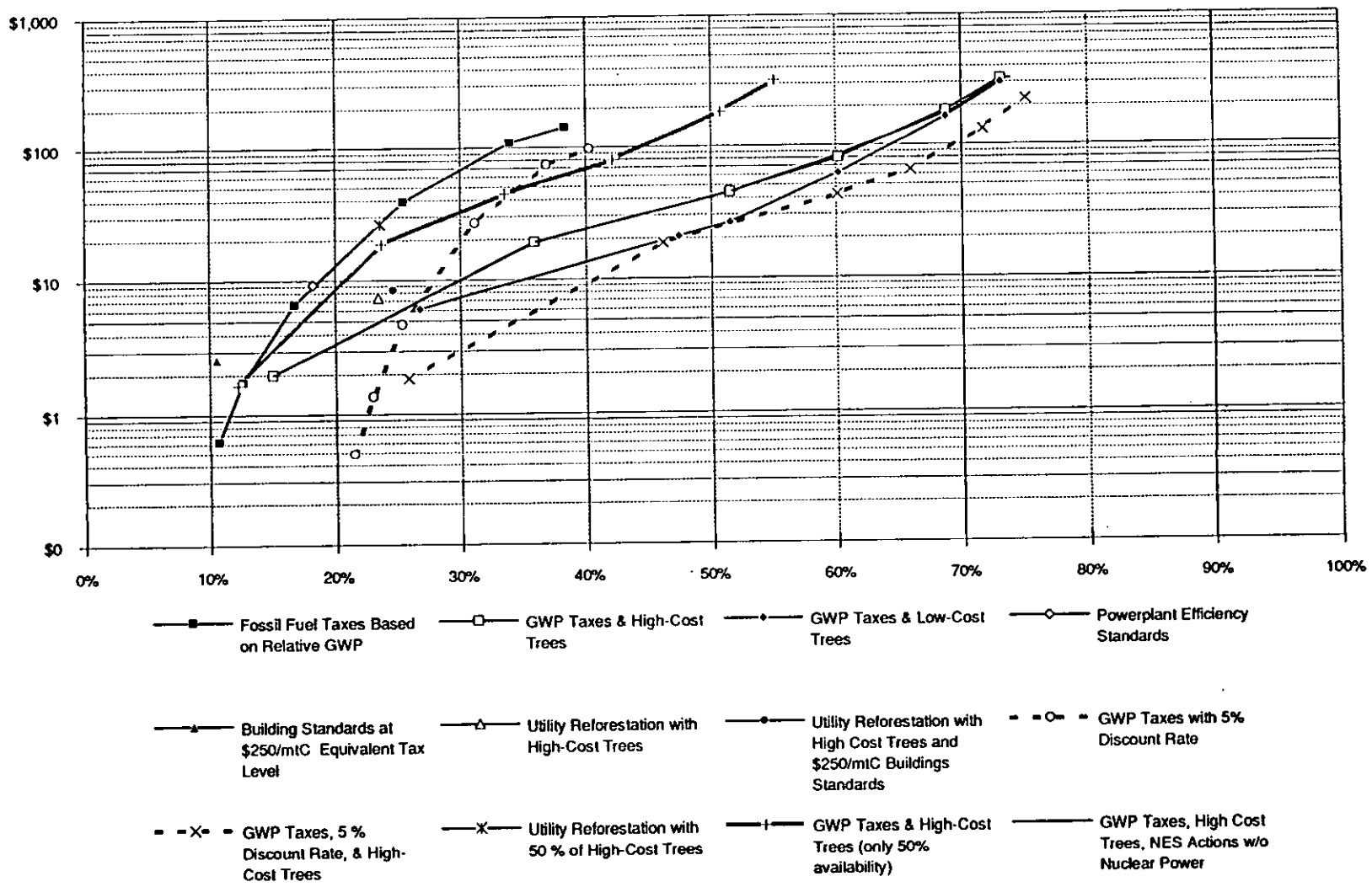

Figure ES.1. Total Cost (billions of 1989$) in the Year 2000 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

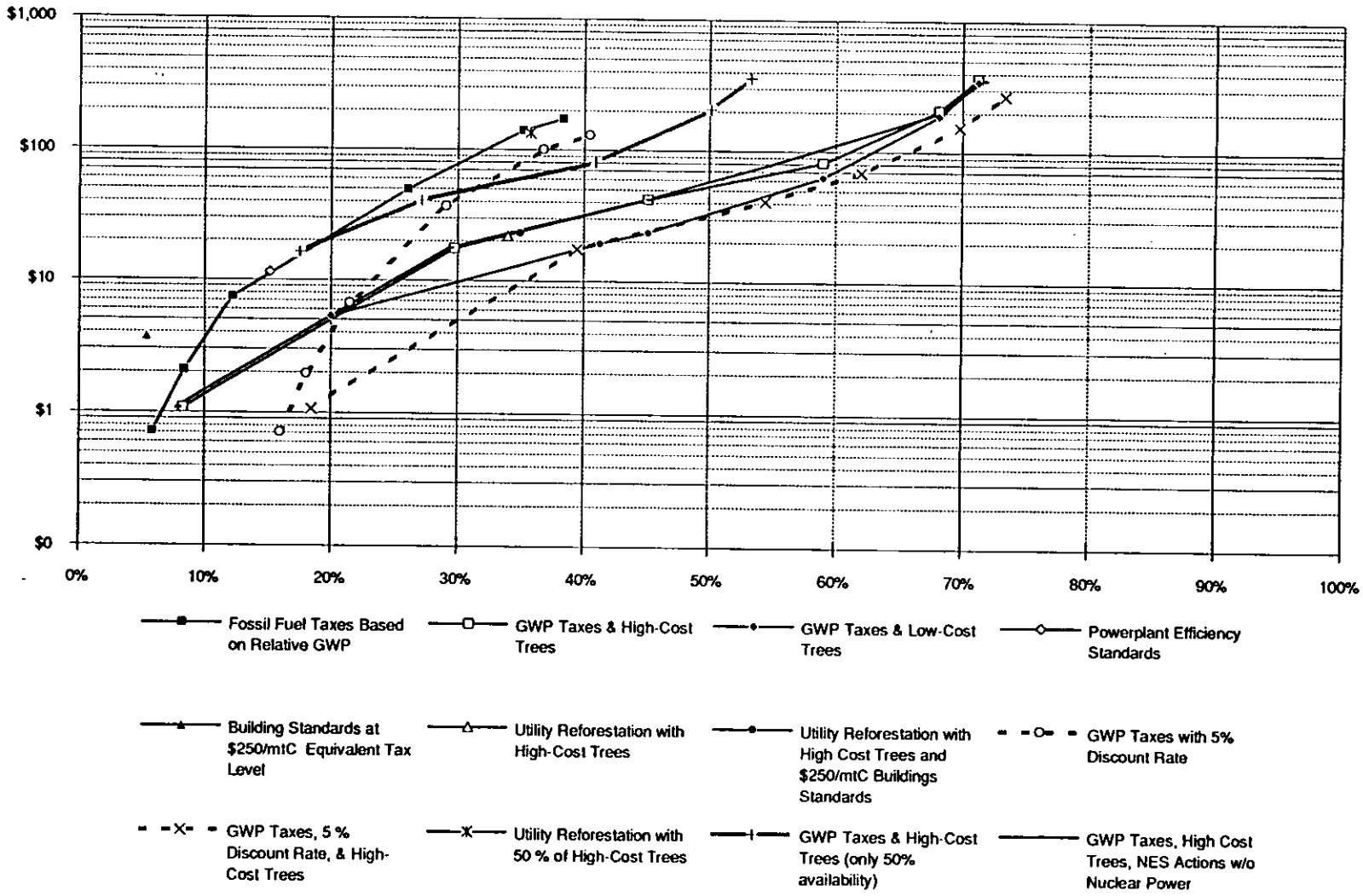

Figure ES.2. Total Cost (billions of 1989$) in the Year 2010 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

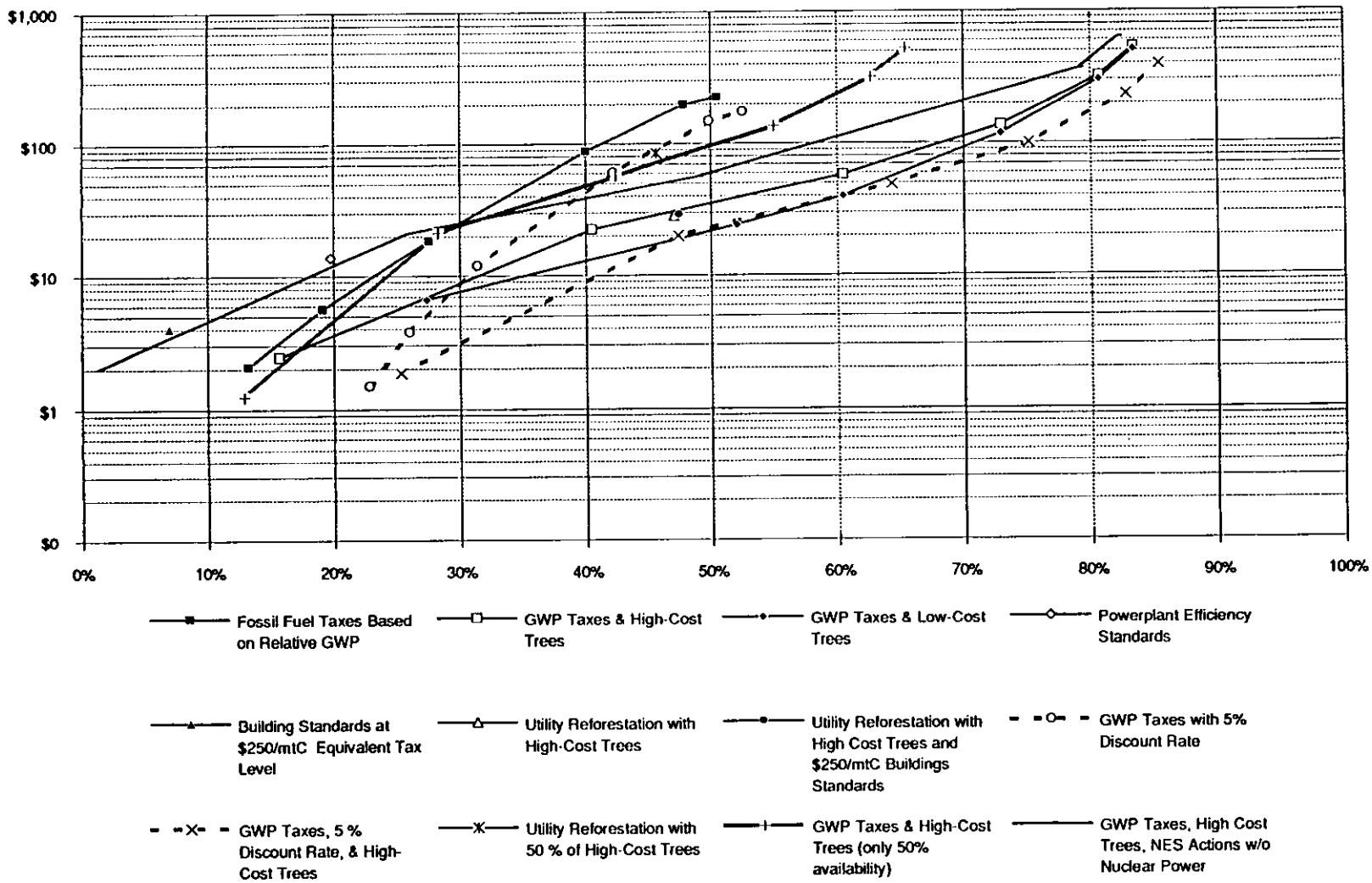

Figure ES.3. Total Cost (billions of 1989$) in the Year 2030 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

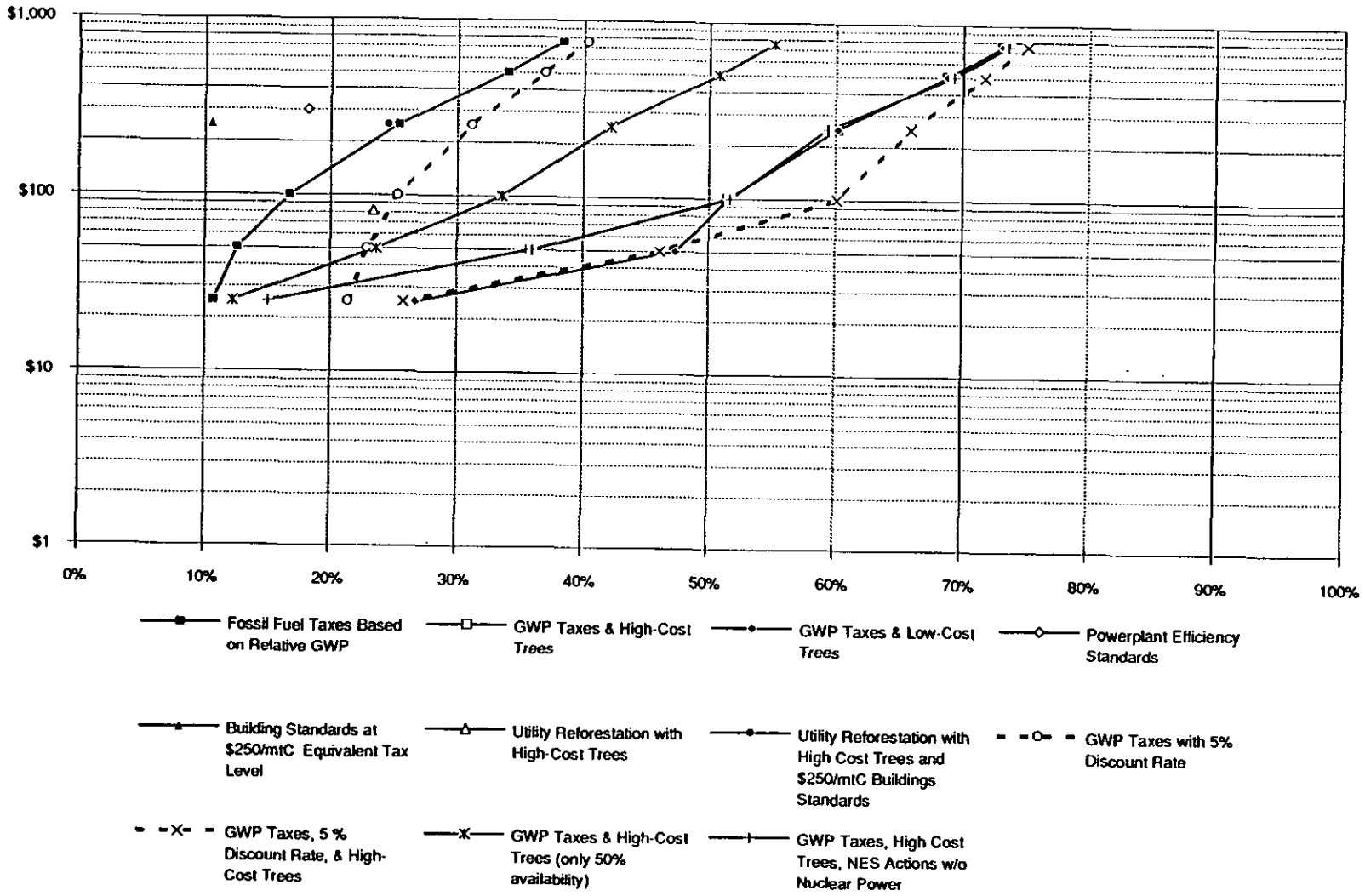

Figure ES.4. Marginal Cost ($/mtC$_e$) in the Year 2000 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

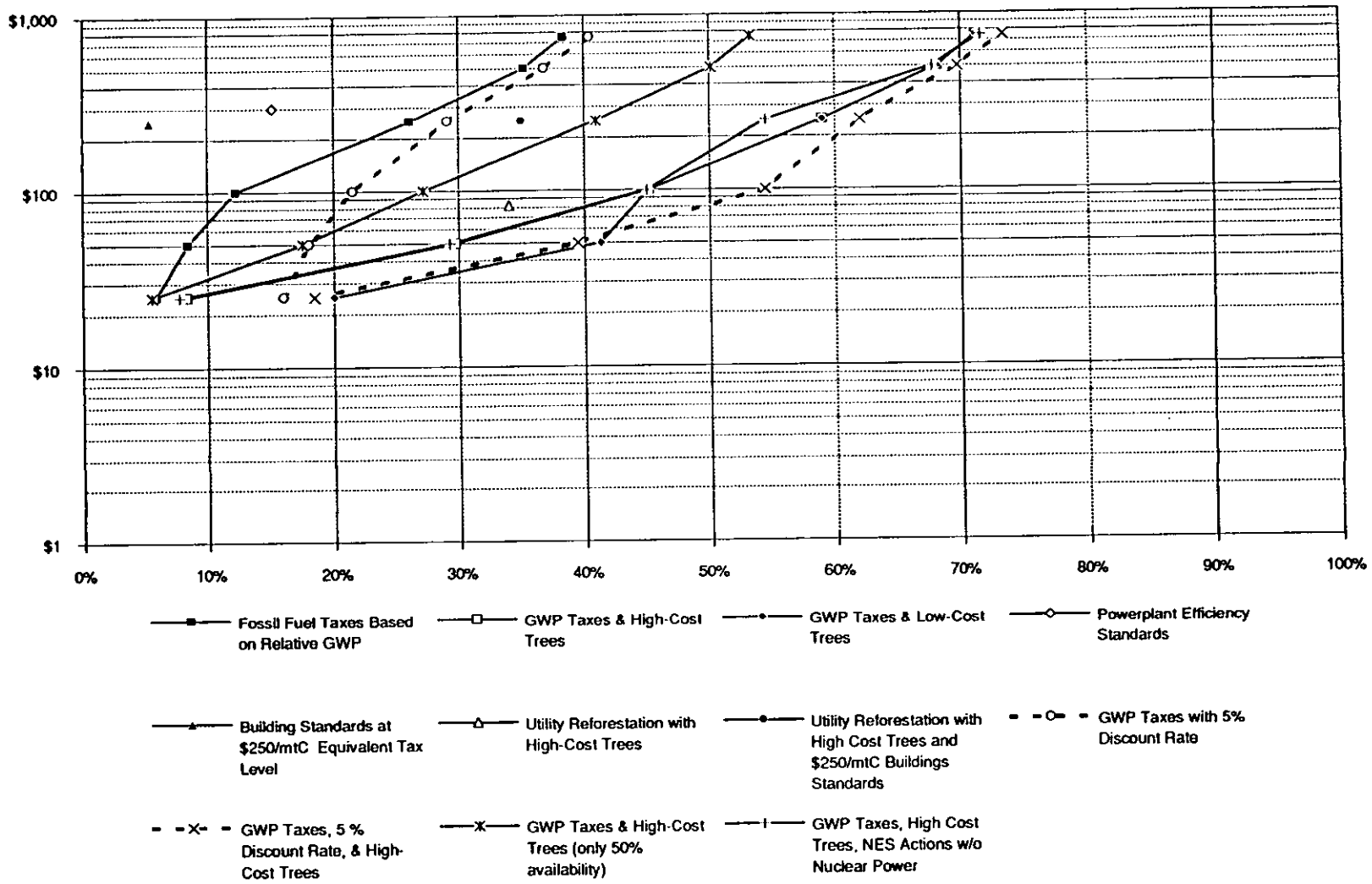

Figure ES.5. Marginal Cost ($/mtC$_e$) in the Year 2010 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

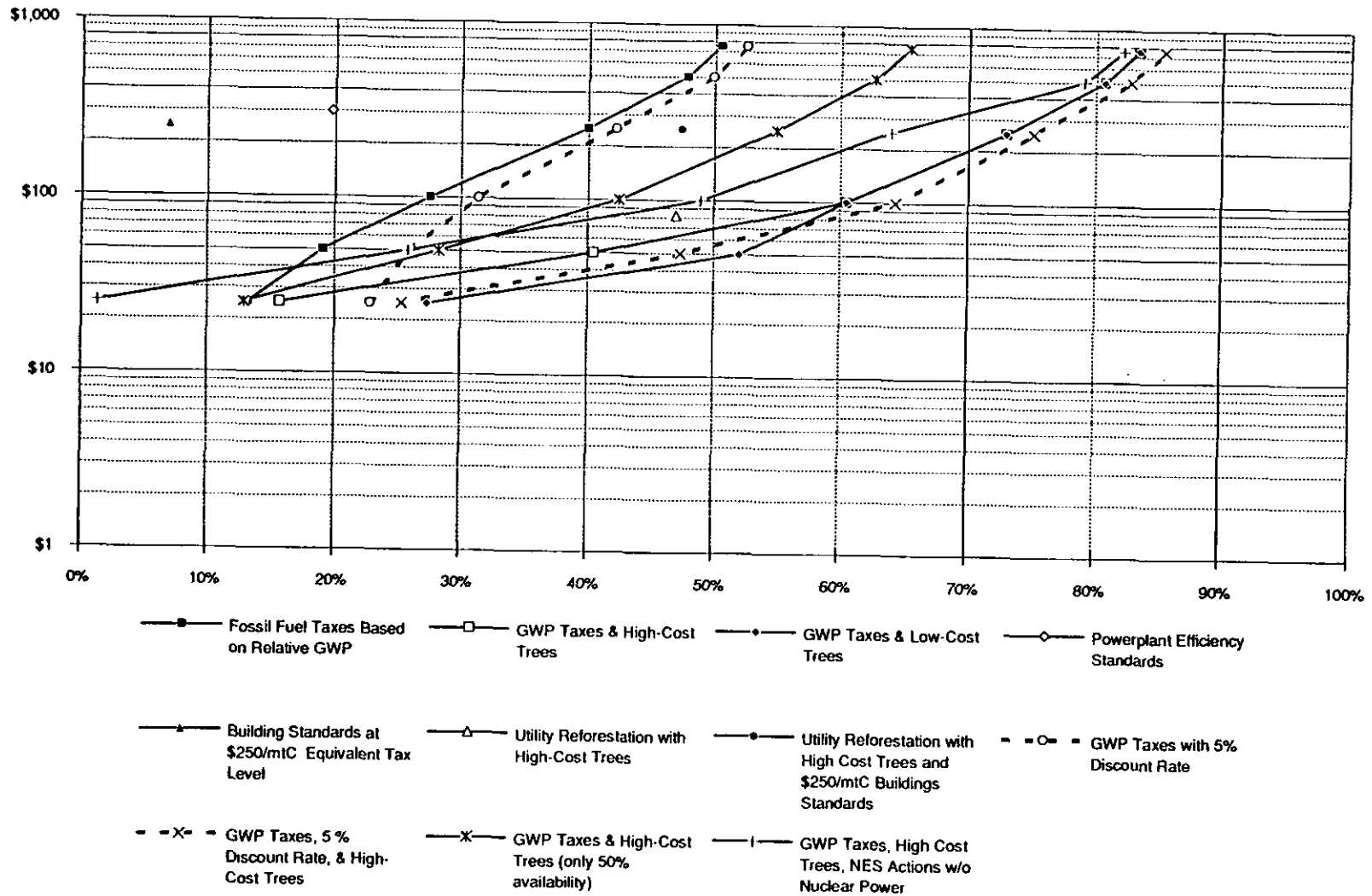

Figure ES.6. Marginal Cost ($/mtC$_e$) in the Year 2030 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

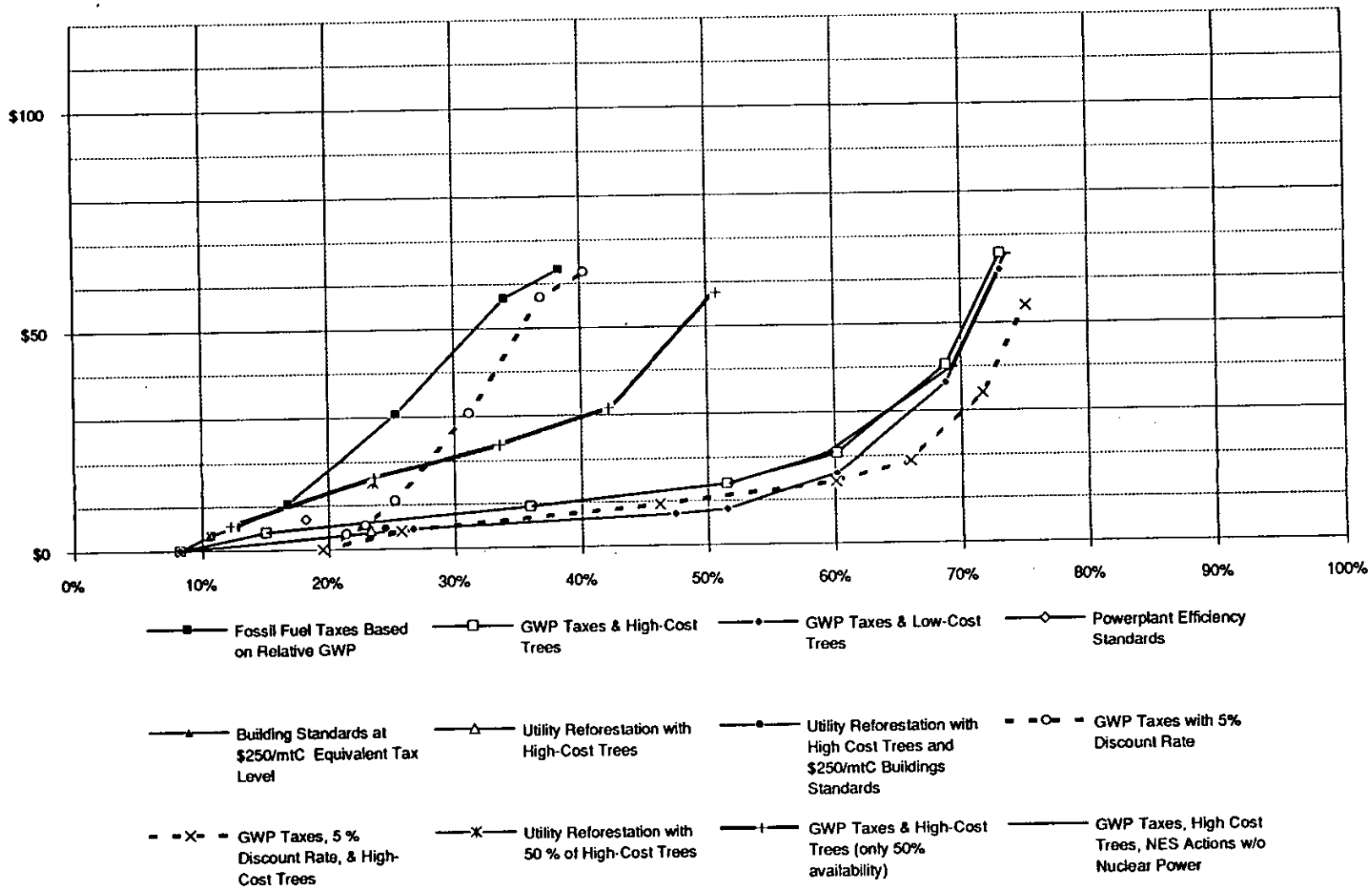

Figure ES.7. Average Cost ($/mtCO$_2$e) in the Year 2000 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

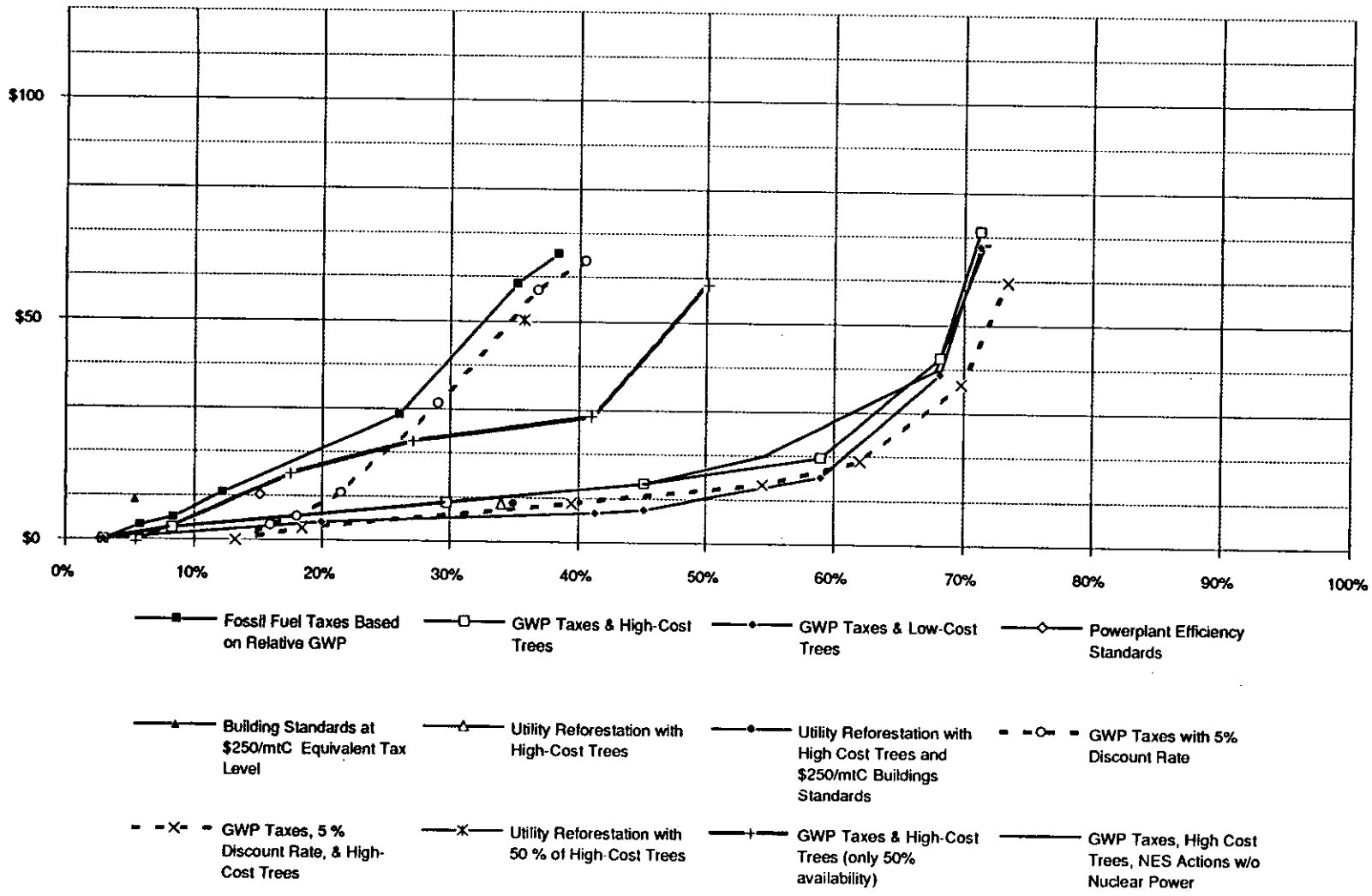

Figure ES.8. Average Cost ($/mtCO$_2$e) in the Year 2010 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

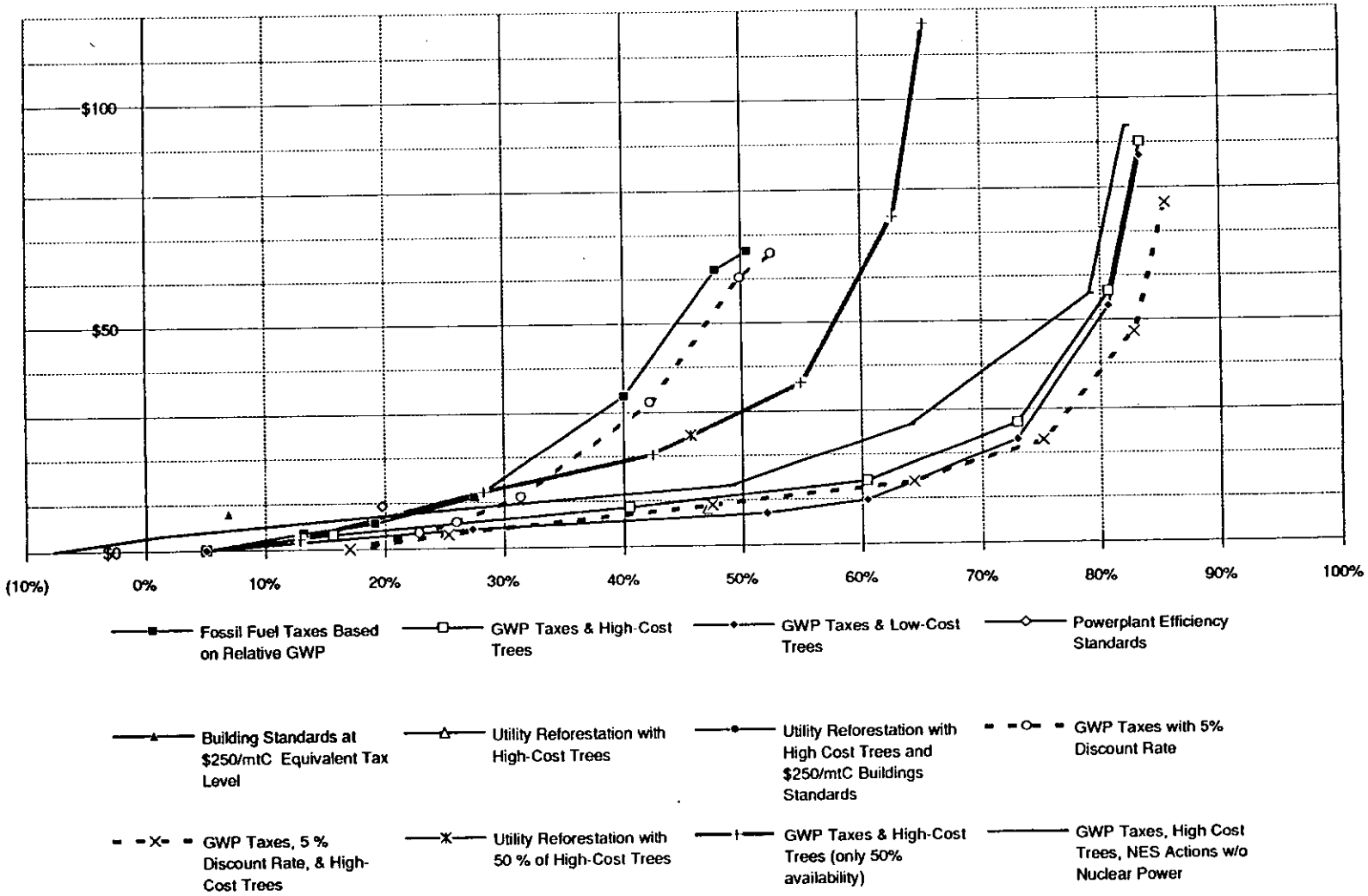

Figure ES.9. Average Cost ($/mtCO$_2$e) in the Year 2030 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

LIST OF ACRONYMS

ABWR	advanced boiling water reactor
AC	alternating current
AFBC	atmospheric fluidized-bed combustion
AFUE	average fuel use efficiency
ALMR	advanced liquid metal reactor
ALWR	advanced light water reactor
APWR	advanced pressurized water reactor
atm	atmosphere
bbl	barrel
BWR	boiling water reactor
°C	degrees Celsius
CAES	compressed air energy storage
C_e	carbon equivalent
CFCs	chlorofluorocarbons
$CFCl_4$	chlorofluorocarbon-11, F-11, CFC-11
$CFCl_2CF_2Cl$	chlorofluorocarbon-113, CFC-113
CF_2Cl_2	chlorofluorocarbon-12, F-12, CFC-12
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	coefficient of performance
CPCM	composite phase-change materials
DC	direct current
DISC	direct-injection stratified-charge
DOE	U.S. Department of Energy
E/GNP	total energy use divided by gross national product
ECPA	Electric Consumers Protection Act of 1986
EJ	exajoule, 10^{18} joules, $1.055 \cdot 10^{15}$ Btu, 1.055 quads
EPA	U.S. Environmental Protection Agency
EOR	enhanced oil recovery
EPRI	Electric Power Research Institute
ERM	Edmonds-Reilly Model
ETBE	ethyl tertiary butyl ether
°F	degrees Fahrenheit
FERC	Federal Energy Regulatory Commission
FGD	flue gas desulfurization
FY	fiscal year
g	gram
GBR	gas-cooled breeder reactor
GJ	gigajoule
GNP	gross national product
GtC	gigatons of carbon

GW	gigawatt
GWe	gigawatt-electric
GWP	global warming potential coefficients
GWt	gigawatt-thermal
HCFC	hydrogenated chlorofluorocarbon
HFC	hydrogenated fluorocarbon
HTGR	high-temperature gas reactors
HTS	high-temperature superconducting
HVAC	heating, ventilation, and air-conditioning
ICCT	Innovative Clean Coal Technology
IFR	Integral Fast Reactor
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
ISTIG	intercooled steam-injected gas turbine
ITH	integration time horizon
kg	kilogram, 10^3 grams
kWh	kilowatt-hour
LHR	low heat rejection
LMFBR	liquid metal fast breeder reactor
LNG	liquefied natural gas
LWR	light water reactor
mbd	million barrels per day
MBOE	million barrels of oil equivalent
MCF	million cubic feet
MCFC	molten carbonated fuel cell
MHD	magnetohydrodynamic
MHTGR	modular high-temperature gas-cooled reactor
mpg	miles per gallon
MRS	monitored retrievable storage
mt	metric tonne
MTBE	methyl tertiary butyl ether
mtC_e	metric tonne carbon equivalent
$mtCO_2$	metric tonne carbon dioxide
$mtCO_2e$	metric tonne carbon dioxide equivalent
MWe	megawatt-electric
MWt	megawatt-thermal
NAPAP	National Acid Precipitation Assessment Program
NAS	National Academy of Sciences
NEA	National Energy Accounts
NES	National Energy Strategy
NGCC	natural gas combined cycle
NO_x	nitrogen oxides
NPR	New Production Reactor
NRC	U.S. Nuclear Regulatory Commission
N_2O	nitrous oxide
NWPA	Nuclear Waste Policy Act of 1982
O_3	ozone

O&M	operation and maintenance
OECD	Organization for Economic Cooperation and Development
PAFC	phosphoric acid fuel cell
PCF	pulverized-coal-fired
PCM	phase-change materials
PFBC	pressurized fluidized bed combustion/combustor
Pg	petagram, 1×10^{15} grams, 1 billion metric tonnes
PIUS	process-inherent ultimately-safe (reactor)
ppb	parts per billion
ppbv	parts per billion volume
ppm	parts per million
ppmv	parts per million volume
ppt	parts per trillion
pptv	parts per trillion volume
PRISM	power reactor inherently safe module
PURPA	Public Utilities Regulatory Policies Act of 1978
PWR	pressurized water reactor
quad	quadrillion (10^{15}) Btu
R&D	research and development
RD&D	research, development, and demonstration
RDF	refuse-derived fuel
RRY	reference reactor year
SAFR	sodium advanced fast reactor
SBWR	simplified boiling water reactor
SCR	selective catalytic reduction
SMES	superconducting magnetic energy storage
SNG	synthetic natural gas
SOFC	solid oxide fuel cell
SO_2	sulfur dioxide
STES	seasonal thermal energy storage
STIG	steam-injected gas turbine
T&D	transmission and distribution
TAHP	thermally activated heat pump
TCF	trillion cubic feet
Tg	teragram, 1×10^{12} grams, 1 million metric tonnes
$TgCO_2e$	teragram carbon dioxide equivalent
TVA	Tennessee Valley Authority
yr	year

ENERGY AND EMISSION CONVERSION FACTORS

1 Btu	1054.8 joules
	2.93×10^{-4} kWh
1 barrel of petroleum	5.8×10^{6} Btu
1 metric ton petroleum	42×10^{6} Btu
1 metric ton petroleum	73 barrels of petroleum
1 cubic foot of natural gas	1030 Btu
1 ton coal (U.S. average)	22×10^{6} Btu
1 metric ton of coal (U.N. standard coal equivalent)	27.8×10^{6} Btu
1 kilogram	10^{3} grams
1 teragram	1×10^{12} Btu
	1 million metric tonnes
1 petagram	1×10^{15} grams
	1 billion metric tonnes
1 quad	10^{15} Btu
1 quad	1.055×10^{18} joules = 1.055 EJ (exajoule)
1 quad	0.47 million barrels oil per day
	CO^{2} emissions as 10^{9} metric tons of carbon
1 quad of oil	0.02 GtC (gigatons of carbon)
1 quad of coal	0.025 GtC
1 quad of natural gas	0.015 GtC
1 exajoule	10^{18} joules
	$1.055 * 10^{15}$ Btu
	1.055 quads

ACKNOWLEDGMENTS

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1.0 STATE OF THE SCIENCE IN ESTIMATING ATMOSPHERE/ CLIMATE CHANGE RELATIONSHIPS

Concern about the increasing release of "greenhouse gases" such as carbon dioxide (CO_2), methane (CH_4), and the chlorofluorocarbons (CFCs) by human activities has grown out of lengthy research by natural scientists that documents the buildup of gases in the atmosphere and estimates the implications of continued accumulations. A useful policy option menu can be developed by understanding the natural science relevant to global climate change and its attendant knowns, uncertainties, and unknowns.

This chapter summarizes the natural science literature needed to understand the role of greenhouse gases in the atmosphere. It summarizes:

- the nature of the greenhouse effect,
- the Earth's radiation budget,
- the concentrations of these gases in the atmosphere,
- how these concentrations have been changing,
- natural processes that regulate the concentrations and residence times for these gases in the atmosphere, and
- the rate at which human activities release these gases.

We address the issue of the greenhouse effect itself in the first section. In the second section, we examine trends in atmospheric concentration of greenhouse gases and emissions sources. In the third section, we examine the carbon cycle and its role in determining the atmospheric residence time of carbon dioxide (CO_2). In the fourth section, we examine the role atmospheric chemistry plays in determining the concentrations of greenhouse gases. This chapter is not intended to be an exhaustive treatment of these issues; such discussion can be found in other works, many of which are cited throughout this chapter. Rather, this chapter summarizes some major findings, unknowns, and uncertainties associated with the current state of knowledge regarding the role of greenhouse gases in the atmosphere. Other, more detailed summaries that might be of interest include: Trabalka (1985), MacCracken and Luther (1985a, b), Bolin et al. (1986), Wuebbles and Edmonds (1988, 1991), MacCracken, et al. (1990), and IPCC (1990).

1.1 THE GREENHOUSE EFFECT

A suite of naturally occurring gases, including water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), and nitrous oxide (N_2O), and gases of anthropogenic origin such as the chlorofluorocarbons (CFCs) and CFC-substitute chemicals, are largely transparent to incoming solar radiation, but can absorb infrared radiation re-emitted by the Earth. Because of this energy "trapping" property, such a gas is referred to as a greenhouse gas. Ironically, the trapping mechanism for a greenhouse is quite different from that for a greenhouse gas: in the greenhouse, glass blocks the convective rise of warm air. For a greenhouse gas, the warming of the surface of the Earth and cooling of the stratosphere is achieved via molecular absorption and reradiation in the infrared spectrum.

Figure 1.1 illustrates the relationship between solar radiation, Earth's re-emission of energy, and the greenhouse gases. The Sun emits most of its energy between 0.2 μm and 4.0 μm, primarily in the ultraviolet, visible, and near-infrared wavelength regions. A very small fraction of this energy is intercepted by the Earth as it orbits the Sun. Approximately 23% (MacCracken and Luther 1985b) of the incoming solar radiation is absorbed, principally by ozone in the ultraviolet and visible wavelength regions, and by water vapor in the near-infrared.

The Earth re-emits the energy it absorbs back to space, thus maintaining an energy balance. Satellite measurements indicate that the incoming and outgoing radiation of the atmosphere are in balance (Shine 1989). Because the Earth is much colder than the Sun, the bulk of the Earth's emission takes place at longer wavelengths than those of incoming solar radiation. Most of this radiation is emitted in the wavelength range from 4 μm to 100 μm, which is longwave or infrared radiation (Figure 1.1). While water vapor, carbon dioxide, and other greenhouse gases are relatively inefficient absorbers of solar radiation, they are strong absorbers of longwave radiation. Clouds also play an important role in determining the energy balance (Figure 1.2); one of the largest uncertainties in determining the climate change expected from greenhouse gases is our current limitation in understanding cloud processes (IPCC 1990; Ramanathan 1988). However, there is general agreement that the annual global mean effect of clouds is to cool the climate system (Arking 1991).[a]

The greenhouse gases (and clouds) re-emit the absorbed longwave radiation at a wavelength and intensity dependent on their local atmosphere temperature, which tends to be cooler than the Earth's surface temperature. Some of this radiation reaches space. Some of the radiation, however, is transmitted downward, leading to a net trapping of longwave radiation and a warming of the surface. As the concentrations of greenhouse gases increase, this net trapping of infrared radiation is enhanced. The net result is that surface temperatures rise until the amount of radiative energy being emitted to space balances the incoming solar radiation.

1.1.1 The Direct Radiative Influence

The contribution of a gas to the greenhouse effect depends on the wavelength at which the gas absorbs infrared radiation, the concentration of the gas, the strength of the absorption per molecule (line strength), and whether or not other gases absorb at the same wavelengths (see, for example, Ramanathan et al. 1985, 1987; Wang et al. 1985, 1986; Mitchell 1989). Gases absorb and emit radiation at wavelengths that correspond to transitions between discrete energy levels. Absorption at infrared (greenhouse) wavelengths occurs for triatomic or larger molecules where vibrational and rotational energy transitions occur at appropriate wavelengths. Although each transition is associated with a discrete wavelength, the interval over which absorption occurs is "broadened" either by addition or removal of energy due to molecular collision (pressure broadening) or by the Doppler frequency shift due to the random velocities of molecules (Doppler broadening). If absorption is strong, there may be complete absorption (saturation) around the central wavelength of the spectral line.

As shown in Figure 1.1, at a number of wavelengths, the high concentrations of water vapor and CO_2 almost completely absorb the radiation emitted at the surface before it can be lost to space. Increases in the concentrations of these species, therefore, lead only to increased absorption in the wings of the absorption lines, with the result that the net trapping of infrared radiation due to these gases (CO_2 and H_2O) increases logarithmically rather than linearly with concentration. Because the atmospheric temperature changes with altitude, additional concentrations of these gases also change the effective altitude of emission, thereby changing the infrared flux and further enhancing the greenhouse effect of these gases. Gases absorbing at wavelengths similar to those at which CO_2 and H_2O absorb will contribute little to the greenhouse effect unless they are present in comparable concentrations. However, Figure 1.1 shows that there is a region from about 7 μm to 13 μm where absorption by CO_2 and H_2O is weak; this is referred to as the "window region." Nearly 80% of the radiation emitted by the surface in the window region escapes to space (Ramanathan 1988). Most of the non-CO_2 gases with the potential to cause radiative forcing, including CH_4, N_2O, O_3, and the CFCs, have absorption lines in the window region. Some of these gases, such as CH_4 and N_2O, have absorption lines that lead to saturation of the line cores and emission

(a) Based on satellite data, the magnitude of the cooling is estimated to be in the range 17,027 W/m^2.

from the pressure-broadened Lorentz line wings; the net result is that their absorption increases as approximately the square root of their concentration. Gases with little overlap, such as CFC-11 and CFC-12, exhibit absorption that increases linearly with concentration.

The net result of these varying radiative characteristics is that comparable increases in concentrations of different greenhouse gases, including both those trace gases currently found in the atmosphere and possible new gases that may be introduced to replace CFCs, have vastly different effects on radiative forcing, as shown in Table 1.1. The instantaneous radiative forcing of the surface-troposphere system is the change in the net radiative flux at the tropopause (that layer of the atmosphere dividing the troposphere and the stratosphere); it can also be defined as the surface temperature change with zero climate feedbacks. The addition of one molecule of methane has about 21 times the effect on climate that the addition of one CO_2 molecule has; one CFC-11 molecule is about 12,400 times as effective as one molecule of CO_2. These differences occur because CH_4 and CFC-11 absorb in the window region, whereas the CO_2 molecule competes with not only H_2O, but also many other CO_2 molecules (i.e., the 15μm region of CO_2 absorption is saturated). Of the gases considered, added CO_2 has the least effect on radiative forcing of the gases, on a per molecule basis; however, it is still the primary gas of concern for climate change because it has the largest absolute change in concentration attributable to human activities.

Ozone plays an important dual role in affecting climate. Although the climate effect of CO_2 and the other trace constituents depends primarily on their concentration in the troposphere, the climatic effect of ozone depends on its distribution throughout the troposphere and stratosphere. Ozone and molecular oxygen are the primary absorbers of the ultraviolet and visible solar radiation in the atmosphere; absorption of solar radiation by ozone is responsible for the increase in temperature with altitude in the stratosphere. Ozone is also an important absorber of infrared radiation. It is the balance between these radiative processes and the local changes in ozone with altitude[(a)] that determines the net effect of ozone on climate. Increases in ozone above about 30 km tend to decrease surface temperature; increases in ozone below 30 km tend to increase surface temperature.

Several research studies using global atmospheric models have attempted to examine the relative effects of other trace gases on radiative forcing as compared to the effects of the increasing CO_2 concentrations (Lacis et al. 1981; Hansen et al. 1988; Ramanathan et al. 1985, 1987; Wang et al. 1986; Wigley 1987). Each of these studies indicates that the combined effects of the other trace gases are comparable to those of CO_2 emissions for both recent observed changes in species abundances and reasonable assumptions about future changes in their concentrations. For example, model calculations by Lacis et al. (1981) and Hansen et al. (1988) are shown in Figure 1.3; note that the radiative forcing is only the direct radiative effect on climate and does not account for the additional temperature change expected from the climate feedback effects of clouds, water vapor, sea ice, etc., nor for changes resulting from ocean-atmosphere interactions. These calculations indicate that by the 1980s, the combined effects of the other greenhouse gases on radiative forcing have become as large as the effects of the increasing CO_2 concentration.

Evaluations of future scenarios such as those by Ramanathan et al. (1985, 1987), Wang et al. (1985, 1986), and Hansen et al. (1988) suggest that these gases could effectively double, or more than double, the climate effect of the increasing CO_2 concentration alone. It is not surprising then, given the significant uncertainties concerning future trace constituent concentrations, that published scenarios for future changes in radiative forcing extend over a wide range of values.

1.1.2 The Greenhouse Gases

A number of greenhouse gases and other gases of importance or potential importance to climate

(a) See A. A. Lacis, D. J. Wuebbles, and J. A. Logan. 1990 (in press). "Radiative Forcing of Global Climate Changes in the Vertical Distribution of Ozone." *Journal of Geophysical Research.*

Table 1.1. Radiative Forcing (°F) Relative to CO_2 per Unit Molecule Change, and per Unit Mass Change in the Atmosphere for Various Greenhouse Gases at Present Day Concentrations

Trace Gas	Common Name	°F per Molecule Relative to CO_2	°F per Unit Mass Relative to CO_2
CO_2	Carbon Dioxide	1	1
CH_4	Methane	21	58
N_2O	Nitrous Oxide	206	208
CFC-11		12,400	3,970
CFC-12		15,800	5,750
CFC-11		315,800	3,710
CFC-11		418,300	4,710
CFC-11		514,500	4,130
HCFC-22		10,700	5,440
CCl_4	Carbon tetrachloride	5,720	1,640
CH_3CCl_3	Methyl chloroform	2,730	900
CF_3Br	Ha-1211	16,000	4,730
Possible CFC substitutes:			
HCFC-123		39,940	2,860
HCFC-124		410,800	3,480
HFC-125		513,400	4,920
HFC-134a		9,570	4,130
HCFC-141b		7,710	2,900
HCFC-142b		10,200	4,470
HFC-143a		7,830	4,100
HFC-152a		6,590	4,390

Source: Based on IPCC 1990.

change have been mentioned in the prior discussion. Table 1.2 indicates the direct and indirect means by which the gases affect climate, and Table 1.3 contains a synopsis of basic information on these gases.

1.1.3 The Climate Response

It is relatively easy to determine the direct forcing effect on surface temperature due to increases in greenhouse gases because the radiative properties of the greenhouse gases are reasonably well understood. In contrast, there are many uncertainties remaining about the extent of processes acting to amplify (through positive feedbacks) or reduce (through negative feedbacks) the expected warming. Some of the most important feedbacks that have been identified are discussed below.

H_2O Greenhouse Feedback. As the lower atmosphere (the troposphere) warms, it can hold more

Table 1.2. Greenhouse Gases and Their Importance to Climate

Trace Constituent	Common Name	Importance for Climate
CO_2	Carbon dioxide	Absorbs infrared radiation; affects stratospheric O_3
O_3	Ozone	Absorbs ultraviolet (UV) and infrared radiation
CH_4	Methane	Absorbs infrared radiation; affects tropospheric O_3 and OH; affects stratospheric O_3 and H_2O; oxidizes to CO_2
N_2O	Nitrous Oxide	Absorbs infrared radiation; affects stratospheric O_3
$CFCl_3$	CFC-11	Absorbs infrared radiation; affects stratospheric O_3
CF_2Cl_2	CFC-12	Absorbs infrared radiation; affects stratospheric O_3
$C_2F_3Cl_3$	CFC-113	Absorbs infrared radiation; affects stratospheric O_3
C_2F_5Cl	CFC-115	Absorbs infrared radiation; affects stratospheric O_3
CHF_2Cl	HCFC-22	Absorbs infrared radiation; affects stratospheric O_3
CCl_4	Carbon tetrachloride	Absorbs infrared radiation; affects stratospheric O_3
CH_3CCl_3	Methyl chloroform	Absorbs infrared radiation; affects stratospheric O_3
OH	Hydroxyl	Scavenger for many atmospheric pollutants, including CH_4, CO, CH_3CCl_3, and CHF_2Cl
CO	Carbon monoxide	Affects tropospheric O_3 and OH cycles; produces CO_2
NO_x	Nitrogen oxide	Affects O_3 and OH cycles; precursor of acidic nitrates
CF_2ClBr	Ha-1211	Absorbs infrared radiation; affects stratospheric O_3
CF_3Br	Ha-1301	Absorbs infrared radiation; affects stratospheric O_3
SO_2	Sulfur dioxide	Forms aerosols, which scatter solar radiation
$(CH_3)_2S$	Dimethyl sulfide (DMS)	Produces cloud condensation nuclei, affecting cloudiness and albedo
C_2H_2, etc.	NMHC	Absorbs infrared radiation; affects tropospheric O_3 and OH
COS	Carbonyl sulfide	Forms aerosol in stratosphere that alters radiation scattering

Table 1.3. Synopsis of Basic Information on Greenhouse Gases

Chemical Symbol	Are Source/Sink Rates Well Known?	Are Major Sources Energy Related?	Concentration in the Late 1980s (ppmv)[a]	Trend In Concentration	Radiatively Interactive?	Chemically Interactive?[b]
CO_2	yes/no	yes	350	increasing	yes	no
O_3	no/no	no	0.02-10	troposphere: increasing stratosphere: decreasing	yes	yes
CH_4	no/no	yes	1.7	increasing	yes	yes
N_2O	no/yes	yes	0.31	increasing	yes	yes
$CFCl_3$	yes/yes	yes	2.8×10^{-4}	increasing	yes	yes
CF_2Cl_2	yes/yes	yes	4.8×10^{-4}	increasing	yes	yes
CFC-113	yes/yes	no	60×10^{-6}	increasing	yes	yes
CFC-115	yes/yes	yes	5×10^{-6}	increasing	yes	yes
HCFC-22	yes/no	yes	120×10^{-6}	increasing	yes	yes
CCl_4	yes/yes	no	146×10^{-6}	increasing	yes	yes
CH_3CCl_3	yes/no	no	158×10^{-6}	increasing	yes	yes
OH	no/no	no	1.5×10^{-7} - 3×10^{-4}	?	no	yes
CO	no/no	yes	0.12 (N.H.) 0.06 (S.H.)	increasing	yes (weak)	yes
NO_x ($=NO+NO_2$)	no/no	yes	1×10^{5} - 0.02	?	yes (weak)	yes
CF_2ClBr	no/no	no	2×10^{-6}	increasing	yes	yes
CF_3Br	no/no	no	2×10^{-6}	increasing	yes	yes
SO_2	no/no	yes	$(0.1\text{-}2) \times 10^{-4}$	?	yes	yes
COS	no/no	yes	5×10^{-4}	increasing	yes	yes

(a) ppmv = parts per million volume

(b) The term interactions, as used here, refers to direct chemical interactions. Besides influencing atmospheric fluxes and temperatures, all greenhouse gases also directly affect the concentrations of other species by changing the rate of reaction, photodissociation rates, and/or other factors.

water vapor. The enhanced water vapor traps more infrared radiation and amplifies the greenhouse effect. Ramanathan (1988) indicates that, based on studies with one-dimensional climate models, this feedback amplifies the air temperature by a factor of approximately 1.5 and the surface warming by a factor of approximately 3. The recent IPCC (1990) report determined a surface temperature amplification factor of 1.6 for water vapor feedback.

Ice-Albedo Feedbacks. Global warming melts sea ice and snow cover. Whether it is ocean or land, the underlying surface is much darker (i.e., it has a lower albedo) than the ice or snow, so it absorbs more solar radiation, thus amplifying the initial warming. According to Ramanathan (1988), ice-albedo feedback amplifies the global warming by 10% to 20%, with larger effects near sea-ice margins and in polar oceans. More recent work by Cess et al. (1991)[a] involving 17 general circulation models, indicates that

(a) R. D. Cess et al. 1991. *Interpretation of Snow-Climate Feedback as Produced by 17 General Circulation Models.* Institute for Terrestrial and Planetary Atmospheres. Draft paper, State University of New York, Stonybrook, New York.

the net effect of snow-climate feedbacks is so uncertain that it is not even clear whether these feedbacks amplify or reduce warming.

Cloud Feedback. Cloud feedback mechanisms are extremely complex and are still poorly understood. Changes in cloud type, cloud amount, cloud altitude, and cloud water content can all affect the extent of the climate feedback. The sign of the feedback is also not understood, although current climate models generally find this to be a positive feedback. [This result is consistent with the findings of Cess et al. (1989) and Ramanathan et al. (1989), that the overall effect of clouds in the current atmosphere results in net cooling.] Because clouds are still treated rather crudely in existing three-dimensional climate models (general circulation models or GCMs), it is premature to draw reliable conclusions about the magnitude of cloud feedback processes, but it is clear that they cannot actually change the sign of the effect.

Ocean-Atmosphere Interactions. The oceans influence the climate in two fundamentally important ways (Ramanathan 1988). First, because of the importance of the water vapor greenhouse feedback, the air and land temperature response is affected by the warming of the ocean surface. If the oceans didn't respond to the greenhouse heating, the H_2O feedback would be turned off, since increased evaporation from warmer ocean is the primary source of increasing atmospheric water vapor. Second, oceans can sequester the radiative heating into the deeper layers, which, because of their enormous heat capacity, can significantly delay the overall global warming effect over land surfaces. Current climate models suggest this delaying effect may cause a lag of at least a few decades in the expected temperature response, with the best estimate being about 50 years (Schlesinger and Jiang 1990). However, the delay does not alter the fact that the equilibrium temperature will ultimately change.

Other feedbacks exist, such as changes in albedo related to changes in land features and biomass, but many of these feedbacks are not well understood. Figure 1.4 gives a schematic illustration of the many components of the coupled atmosphere-ocean-ice-land climatic system. It is the combined effect of the many uncertainties in feedback processes that has resulted in the factor of five (1.0° to 5.0°C) difference in the amount of equilibrium warming estimated to result from a radiative equivalent doubling of CO_2 concentrations relative to pre-industrial levels (NAS 1991).

At this time, climate models disagree as to the sign of changes in key climate variables on a regional scale for scenarios that double the pre-industrial concentrations of CO_2 (MacCracken et al. 1990). The present ability of general circulation models to predict changes in regional climatic variables limits the ability of researchers to adequately characterize the consequences of atmosphere/climate change.

It should also be noted that good agreement on radiation budgets does not extend to the majority of the models. In fact, "major model uncertainties...dwarf the radiative forcing effects due to potential increases in the concentration of atmospheric trace gases....These large disagreements among radiation computations do not manifest themselves as different computed climates because most climate models are tuned to give the 'right' answer" (DOE/ARM 1990).

Recent results obtained by Wang and Shi (1991) and Wang et al. (1991) have shown that the precise change in the composition of the atmosphere matters in calculating estimates of climate change. That is, there are significant differences in the resulting change in climate associated with, for example, carbon dioxide versus methane, even when they are both associated with the same change in radiative forcing.[a] Thermal infrared opacity of all radiatively active trace gases needs to be explicitly accounted for when attempting to predict the climate responses to increasing concentrations of greenhouse gases. Most general circulation models used to predict the climate

(a) For example, the overlapping between gaseous absorption bands has quite a large effect on the longwave flux calculations. The addition of 1.75 ppmv of methane contributes to a downward flux of 6.94 W/m^2 at the surface, but only 0.75 W/m^2 when the overlapping effect is included.

responses to increasing concentrations of greenhouse gases neglect explicit consideration of gases other than carbon dioxide.

1.2 ATMOSPHERIC CONCENTRATIONS AND EMISSIONS SOURCES OF GREENHOUSE GASES

The quality and detail of knowledge of historical emissions of greenhouse gases vary considerably among gases and sources. The general relationship between gaseous emissions and human activities is shown in Table 1.4. We will discuss the atmospheric concentration and emissions sources of the major emitted greenhouse gases.

1.2.1 Carbon Dioxide

Accurate observations of the concentration of greenhouse gases began in 1958, with measurements at the Mauna Loa Observatory in Hawaii. Figure 1.5 shows that the average annual concentration of CO_2 in the atmosphere has risen from approximately 315 ppmv in 1958 to approximately 350 ppmv in 1988. The average annual rate of growth of the CO_2 concentration is approximately 0.4%/yr. There is a clear annual cycle in the Mauna Loa data that corresponds to the annual cycle of plant respiration in the Northern Hemisphere. CO_2 concentrations increase during the fall and winter and decline during spring and summer seasons. This cycle, which follows the growth and decay of vegetation, is reversed and of smaller amplitude in the Southern Hemisphere. The smaller amplitude in the Southern Hemisphere reflects the smaller extent of landmass relative to the North. Estimates of the pre-industrial concentration of CO_2 have been made by sampling air trapped in ice cores. These estimates indicate that the pre-industrial concentration of CO_2 was approximately 280 ppmv. These estimates are shown in Figure 1.6, along with more recent observations. Jaworski et al. (1990) have recently questioned the reliability of the nineteenth century measurements and ice core data used to estimate pre-industrial concentrations at around 270 ppmv to 290 ppmv. Because of the importance of these data as a basis for determining the increase in CO_2 concentration due to human activities, it is important to critically evaluate their reliability.

Anthropogenic emissions of CO_2 are released principally from two human activities: fossil fuel use releases approximately 5.9 PgC/yr in 1988 (MacCracken et al. 1990), and land-use changes (deforestation) release approximately 1.5 PgC/yr in 1988. Lesser amounts are released by industrial processes such as cement manufacture--0.15 PgC/yr in 1988 (Boden et al. 1990; MacCracken et al. 1990). Confidence bounds for global fossil fuel CO_2 emissions of plus or minus 10% are frequently cited. Even if these bounds are overly optimistic, they are considerably narrower than the bounds that surround estimates for most other radiatively important greenhouse gas emissions, with the exception of CFCs. Fossil fuel CO_2 emissions levels are known with much greater certainty than are levels of CO_2 emissions from land-use change. Emissions of CO_2 caused by human activities take place against a background of enormous natural exchanges between the atmosphere and oceans and between the atmosphere and the terrestrial biosphere. Each of these fluxes is estimated to be in the range of 100 PgC/yr or more (Trabalka 1985). Sources of net CO_2 emissions and associated data quality are discussed in Chapter 3.

More is known about fossil fuel CO_2 emissions than about most other gas-emission sources. Since 1860, global annual emissions of fossil fuel CO_2 have increased from 0.1 (Trabalka 1985; Marland et al. 1989) to approximately 5.9 PgC/yr in 1988. During the period 1945 through 1979, the rate of CO_2 emissions from fossil fuel use grew at 4.5%/yr (Marland et al. 1989). Emissions declined from 1979 until 1983, but emissions have risen subsequently (Marland et al. 1989; Boden et al. 1990). The United States, the Soviet Union, and the People's Republic of China account for half of the world's fossil fuel CO_2 emissions (Marland et al. 1989). U.S. fossil fuel CO_2 emissions accounted for more than 40% of global emissions in 1950 (Trabalka 1985; Marland et al. 1989). The U.S. share has steadily declined to less than 25% in 1988 (Boden et al. 1990). U.S. CO_2 emissions peaked in

Table 1.4. Primary Anthropogenic Sources of Greenhouse Gases

Gas	Primary Anthropogenic Sources
CO_2	Fossil fuel burning; land-use conversion
CH_4	Ruminant animals; rice paddies, biomass burning; gas and mining leaks
CO	Energy use; agriculture; biomass burning (becomes a CO_2 source)
N_2O	Cultivation and fertilization of soils; combustion; nitric acid production, adipic acid production, and waste in ground and surface waters in N_2O sources
NO_x (=NO + NO_2)	Fossil fuel burning; biomass burning
$CFCl_3$	Industrial chemical
CF_2Cl_2	Industrial chemical
$C_2Cl_3F_3$	Industrial chemical
CH_3CCl_3	Industrial chemical
CF_2ClBr	Fire extinguishing
CF_3Br	Fire extinguishing
SO_2	Coal and petroleum burning
COS	Biomass burning; fossil-fuel burning
DMS	Primarily natural
NMHC	Incomplete combustion, agriculture
O_3	Not directly emitted, created by reactions involving NO_x in troposphere and by photolysis of O_2 in the stratosphere
OH	Not directly emitted, created naturally
H_2O	Anthropogenic emissions are small compared to natural evaporation; oxidation of CH_4 produces H_2O in the stratosphere

1973 (1.27 PgC/yr) and again in 1979 (1.30 PgC/yr) and remained below that level until 1988 (1.31 PgC/yr) (Boden et al. 1990). Global average per capita emissions of fossil fuel CO_2 to the atmosphere were approximately 1.2 mtC/capita/yr in 1988 (Boden et al. 1990). U.S. emissions were approximately 5.3 mtC/capita/yr in 1988 (Boden et al. 1990). Emissions of fossil fuel carbon dioxide are discussed further in Chapter 3.

There are approximately 600 PgC in the form of terrestrial biomass, principally stored in forests--Trabalka (1985) estimates the value at 560 PgC, and Bolin (1986) estimates 640 PgC. This is estimated to be about 15% to 20% (≈120 PgC) less than was present in the mid-nineteenth century (Trabalka 1985). On a global basis, this is estimated to vary less than about 10 PgC through the seasons as leaves and grasses grow and die. The phase pattern of Northern and Southern Hemispheric cycles is, of course, offset by one-half year (Trabalka 1985; Bolin 1986; Boden et al. 1990).

Estimates of the rate of annual emissions of carbon from land-use change are discussed in Chapter 3. The range of estimates of net releases of carbon from land-use change is far greater than for fossil fuel carbon, 0.4 PgC/yr to 2.6 PgC/yr (Chapter 3).

Conventional estimates of net CO_2 release from land-use change do not take into account the possibility of a CO_2 fertilization effect. While a matter of heated debate, it has been suggested that increases in the atmospheric concentration of CO_2 could accelerate the rate at which the terrestrial biosphere stores carbon. Most analysis is predicated on the proposition that the CO_2 fertilization effect, if it exists at all, must be small, and that the terrestrial biosphere is a net source of carbon release to the atmosphere [see, for example, Bolin (1986)]. Recent papers, including Tans et al. (1990), Goudriaan (1989, 1991), Goudriaan and Ketner (1984), and Esser (1991), have estimated that the terrestrial biosphere may be a large net sink for carbon. Tans et al. (1990) imputed a missing sink of carbon, most likely located in the northern mid-latitudes, from a detailed analysis of atmospheric and oceanographic records. Goudriaan (1991) estimates that the CO_2 fertilization effect could more than compensate for carbon releases from land-use changes and still provide a net sink for carbon in the range of 0.5 PgC/yr to 1.5 PgC/yr. Esser (1991) finds that the CO_2 fertilization effect may have resulted in a net carbon uptake of 70 Pg over the period 1860 to 1980.

Atmospheric chemistry is also a small net source of atmospheric CO_2. All of the carbon gases, in particular CO and CH_4, eventually oxidize to CO_2. Total annual oxidation of CO and CH_4 is estimated to be less than 1 PgC/yr, most of this from CO (WMO 1985; MacCracken and Luther 1985b; IPCC 1990). Most of the carbon released in one year is oxidized to CO_2 during that same year. In addition, the convention by which CO_2 emissions are calculated assumes complete oxidation of all of the carbon from fossil fuel combustion byproducts and deforestation. This convention does not always reflect reality, but is a useful first approximation and reflects the eventual disposition of all forms of the carbon release.

1.2.2 Methane

Ice core data going back 160,000 years indicate that concentrations of CH_4 in the pre-industrial atmosphere were less than half the present concentration of 1700 ppbv (Pearman et al. 1986; Khalil and Rasmussen 1987; Raynaud et al. 1988; Figure 1.7.) Methane concentrations were about 700 ppbv until the beginning of the nineteenth century. Concentrations during glacial periods were even smaller, as low as 350 ppbv (Raynaud et al. 1988). Current concentrations have been growing at approximately 0.9%/yr (Blake and Roland 1988; Steele et al. 1987; IPCC 1990; Figure 1.8).

Annual estimates of emissions sources are not generally available for CH_4. Source strength uncertainties are so high that emissions budgets are typically referenced by decade rather than by individual year. Whereas emissions of fossil fuel and land-use change CO_2 are developed for specific years based on databases for a small number of human activities, the sources and sinks for CH_4 are developed using an observed globally averaged atmospheric

burden of CH_4 (approximately 4800 Tg), the average annual rate of increase, and an atmospheric lifetime (approximately 12.5 years) derived from an atmospheric chemistry model to calculate a global emissions budget constraint of approximately 540 (400 to 640) Tg/yr. Information about the changing isotopic ratio of methane (i.e., $^{14}CH_4/^{12}CH_4$) is used to partition the constraint by broad period of origin and, by inference, to provide a ratio of the contribution of fossil fuels to total emissions. A summary of the best current understanding of the sources and sinks of CH_4 is given in Chapter 3.

The emissions sources of methane are discussed in Chapter 3. It is presently unclear whether or not all of the major sources of CH_4 emissions have been identified. Furthermore, emissions rates from methane sources that have been identified are less certain than those for fossil fuel carbon sources. At present, it is thought that more than half of total annual emissions of methane to the atmosphere can be attributed to human activities. Agricultural activities, in particular cattle raising and wetland rice cultivation, energy production, transmission, and distribution, and landfills are estimated to be the largest contributors to anthropogenic emissions.

As a result of climatic warming, carbon emissions could significantly increase through the release of carbon now stored in frozen soils in Arctic regions and in peat and humus in other regions. Estimates of potential releases are highly speculative, but potentially of an order of magnitude equivalent to current fossil fuel CO_2 emissions. This carbon may be released in the form of CH_4. The attendant effect on the CH_4 budget would be significantly greater than on the CO_2 budget. Another relatively short-term positive climatic feedback may occur from increases in the decomposition of vegetation resulting from increased mortality due to rapid climatic change.

1.2.3 Nitrous Oxide

The atmospheric concentration of N_2O is increasing at the rate of about 0.3%/yr (Watson and Ozone Trends Panel et al. 1988; Khalil and Rasmussen 1988; IPCC 1990; Figure 1.9). Current tropospheric concentrations are about 310 ppbv (IPCC 1990). Ice core data indicate that the concentration of N_2O was stable for approximately 2000 years to 3000 years at about 285 ppbv, though there is some doubt about the absolute calibration (IPCC 1990). Concentrations began to increase about 200 years to 300 years ago (IPCC 1990).

The sources and sinks of N_2O are poorly documented (see Chapter 3). Emissions rates are small, relative to atmospheric stocks. While the atmospheric burden and annual rate of increase are known with some confidence, the atmospheric lifetime is uncertain within the range 100 years to 175 years. This leads to significant uncertainties in the estimates of sources and sinks derived from atmospheric chemistry models. Individual source estimates are subject to even greater uncertainty. Total emissions are estimated to be between 7 TgN/yr and 21 TgN/yr. Even the categories of nitrous oxide emissions sources are highly uncertain. At present, the most important sources of emissions are considered to be biogeochemical cycles and combustion processes. The largest sources of emissions are presently estimated to occur from soils, including cultivated, natural, and fertilized soils, as well savanna burning, forest fires, forest clearing, fuelwood burning, and fossil fuel combustion. Oceans and aquifers provide emissions sources of secondary importance.

1.2.4 Chlorofluorocarbons

The term chlorofluorocarbons (CFCs) refers to a family of compounds synthetically derived from the methane (CH_4) or ethane (C_2H_6) molecule. A CFC is formed by replacing all hydrogen molecules with the halogens chlorine (Cl) or fluorine (F). When the bromine (Br) atom is also used a replacement, the compound is referred to as a halon.

The CFCs receiving the most attention, primarily because of their more extensive use and hence, larger concentrations and potentially significant effects on stratospheric ozone, are $CFCl_3$ (referred to as CFC-11) and CF_2Cl_2 (referred to as CFC-12). Other

similar compounds, including CCl_4 (carbon tetrachloride), CH_3CCl_3 (methylchloroform), and the halons currently exert less influence, but are still significant; their effects could become quite substantial if present emission trends continue.

CFC-11 and CFC-12 have the highest concentrations of the manufactured CFCs: 0.280 ppbv and 0.484 ppbv (measured at Mauna Loa), respectively, in 1990 (IPCC 1990). These concentrations are far more dilute than is the case for other radiatively important gases. The surface air concentrations of these two gases are currently increasing at a rate of more than 4%/yr (IPCC 1990; Figure 1.10). These gases have relatively long lifetimes: 75 years for CFC-11, 110 years for CFC-12. In addition, they are strong infrared absorbers in the "atmospheric window." A molecule of CFC-12 has several thousand times the radiative forcing impact of a molecule of CO_2 (IPCC 1990; Ramanathan et al. 1987). CFC-11 and -12 are thought to have contributed about one-quarter of the radiative forcing of gases other than CO_2 during the 1980s (Hansen et al. 1989; Ramanathan et al. 1985).

Other important chlorocarbons include CFC-113 ($CF_2ClCFCl_2$), HCFC-22 (CHF_2Cl), and methyl chloroform (CH_3CCl_3). The atmospheric concentration of CFC-113 is increasing by about 10%/yr (IPCC 1990), with the present surface air concentration being about 0.06 ppbv in 1990 (IPCC 1990). HCFC-22 and CH_3CCl_3 are used primarily as solvents, while HCFC-22 is used in air conditioning and refrigeration equipment. Carbon tetrachloride is used primarily as a feedstock in the production of CFCs by the chemical industry. Halons are used extensively in fire extinguishing applications (EPA 1989).

All of these synthesized chlorocarbons have relatively long atmospheric lifetimes; that is, relatively slow removal rates. Methyl chloroform has the shortest chemical lifetime, about 6 years to 7 years, while CFC-113 has the longest lifetime, about 400 years (IPCC 1990). The long lifetimes contribute to the rapidly increasing concentrations of these gases. The effects of fully halogenated chlorocarbons, particularly CFC-11 and CFC-12, on stratospheric ozone concentrations are of primary concern because they are destroyed in the stratosphere, primarily by photolysis, which releases all of their chlorine atoms to act as catalysts for ozone destruction for decades. Chlorinated halocarbons also release chlorine to the stratosphere, while the destruction of halons releases bromine. The chlorine and bromine atoms can then react catalytically to destroy ozone without being altered themselves.

Although CFCs are exclusively anthropogenic in origin, it should be noted that natural sources of methyl chloride contribute to chlorine in the stratosphere.

Production and emissions of CFCs are discussed in Chapter 3.

1.2.5 Carbon Monoxide

Carbon monoxide is important not as a radiatively active gas, but because it reacts with the hydroxyl radical, OH.[a] The primary sinks for hydroxyl are through the reactions of OH with CO and CH_4. These interactions suggest that the increases in CO and CH_4 now occurring should lead to a decrease in tropospheric OH concentrations, with a subsequent positive feedback on the lifetime and abundance of CH_4, CO, and other gases scavenged by OH. This feedback could play an important role in the future concentration trends of CH_4 and other greenhouse gases.

(a) The hydroxyl radical, OH, is not itself a greenhouse gas with a direct effect on climate, but it is an important chemical scavenger of many trace gases in the atmosphere that are greenhouse gases. OH is the primary tropospheric scavenger of CH_4, CO, CH_3CCl_3, CH_3Cl, CH_3Br, H_2S, SO_2, DMS and other hydrocarbons and hydrogen-containing halocarbons. The atmospheric concentrations of OH affect the atmospheric lifetime of these species and thus affects their abundances and ultimately the effect these species have on climate.

The production of OH depends on the reaction of excited oxygen atoms (produced via photolysis of ozone) with water vapor. Therefore, increases in the concentrations of O_3 or H_2O in the troposphere would increase the amount of OH. Global increases in temperature, driven by climate change, are expected to lead to an increase in the tropospheric water vapor concentration.

Peak concentrations of about 200 ppbv occur at high northern latitudes, with minimum concentrations of about 50 ppbv found throughout the Southern Hemisphere. Concentrations are increasing by about 1.1%/yr globally, although there is little evidence of an increase occurring in the Southern Hemisphere (Khalil and Rasmussen 1988; Cicerone 1988). Carbon monoxide has a relatively short lifetime, on the order of a few months, before being transformed to CO_2. Because of the relatively high efficiency of combustion processes, this source of CO_2 is a relatively minor addition, on the order of 2% to 3% of anthropogenic emissions of carbon from fossil fuel combustion and land-use changes.

As discussed in Chapter 3, CO is generated by incomplete combustion processes (complete combustion yields CO_2 rather than CO), oxidation of anthropogenic hydrocarbons, the decomposition of CH_4, and other minor sources. Because CO is highly reactive, it has a relatively short atmospheric lifetime (0.4 year) and is poorly mixed in the global atmosphere (IPCC 1990; Wuebbles and Edmonds 1988). Annual emissions estimates range from 600 TgC/yr to 1700 TgC/yr (Wuebbles and Edmonds 1988), with the IPCC (1990) estimating 1030 TgC/yr. Concentrations of CO are significantly higher in the Northern Hemisphere than in the Southern Hemisphere, indicating higher emissions in those latitudes (IPCC 1990). This is consistent with the pattern of combustion activities. U.S. emissions of CO from fossil fuel use were estimated to be between approximately 24 TgC/yr and 29 TgC/yr in 1985 (NAPAP 1989; EPA 1990).

1.3 THE CARBON CYCLE

Over the period 1860 to 1980, approximately 160 PgC were introduced into the atmosphere by fossil fuel use (Marland et al. 1989). Estimates of the emissions of carbon from the terrestrial ecosystems vary. Peng et al. (1983) estimate that, from 1860 to 1980, 265 PgC were released from forests and soils. Emanuel et al. (1984) and Stuiver et al. (1984) derive estimates of 230 PgC and 150 PgC, respectively. Trabalka (1985) estimates the net carbon flux from land biosphere between 1800 and 1982 to be only 120 PgC with a range of 90 PgC to 180 PgC, which is roughly the same order of magnitude as fossil fuel carbon release, estimated to be between 150 PgC and 190 PgC over that same period (Trabalka 1985). Net deforestation was the principal source of carbon release into the atmosphere in the earlier part of the period, while fossil fuel use dominates releases in the latter portion. The average carbon content of the atmosphere increased by approximately 125 PgC over the period 1960 to 1986; thus, the increase in atmospheric carbon corresponds to between 30% and 45% of the carbon emitted over the period from 1860 to 1980. Bolin (1986) obtains a range of 32% to 60% by including a range of estimates for pre-industrial atmospheric carbon in addition to a range of estimates for carbon released from the terrestrial biosphere. A similar range of estimates of atmospheric retention can be derived for shorter time periods as well. Approximately 3 PgC/yr accumulate in the atmosphere. The annual net injection from anthropogenic activities is thought to range from 6 PgC/yr to 8 PgC/yr. Atmospheric retention is therefore approximately half the anthropogenic emissions.

These observations raise questions. First, are the accumulation of CO_2 in the atmosphere and the net emission to the atmosphere of carbon by human activities related? And second, if the two are related, what is the nature of that relationship? Why is the buildup of carbon in the atmosphere less than the level of anthropogenic emissions?

1.3.1 Background on the Carbon Cycle

Attempts to answer the two questions posed above have lead researchers to study the flows of carbon throughout the global system. Estimates of the stocks (figures found within boxes) and the flows (figures associated with arrows between boxes) of carbon are given in Figure 1.11. Estimates of the stocks and fluxes between various gross reservoirs of carbon are subject to great uncertainty. Only the atmospheric concentration of CO_2 and the fossil fuel CO_2 emissions rate are known with relatively high precision. The stock of carbon in the atmosphere in 1988 was approximately 742 PgC (Boden et al. 1990). This

compares to the approximately 5.9 PgC/yr emitted by fossil fuel use (Boden et al. 1990), and the 0.5 PgC/yr to 3 PgC/yr estimated to have been added by deforestation. [Trabalka (1985) gives a range of 0 to 2.6 PgC/yr, while IPCC (1990) gives a range of 0.6 to 2.6 PgC/yr.] As noted earlier, the estimates of net deforestation make no allowance for either a CO_2 fertilization carbon uptake or other significant, unidentified terrestrial carbon uptake mechanisms.

Flows of carbon into and out of the atmosphere are very large, compared to human annual emissions. Annual fluxes into and out of the atmosphere are estimated to be on the order of 200 PgC/yr (Trabalka 1985; Bolin et al. 1986; IPCC 1990).

CO_2 is a stable form of carbon in the atmosphere; it is therefore not chemically active, and there are no significant sinks for CO_2 in the atmosphere. The only generally agreed-upon permanent sinks for carbon are the oceans and soils. The net buildup of carbon in soils is thought to proceed at a slower pace than the removal of carbon to oceans (Trabalka 1985; Bolin 1986). At present, soils may be a net source of carbon to the atmosphere as a result of land-use changes (as well as the biomass lost in forest stands). Ocean models can account for only part of the 3 PgC/yr to 5 PgC/yr net removal of carbon from the atmosphere associated with human activities. The disposition of the so-called "missing carbon" cannot yet be adequately explained by present research models.[a] IPCC (1990) presents the accounts for a typical year[b] during the 1980s as follows:

	PgC/yr
Emissions from fossil fuels into the atmosphere	5.4±0.5
Emission from net deforestation and land-use change	1.6±1.0
Total Net Emissions	**7.0±1.5**
Accumulation in the atmosphere	3.4±0.2
Uptake by the ocean	2.0±0.8
Total Disposition	**5.4±1.0**
Net imbalance (the "missing carbon" sink)	***1.6±1.4***

We note that the "missing carbon" problem grows out of an attempt to account for annual anthropogenic fluxes. Annual anthropogenic fluxes take place within the context of larger annual gross fluxes within the carbon cycle (see Figure 1.11).

1.3.2 Evidence of the Relationship Between Anthropogenic Net Carbon Emissions and the Accumulation of CO_2 in the Atmosphere

If the fluxes of carbon into and out of the atmosphere generated by natural sources are so large, relative to those generated by human activities, it is natural to question whether the observed buildup of CO_2 in the atmosphere is simply a small variation in natural processes and merely coincident with the emission by human activities. After all, total annual emissions from fossil fuel use and land-use changes amount to only 3% of the annual natural flux, well within the bounds of uncertainty of the natural flux rates. Nevertheless, circumstantial evidence provides a strong case that human activities are principally responsible for the observed increase in atmospheric CO_2.

First, ice core records show concentrations of atmospheric CO_2 remaining between 270 ppmv and 290 ppmv over the past 1000 years. Concentrations have risen relatively steadily to 350 ppmv since 1860

(a) "Missing carbon" refers to the fact that estimates for cumulative emissions of carbon to the atmosphere cannot be reconciled with estimates of carbon disposition; that is, some of the carbon that is estimated to have entered to atmosphere cannot be accounted for and is therefore referred to as "missing." It is important to note that this phenomenon emerges from observations over extended periods of time. It may be possible to "balance" carbon emissions and sinks in any given year; it is not possible to balance the carbon accounts over extended periods. Thus, the IPCC presented results for a "typical" year averaged over the entire decade of the 1980s, rather than any particular year within the decade.

(b) A typical year for the decade is used because there is sufficient variability from year to year that annual accounts may look quite different from the decadal average.

(Neftel et al. 1985; Friedli et al. 1984; Raynaud and Barnola 1985; Pearman et al. 1986). Despite the enormous rates of flux of carbon to the atmosphere from terrestrial and oceanic sources and the great uncertainty surrounding the actual rates, the atmosphere, whose carbon content is known with relative certainty, shows a slow but steady increase in concentration that closely parallels the release of CO_2 from fossil fuel use into the atmosphere. The relationship is particularly strong since 1958, when precise measurements of atmospheric CO_2 at Mauna Loa began (Trabalka 1985; IPCC 1990). The ratio of accumulation in the atmosphere to fossil fuel CO_2 release has been a remarkably stable 0.58. The rate of growth of atmospheric CO_2 also shows declines in 1973, corresponding to the OPEC oil embargo, and 1979, corresponding to the Iran-Iraq war oil price spike.

Another important piece of evidence is the observed buildup of geologically older carbon in the atmosphere. The ratio of $^{12}CO_2$ to $^{14}CO_2$ has been decreasing in the atmosphere, signaling an increasing proportion of CO_2 that is radiocarbon-free (and hence stored longer than 40,000 years) in the atmosphere. This is consistent with the injection of a large quantity of fossil fuel CO_2 into the atmosphere (Trabalka 1985; IPCC 1990).

Furthermore, the differential between the concentration of CO_2 in the Northern and Southern Hemispheres has grown from approximately 1 ppmv (1960) to 3 ppmv (1985). This is consistent with the larger release of human-related CO_2 in the Northern Hemisphere compared to the Southern (Trabalka 1985; IPCC 1990).

Finally, the current rate of change in the concentration of CO_2 in the atmosphere (1.4 ppmv/yr) is unprecedented. The most rapid average rate of change in concentration observed in ice core records extending over the preceding 160,000 years is significantly lower (0.5 ppmv/yr). The present concentration of 350 ppmv is also unmatched in the preceding 160,000 years. The previous maximum concentration associated with an interglacial period was 320 ppmv, observed 120,000 years ago.

1.3.3 Alternative Models of the Atmospheric Retention of Fossil Fuel CO_2

Several models have been used to describe the relationship between the net emission of anthropogenic CO_2 into the atmosphere and atmospheric concentrations of CO_2. These models range from very simple to extremely complex. The two most popular simple models will be referred to as the **Airborne Fraction Model (AFM)**, [World Meteorological Organization (WMO) 1981; Nordhaus and Yohe 1983; Edmonds and Reilly 1985; Bolin 1986], and the **Atmospheric Decay Model (ADM)** (Nordhaus and Yohe 1983). These models are reduced form, not realistic, models. They make no attempt to trace the movement of carbon through the Earth's system. The question is, are they useful predictive tools? That depends on the specific issue being addressed.

The AFM assumes that the change in the carbon content of the atmosphere is proportional to net carbon emission. Two variants of this model exist. The first computes the ratio of accumulation of carbon in the atmosphere to the release of fossil fuel CO_2. This ratio is relatively stable in the post-1958 period at 0.58. The second variation computes the ratio of accumulation of carbon in the atmosphere to the net anthropogenic release of CO_2 (the sum of fossil fuel release plus release from deforestation). This second ratio is less certain because the net release rate from deforestation and other land-use changes is less certain. As noted earlier, estimates of the release rate for land-use changes vary between 0.5 PgC/yr and 3 PgC/yr. Assuming a net release rate for land-use changes of approximately 1 PgC/yr yields an airborne fraction of approximately 0.5, but the ratio can vary between 0.6 (no net release from land-use change) to 0.4 (3 PgC/yr release rate for land-use change). See Bolin (1986) for further discussion. These calculations are consistent with those obtained using the IPCC (1990) values for carbon balance cited earlier.

The strength of this model is that it is statistically tied to recent experience. Its principal weakness is that it is not based on a realistic model of the carbon cycle and is therefore an uncertain guide to

atmospheric accumulation under emissions scenarios outside the bounds of historical experience. One of the implications of the reduced form models is that CO_2 will continue to accumulate in the atmosphere as long as net emissions continue; that is, fossil fuel releases of CO_2, plus net releases from land-use change would have to be cut to zero to stabilize the concentration of CO_2 in the atmosphere. This result contradicts the findings of more sophisticated carbon cycle models (Bolin 1986; Trabalka 1985; IPCC 1990).

The ADM is a different model of CO_2 accumulation in the atmosphere. The ADM is based on the assumption that the average molecule of CO_2 has a fixed lifetime in the atmosphere. A fixed fraction of the stock of carbon in the atmosphere is removed annually, presumably into the oceans. Such models can also replicate the post-1958 experience reasonably well using, for example, the Mauna Loa record and fossil fuel carbon release estimates reported in Boden et al. (1990), the assumptions that the average lifetime of a molecule of carbon is 250 years[(a)] and that approximately 1 PgC/yr net is released from the biosphere are used. For this model, the implied instantaneous removal rate without additional injections of carbon is approximately 3 PgC/yr. Because the removal rate depends on the stock of carbon in the atmosphere, the rate of carbon removal varies only slowly as long as the rate of emission to the atmosphere is small, relative to the stock. As a first approximation, the model predicts that a cessation of emissions would result in approximately 3 PgC/yr continuing to be removed by the oceans annually, or, alternatively, that the atmospheric concentration of CO_2 would stabilize if emissions were cut to 3 PgC/yr.

The strengths of this model are that it appears to track the post-1958 experience reasonably well and that it can also be loosely tied to more sophisticated carbon cycle processes, specifically ocean carbon uptake. The major problem with this model is that it cannot explain why there was any atmosphere at all in 1860, if the 3 PgC/yr removal rate is independent of atmospheric concentrations; that is, if the removal rate for carbon from the total atmosphere were 1/250 per year, then at the end of a millennium there would be no atmospheric carbon left. But the atmosphere was clearly stable over the preceding millennium.

Research models of the carbon cycle have tried to provide detailed descriptions of the flows of carbon in the Earth's system. These models include interactions between living biomass, soils and detritus, rivers, and oceans, including segmented ocean elements, ocean biota, and ocean sediments. No model of the Earth's carbon system can hope to approximate reality unless it can adequately explain the behavior of oceans in the removal and release of carbon. Initial models of oceans segmented the waters into a set of average layers differentiated by depth. Carbon is diffused from the atmosphere into the surface layer, and then from the surface layer into ever-deeper layers. Such models are termed box-diffusion models. Diffusion coefficients were established so as to agree with observations of diffusion of radiocarbon and other tracers.

The earliest models of ocean carbon processes were two-box models containing simple reservoirs for carbon in surface and deep-water layers. Such models were explored by, among others, Craig (1957), Bolin and Eriksson (1959), and Keeling (1973). The course of research made it increasingly clear that simple two-dimensional models of the ocean carbon system were inadequate for either explaining the system or forecasting potential future ocean carbon uptake. Oeschger et al. (1975) proposed a box model that disaggregated the oceans into two parts: a well-mixed

(a) The atmospheric decay is not a simple function, however. The IPCC (1990) estimated the decay function associated with an ocean uptake model for a one kilogram net release of carbon dioxide into the atmosphere to take the form:

$$F = 0.30036\, e^{-t/6.993} + 0.34278\, e^{-t/71.109} + 0.34686\, e^{-t/815.727},$$

where F is the fraction remaining in the atmosphere at time t. Note that the instantaneous e-folding time or "lifetime" of carbon in the atmosphere depends on t. The extreme differences between the marginal and average rate of removal of carbon from the atmosphere serve to underline the complexity associated with an analysis of the carbon cycle and the fact that there is no such thing as a simple "lifetime" of carbon dioxide in the atmosphere.

surface layer approximately 75 meters in depth and a deep ocean. Carbon transport within the deep ocean would be accomplished by eddy-diffusion. Work by Bjorkstrom (1979), Hoffert et al. (1981), Killough and Emanuel (1981), Enting and Pearman (1982), Bolin et al. (1983), Peng et al. (1983), and Siegenthaler (1983) refined and extended this model. More recent models have included three-dimensional transport and chemistry--Maier-Reimer and Hasselmann (1987) for example. These models include improved understanding of ocean chemistry, deep water formation, upwelling, biological sequestering, and three-dimensional transport and chemistry. Interestingly, the most sophisticated models of ocean carbon cycle yield net results for carbon uptake similar to the simpler box-diffusion models.

Oceans and the terrestrial system are conventionally assumed to be weakly coupled except through their interchanges with the atmosphere and therefore are treated as if they were two separate systems. The terrestrial system is conventionally assumed to be in rough equilibrium with the atmosphere. CO_2 uptake by plants, 110 PgC/yr, is just balanced by releases from the biosphere to the atmosphere, 50 PgC/yr, and from soils and detritus to the atmosphere, 60 PgC/yr (Figure 1.11). Carbon leaving the biota to soils, 60 PgC/yr, leaves both the biota and soils as neutral carbon sources (sinks). Uncertainty surrounds this conventional view of the terrestrial system. Because CO_2 is a fertilizer for plants, the net increase in atmospheric CO_2 should, in principle, stimulate plant growth and add to the net carbon stock in the biota. This is referred to as the CO_2 fertilization effect. While the CO_2 fertilization effect is a well-established phenomenon, the extent to which it affects the carbon cycle is a matter of heated debate. As noted earlier, estimates of up to 2.5 PgC/yr net removal of carbon from the atmosphere by some unexplained terrestrial system mechanism have been estimated either by inference or by direct calculation (Enting and Mansbridge 1989; Goudriaan 1989; Esser 1991; Tans et al. 1990). Empirical evidence confirms that increased CO_2 enhances CO_2 fixation by vegetation, but whether increased carbon is retained by terrestrial ecosystems is uncertain.

Holistic models of the global carbon cycle that include both oceans and terrestrial ecosystems have been developed by various researchers including Peng et al. (1983), Emanuel et al. (1984), Goudriaan and Ketner (1984) and Goudriaan (1989). These models allow the direct computation of atmospheric concentrations, given external information on emissions from fossil fuel use and land-use change. However, these models do not adequately treat CO_2 from exchange (in and out flux) between the atmosphere and biosphere.

Research carbon cycle models run to determine the amount of net anthropogenic CO_2 emissions that would be consistent with a stable concentration of atmospheric CO_2 at present levels, 353 ppmv, indicate that net emissions would have to be reduced by 60% to 80% (IPCC 1990; EPA 1989).

1.3.4 The Lifetime of CO_2 in the Atmosphere

Unlike other greenhouse gases, the concept of an atmospheric lifetime for CO_2 is troublesome. The concept of atmospheric lifetime of carbon is inherently different from the concept as it has been developed for gases that are chemically active and that have permanent sinks in the atmosphere. For gases other than CO_2, a simple exponential decay model is applied to a stock of the gas resident in the atmosphere to estimate the removal rate of the gas from the atmosphere.

But this model begins to break down for CO_2. The first problem encountered with CO_2 is gross versus net fluxes. The large gross annual fluxes between the atmosphere and oceans and between the atmosphere and terrestrial systems imply that carbon atoms leave the atmosphere and enter oceans or terrestrial systems, but are replaced by other carbon atoms leaving oceans or terrestrial systems and entering the atmosphere. An average residence time for a molecule of CO_2 in the atmosphere can be constructed by taking the ratio of the total annual flux out of the atmosphere to the atmospheric burden of CO_2. Depending upon the gross flux rates, this can yield an average duration of a molecule of CO_2 in the

atmosphere of approximately four years, with a range of 2 years to 6 years. But large bi-directional gross flux rates can exist without any change in the stock of CO_2 in the atmosphere.

If a simple exponential decay function is fitted to the entire atmospheric stock of CO_2, a lifetime of 250 years is reasonable. This is the reciprocal of the net removal rate of carbon from the atmosphere. As we have seen, there is some problem reconciling an ADM (atmospheric decay model) that is consistent with recent experience with the presence of carbon in the atmosphere in the year 1860.

To circumvent the above problems, coupled ocean-atmosphere models have been run in simulation mode to examine their response to small changes in the initial stock of carbon in the atmosphere over time (Maier-Reimer and Hasselmann 1987; Siegenthaler and Oeschger 1987). These models are dynamic equilibrium models and are tuned to reproduce pre-industrial concentrations at initial conditions. They can be perturbed by adding carbon to the system and observing the fraction of the additional carbon remaining in the atmosphere at any future point in time. If the output from the Maier-Reimer and Hasselmann (1987) pulse of carbon experiment is used to fit a simple exponential decay model, an interesting result is observed. The lifetime of the incremental carbon changes depending on the period over which the ADM is fit. If one year is allowed to pass, the computed lifetime of CO_2 is 16 years; that is, incremental carbon is disappearing from the atmosphere at a rate such that, if it persisted over a 16-year period, 1/e would be left. But the longer the period allowed to pass before the exponential decay model is applied, the longer the calculated lifetime. Lifetimes of incremental carbon, as determined by ocean removal, and the number of years after initial introduction of the carbon into the atmosphere are displayed in Table 1.5.

We note that, for the Maier-Reimer and Hasselman calculations, 1/e of the incremental carbon remains at the end of 100 years. This experiment presumes a pre-industrial equilibrium and therefore does not necessarily yield the same result as an experiment in which an additional kilogram of carbon is released into the present, disequilibrium atmosphere.

Table 1.5. The Relationship Between the Computed Lifetime of Incremental Carbon in Maier-Reimer and Hasselmann (1987) and the Period of the Experiment

Period of the Experiment (years)	Lifetime of Incremental Carbon (years)
1	16
5	26
10	34
25	50
50	69
10	100
40	250
50	294
100	516

1.4 ATMOSPHERIC PROCESSES

The actual atmospheric composition of greenhouse gases depends not only on surface emissions, but also on any atmospheric chemical process affecting their concentrations and distributions. Table 1.6 indicates that, with the exception of CO_2, atmospheric chemical processes largely determine the rate of removal of greenhouse gases from the atmosphere. These processes are described in more detail in Ramanathan et al. (1987), Penner et al. (1988), and Wuebbles et al. (1989). The primary removal mechanism for some species, such as CO and CH_4, is reaction with OH (hydroxyl) in the troposphere. Others, such as N_2O and the CFCs, are destroyed primarily by

Table 1.6. Concentration and Lifetimes of Important Atmospheric Trace Gas Constituents

Gas	Nonurban tropospheric concentrations[a] (ppmv)	Trend In atmospheric concentrations[a] (% per year)	Atmospheric lifetime[b] (years)	Primary removal process
CO_2	351(1988)	~0.4%	~250[c]	Uptake by the oceans and perhaps by an unknown terrestrial mechanism.
CH_4	1.7	~1	~10	Chemical oxidation to CO_2 and H_2O.
CO	0.12(N.H.) 0.06(S.H.)	~1(N.H.) ~0(S.H.)	~0.3	Chemical oxidation to CO_2.
N_2O	0.31	~0.3	~150	Photolysis and reaction with $O(^1D)$ in the stratosphere.
NO_x	$1\text{-}20 \times 10^{-5}$	unknown	≤ 0.02	Chemical reaction to nitric acid and removal by precipitation.
$CFCl_3$ CF_2Cl_2 $C_2Cl_3F_3$ CH_3CCl_3	2.6×10^{-4} 4.4×10^{-5} 3.2×10^{-5} 1.2×10^{-4}	~5 ~5 ~10 ~4.5	~70 ~120 ~90 ~6	Photodissociation, particularly in the stratosphere, to chlorine and hydrochloric acid that is subsequently removed by precipitation.
CF_2ClBr CF_3Br	1×10^{-6} 1×10^{-6}	~12 ~15	~12-15 ~110	Dissociation, particularly in the stratosphere, and removal by precipitation.
SO_2	$1\text{-}20 \times 1^{-5}$	unknown	~0.02	Dry deposition and conversion to sulfate that is removed by precipitation.
COS	5×10^4	<3	2-2.5	Conversion to sulfate and removal by precipitation.
DMS	$5\text{-}20 \times 10^{-5}$	unknown	~0.01	Chemical reaction leading to removal by precipitation.
NMHC	<1	unknown	≤ 0.02	Reaction with O_3 and OH.
O_3	0.02-0.1	0.5-1	<0.1	Chemical reaction or removal at surface.
OH	$4\text{-}100 \times 10^{-9}$	unknown	<0.01	Chemical reactions to H_2O.
H_2O	$1\text{-}20 \times 10^3$	unknown	~0.03	Precipitation or chemical reaction.

(a) Corresponds to mid- to late-1980s values.

(b) The estimates of atmospheric lifetimes have an uncertainty of about 10% to 20% for many of these species and are even greater for CO_2 and H_2O. A mid-range value is given.

(c) Computed as ratio of the atmospheric burden to net annual removal. Net annual removal is estimated as emissions less atmospheric accumulation. Carbon dioxide removal processes are not represented well by simple exponential decay functions, however. E-folding time of 50 years to 200 years was used by IPCC 1990 (p. xvi).

photodissociation, often in the stratosphere (dissociation via reaction with a solar photon). In addition, there are indirect effects on climate forcing as a result of chemical interactions affecting the atmospheric concentrations of ozone (in both the troposphere and stratosphere) or water vapor in the stratosphere (tropospheric water vapor concentrations are largely unaffected by chemical processes). Table 1.7 indicates the ways in which chemical processes affect climate.

1.5 CONCLUSIONS

The presence of greenhouse gases in the atmosphere has a significant influence on the energy balance of Earth, which regulates surface temperature. The concentrations of greenhouse gases have been increasing during the industrial era. Most of the important greenhouse gases, such as H_2O, CO_2, CH_4, N_2O, and O_3, occur naturally. Some such as CFCs and CFC substitutes, are of strictly human origin. Increases in the concentrations of greenhouse gases have been associated with emissions from human activities.

It is known that human activities release greenhouse gases into the atmosphere in quantities that are significant relative to the global scale natural system. Furthermore, the relationship between historic fossil fuel use and CO_2 emissions is reasonably well understood. Similarly, the relationship between CFC manufacture and release into the atmosphere is well known. The relationship between human activities and byproduct emissions of other gases is known less precisely.

While the qualitative relationship between emissions of greenhouse gases (and greenhouse-related gases, such as CO) and concentrations of greenhouse gases in the atmosphere are well known, significant work remains before precise relationships between potential future emissions and atmospheric concentrations can be established. For example, uncertainties regarding ocean uptake mechanisms for carbon require further work. Important uncertainties surround the role of terrestrial ecosystems in the carbon cycle. Atmospheric chemistry models need further refinement in areas including the role of cloud effects.

The lack of understanding of the "missing carbon" problem leaves uncertain the specific relationship between anthropogenic carbon emissions and the atmospheric concentration of CO_2. Further, it leaves in doubt the extent of carbon emissions reductions required to achieve alternative future atmospheric concentrations.

That the greenhouse effect exists is indisputable. There is no question that the presence of greenhouse gases in the atmosphere is a major factor in determining the energy distribution of the planet and is therefore a major factor determining climate. Furthermore, changes in atmospheric concentrations of greenhouse gases appear to play an important role in determining planetary surface temperature and climate. Much more work remains to be done in reducing uncertainty surrounding the detailed relationship between atmospheric concentrations and climate dynamics. Even if future atmospheric concentrations were known precisely, there still remains a difference of a factor of three between upper and lower estimates of mean global surface warming associated with radiative forcing changes equivalent to a doubling of atmospheric CO_2. The issue of the role of clouds as a climate feedback mechanism is of particular importance. The relationship between changes in radiative forcing and the regional and seasonal pattern of climate change, including the larger array of characteristics that describe climate, such as precipitations, wind, and frequency of storms, is speculative at this time. Models disagree with regard to the magnitude and direction of local and regional changes in variables for radiative forcing experiments equivalent to a doubling of the preindustrial concentrations of atmospheric CO_2.

Table 1.7. The Role of Chemical Processes in Affecting the Atmospheric Concentrations of Greenhouse Gases

Gas	Are concentrations affected by atmospheric chemistry?	Indirect effects on tropospheric chemistry?	Indirect effects on stratospheric chemistry?
CO_2	no	no	yes, affects O_3
CH_4	yes, reacts with OH	yes, affects OH, O_3	yes, affects O_3, H_2O
CO	yes, reacts with OH	yes, affects OH, O_3	not significantly
N_2O	yes, photolyses in stratosphere	no	yes, affects O_3
NO_x	yes, reacts with OH, O_3	no	yes, affects O_3
$CFCl_3$	yes, photolyses in stratosphere	no	yes, affects O_3
CF_2Cl_2	yes, photolyses in stratosphere	no	yes, affects O_3
$C_2Cl_3F_3$	yes, photolyses in stratosphere	no	yes, affects O_3
CH_3CCl_3	yes, reacts with OH	no	affects O_3
CF_2ClBr	yes, photolyses	no	affects O_3
CF_3Br	yes, photolyses	no	affects O_3
SO_2	yes, reacts with OH	yes, but not significant to climate	yes, affects aerosols
COS	yes, reacts with OH	no	yes, affects aerosols
DMS	yes, reacts with OH	yes, through cloud interaction	no
NMHC	yes, reacts with OH	yes, affects OH, O_3	no
O_3	yes, produced and destroyed via chemical reaction	yes, affects OH	yes
OH	yes, produced and destroyed via chemical reaction	yes, affects O_3, CH_4 CO, CH_3 CCl_3, etc.	yes, affects O_3, H_2O
H_2O	yes, in stratosphere, via oxidation of CH_4	yes, affects OH, O_3	yes

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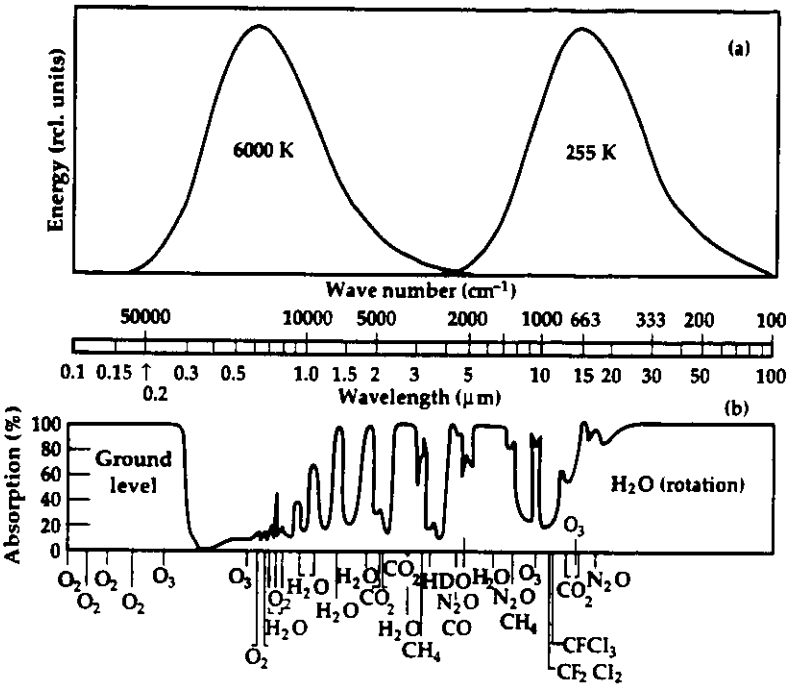

Figure 1.1. Blackbody Curves. These show the variation of emitted energy with wavelength for temperatures typical of the Sun and the Earth, respectively (upper figure); and the percentage of atmospheric absorption for radiation passing from the top of the atmosphere to the surface (lower figure). Source: MacCracken and Luther 1985b.

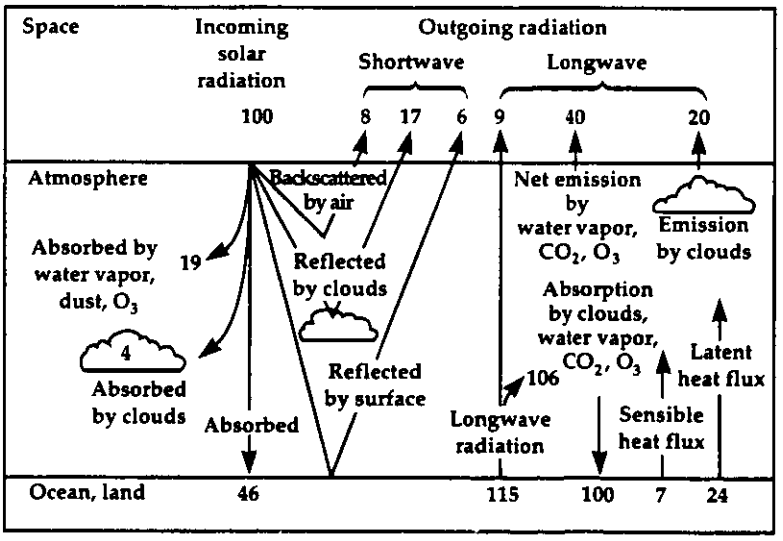

Figure 1.2. Schematic Diagram of the Global Average Energy Balance. Note: the units are percentage of incoming solar radiation on the lefthand side, and the longwave (infrared, IR) fluxes are on the righthand side. Source: MacCracken and Luther 1985b.

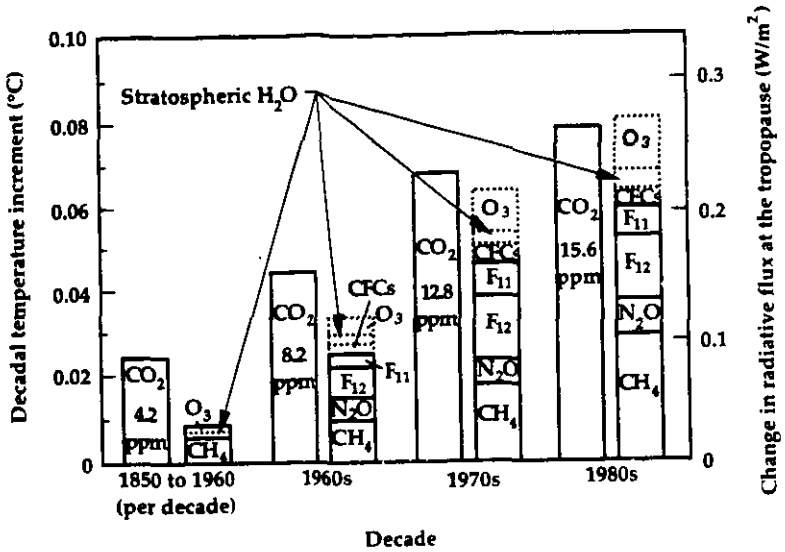

Figure 1.3. Decadal Additions to Global-Mean Greenhouse Radiative Forcing of the Climate System. Note: The computed commitment to future surface temperature change (°C) once equilibrium is reestablished ($t \rightarrow \infty$) is estimated for decadal increases in trace gas abundances, without including the amplifiction that would be induced by climate feedbacks. The change in net radiative forcing of the troposphere-surface system is indicated on the right ordinate. Source: DOE 1990.

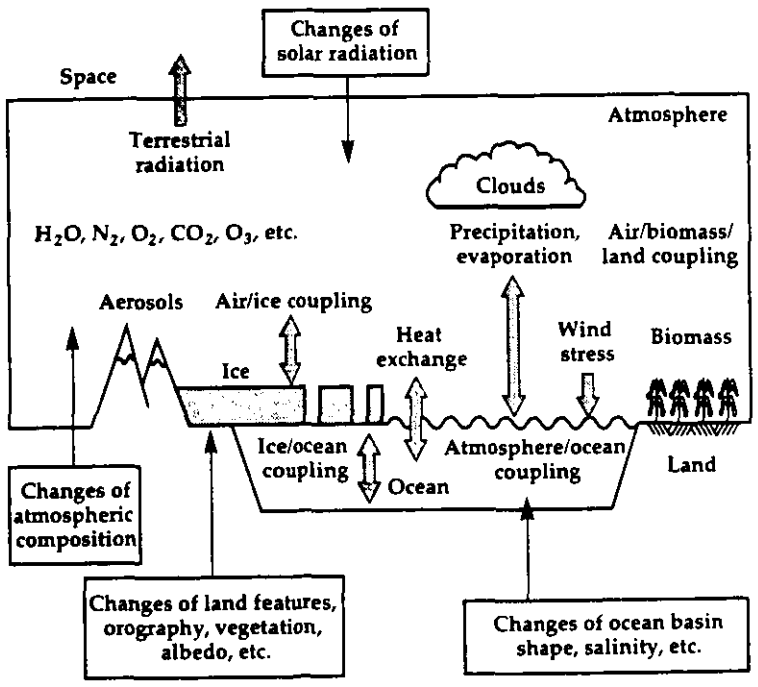

Figure 1.4. Schematic Illustration of the Components of the Coupled Atmosphere-Ocean-Ice-Land Climatic System. Full arrows represent external processes; open arrows represent internal processes in climatic change. Source: Based on IPCC 1990 (from J. T. Houghton, ed. *The Global Climate.* Cambridge University Press, Cambridge, U.K. Used by permission.)

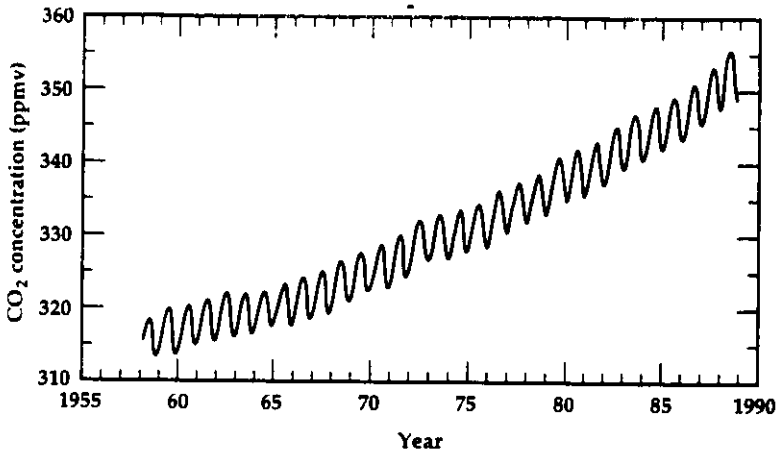

Figure 1.5. Monthly Average CO_2 Concentrations at Mauna Loa, Hawaii - Source: Data derived by C. D. Keeling (Boden et al. 1990).

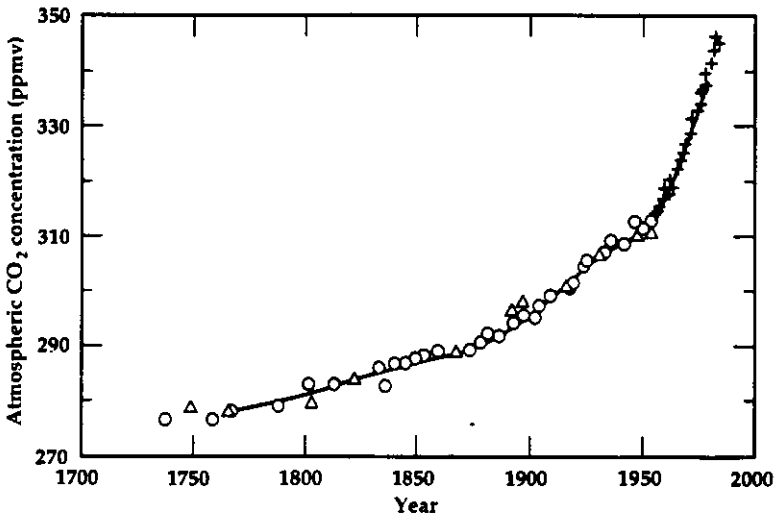

Figure 1.6. Pre-Industrial CO_2 Concentrations Obtained from Published Observations of Air Trapped in Ice Cores - Source: Lashof and Tirpak 1991.

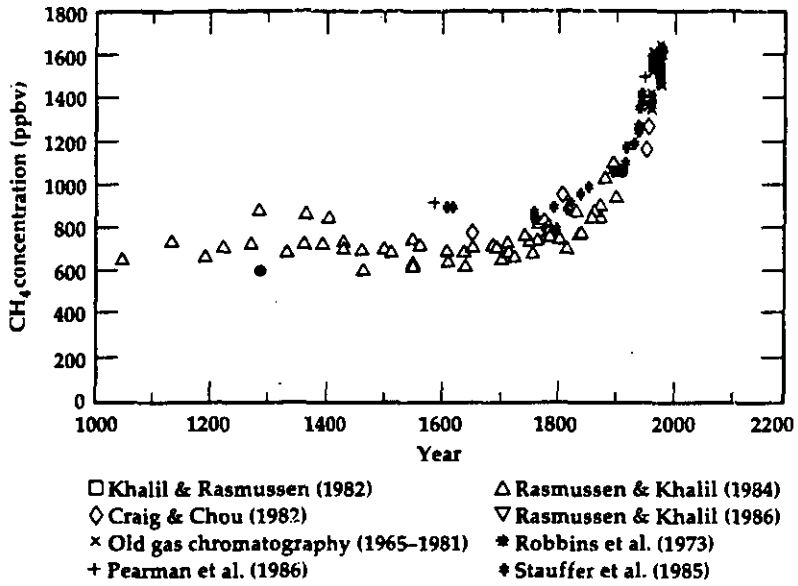

Figure 1.7. Atmospheric Concentration of CH_4 Over the Last 1000 Years - Source: Reprinted with permission from *Atmospheric Environment*, vol. 21, M.A.K. Khalil and R.A. Rasmussen, "Atmospheric Methane: Trends Over the Last 10,000 Years," 1987, Pergamon Press plc.

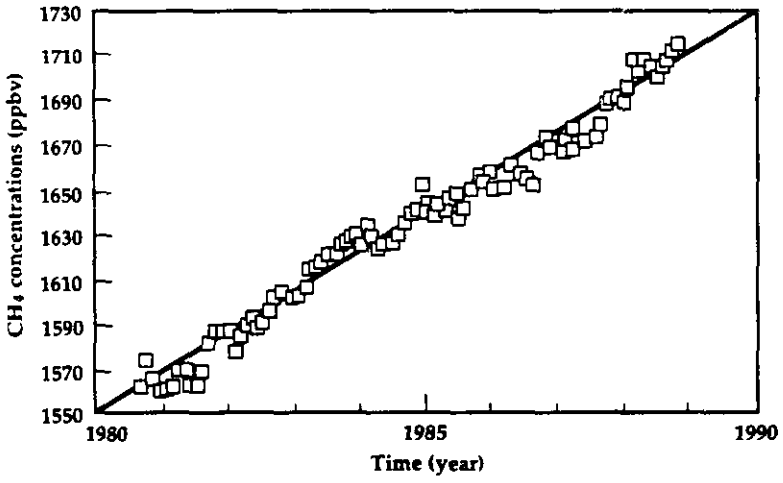

Figure 1.8. Recent Trends in CH_4 Concentration - Source: Reprinted with permission from *Atmospheric Environment*, vol. 21, M.A.K. Khalil and R. A. Rasmussen, "Atmospheric Methane: Trends Over the Last 10,000 Years," 1987, Pergamon Press plc.

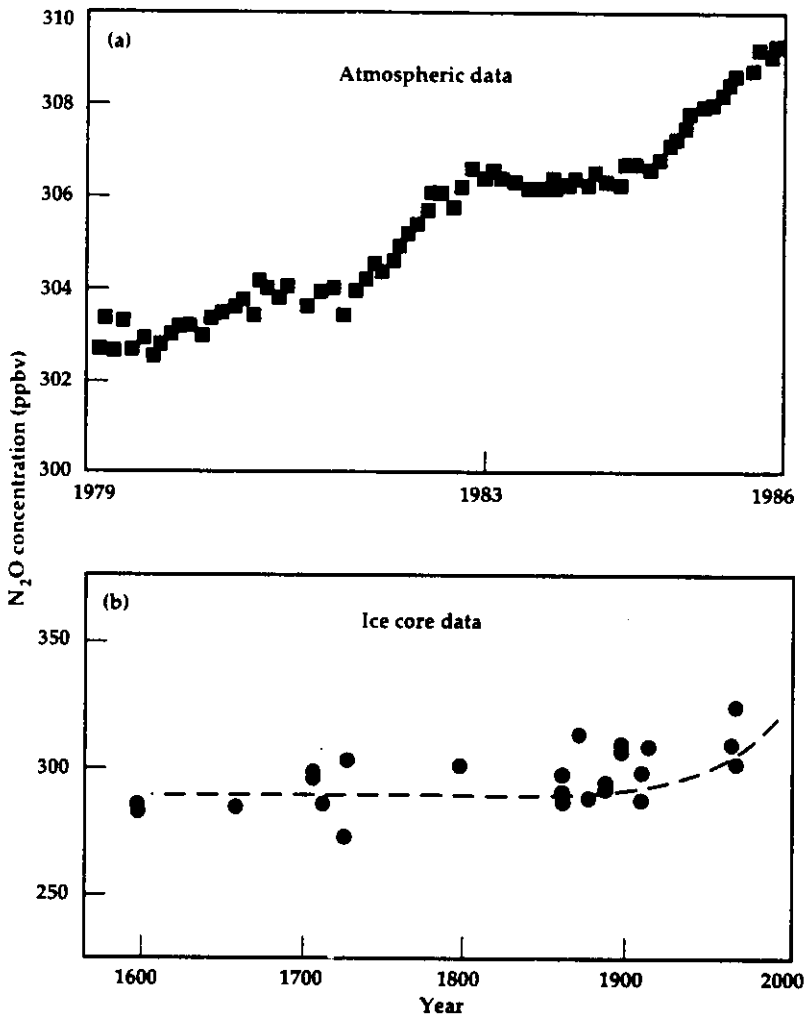

Figure 1.9. Recent and Long-Term Trends in N_2O Concentrations Based on Available Atmospheric and Ice Core Data - Source: Lashof and Tirpak 1991.

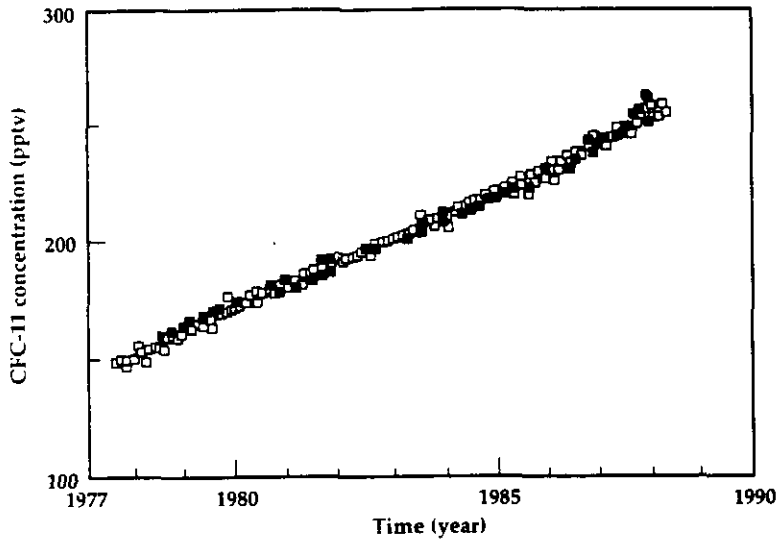

Figure 1.10. Measurements of CFC-11 at Mauna Loa Observatory Since Mid-1977
Source: Based on data from the U.S. National Oceanographic and Atmospheric Administration's Geophysical Monitoring for Climate Change program; private communication with J. Peterson 1989.

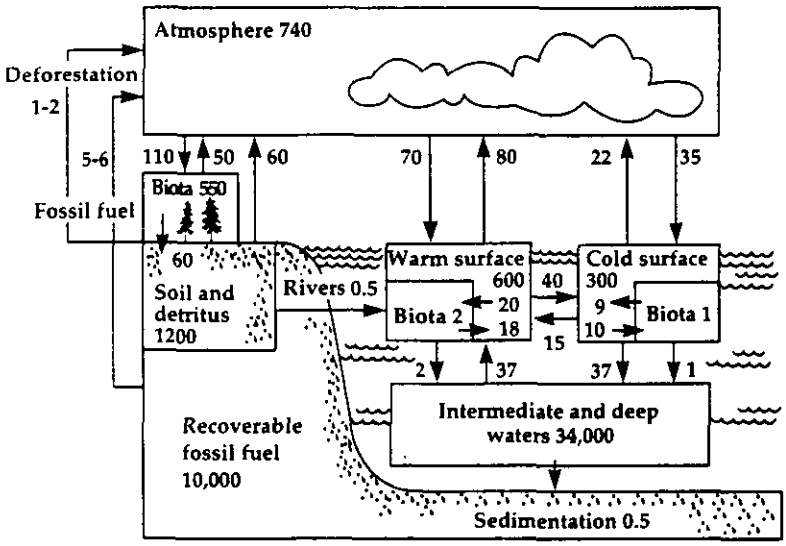

Figure 1.11. Carbon Flow Throughout the Global System (PgC/yr) - Source: Moore 1988.

2.0 THE POTENTIAL CONSEQUENCES OF ATMOSPHERE/CLIMATE CHANGE

2.1 INTRODUCTION

The development of a fully informed global atmosphere/climate change policy requires information on both the causes and consequences of global atmosphere/climate change. Two important pieces of information are the cost of net emissions reductions and the benefits to be obtained by such reductions. As Nordhaus (1990), Cline (1989), and Teisberg and Peck (1991) observe, an economically optimal policy must equate the cost of the last tonne of carbon dioxide (CO_2) equivalent emissions reduction (across all greenhouse gas emissions) to the value of the benefits derived from that last tonne of emissions reduction.

Limiting Net Greenhouse Gas Emissions in the United States provides considerable information with regard to the cost of emissions reductions within the context of a comprehensive approach, beyond those expected to be achieved by full implementation of the National Energy Strategy (NES) (DOE 1991). There are, however, several barriers to computing the comparable benefits associated with U.S. actions to limit greenhouse gas emissions. In the first place, the specific effect of U.S. emissions of greenhouse gases on natural and human resources will depend on the share of the world total that U.S. emissions represent. The U.S. share and world total will both depend in part on actions taken (or not taken) by other nations. While action by the U.S. to reduce emissions by 20% or 50% may make such action by other nations more likely, reducing U.S. emissions alone would not be decisive in determining either the timing or the magnitude of the impacts of future climate change, positive or negative, because U.S. emissions amount to only about 20% of the world total, and this percentage is shrinking as other nations' emissions increase. In the first instance, then, the "benefits" of a U.S. emissions policy will depend on what is assumed about emissions policy elsewhere. Moreover, the information base is not yet available to compute the benefits of emissions reductions. Critical problems exist in predicting and assessing impacts of a given reduction in emissions on the nature and timing of global atmosphere/climate change. Climate models are not yet capable of adequately reflecting local and regional variability in present climate, casting doubt on the likelihood and probability of future local and regional climate scenarios. Even if the general circulation models (GCMs) of climate were capable of forecasting future patterns of local and regional atmosphere/climate change for alternative emissions scenarios with great accuracy, we would still lack the models needed to quantitatively assess the consequences of the difference between a base and policy scenarios, in terms of the "damage" to society. Such models have not yet been developed and validated.

This is not to say that we know nothing about the consequences of global atmosphere/climate change. Much has already been learned from the body of research conducted to date. Summaries of this body of knowledge include Riebsame (1989), Topping (1989), Scott et al. (1990), IPCC (1990), and Riebsame and Magalhaes (1990). In the remainder of this chapter we will indicate the basic methods, results, and uncertainties that have emerged from research for the following topics:

1. Climate scenarios for examining consequences of atmosphere/climate change

2. Expected human reaction and technological adaptation

3. Sectoral studies and findings, including:
   a. Energy
   b. Water resources
   c. Agriculture
   d. Forests, unmanaged ecosystems, and biodiversity
   e. Air quality
   f. Fisheries
   g. Coastal zone
   h. Infrastructure
   i. Health effects

4. Regional studies and findings

5. Analog studies and findings

6. Uncertainty and information needs

7. Discussion and summary.

While the central focus of this report is on the United States, our review will include findings from studies examining the consequences of atmosphere/climate change for the United States and other countries, since the effects of atmosphere/climate change would occur throughout the world. The problem of assessing consequences is likewise global in nature. The consequences of global atmosphere/climate change are experienced regionally and locally, but depend on both the direct regional and local effects of atmosphere/climate change and the indirect effects spread through global markets and patterns of population change experienced throughout the world.

It is impossible to construct a measure of the economic damage to the United States from global atmosphere/climate change and therefore to provide the economic information needed to identify an optimal economic strategy with regard to energy and emissions. *Limiting Net Greenhouse Gas Emissions in the United States* can only provide some information regarding the economic costs associated with the implementation of various policy instruments for going beyond the National Energy Strategy actions, and catalog current understanding of possible climate change consequences from other studies.

2.2 CLIMATE SCENARIOS FOR EXAMINING CONSEQUENCES

Some of the first assessments of climate impacts (e.g., Waggoner 1983) were based on arbitrary "scenarios" of climate change, intended primarily to demonstrate the sensitivity of resources to such change. The next generation of analyses (e.g., Rosenzweig 1985; Cohen 1986) used the month-by-month or season-by-season simulations of climate from general circulation models (GCMs) for various points or gridcells on the surface of the Earth, even though GCMs have not been reliable or consistent at forecasting regional climate (Grotch 1988; Cushman and Spring 1989). One proposed way around the uncertainty has been to use a variety of alternative scenarios (Smith and Tirpak 1989; Riebsame and Magalhaes 1990). Most recently, analyses such as that of Wilks (1988), Wilson et al. (1990), or Rosenberg et al. (1990) have used weather-generating techniques to produce scenarios of simulated local daily weather series from GCM output or from large-scale weather patterns. Detailed climate projections remain a significant problem, however, in part because the very definition of climate is somewhat arbitrary (Liebetrau and Scott 1990b). There is a general need to examine the consequences of time-dependent ("transient") warming scenarios under the technological regime that would prevail when the warming occurs. Only a few studies (e.g., Smith and Tirpak 1989) have attempted this. None of the analyses to date has attempted to link the reduction of emissions to changes in climate scenarios. Table 2.1 summarizes climate scenarios research.

2.3 HUMAN REACTION AND TECHNOLOGICAL CHANGE

The feedback reactions of human institutions on the biophysical environmental relationships may largely ameliorate or may exacerbate the effects of climate alone (Glantz 1988). Many of these adaptive responses will occur without specific policy stimulus. Some studies have recognized these feedbacks. Examples include studies of drought in the Sahel in Africa in the 1970s (Garcia 1981), sea level rise (Titus 1988), agriculture (Parry et al. 1988a, 1988b; Easterling et al. 1990), water (Frederick 1990), forestry (Regens et al. 1989; Bowes and Sedjo 1990) and integrated regions (Smith and Tirpak 1989; Rosenberg and Crosson 1990; Rosenberg et al. 1991), which have recognized, though not necessarily modeled, these feedbacks. Generally, scenarios incorporating human reaction have depended on either analysis of reaction to historical climate variations or on expert opinion concerning implementation of easily foreseeable actions (such as increase in

Table 2.1. Summary of Climate Scenarios Research

Issue	Methods	Findings
What climate scenarios are most appropriate for the analysis of climate effects?	GCMs, GCMs linked to weather using mesoscale models or statistical procedures; paleoclimate reconstructions; historical climate analogs	Multiple alternative scenarios are needed; GCMs, if used, must be linked to simulated, detailed regional weather in a realistic fashion; historical and paleo analogues are useful primarily for methods development and have not proved useful in providing consistent future climate projections.

water-saving technologies as a reaction to rising water prices). A fully integrated approach that also recognizes interactions between sectors was proposed by Callaway et al. (1982). Such an approach was partially implemented by Parry et al. (1988a, 1988b) for agriculture in some regions, and has now been implemented for a single region in a DOE-sponsored study of the effects of climate change, emphasizing anticipated technological change in agriculture and institutional change in water management systems (Crosson et al. 1990; Easterling et al. 1990; Rosenberg et al. 1991).[a] Table 2.2 summarizes human reaction research.

2.4 SECTORAL STUDIES AND FINDINGS

Without a coordinated national or international program in climate impact assessment, most of the studies have focused on particular aspects of individual resource sectors in individual regions (e.g., Rosenzweig 1985; Blasing and Solomon 1984; Cohen 1986; Gleick 1987a; Pastor and Post 1988; Miller et al. 1987). These sectoral studies are described below.

(a) Some technology forecasting is being done for current impact studies; e.g., Rosenberg et al. (1991); Yoshino et al. (1988); Smith and Tirpak (1989). In view of the fact that most effects of atmosphere/climate change are not expected for several decades, more carefully thought-out technological scenarios should at least be attempted.

The results of existing studies for individual sectors have taught us much about the probable impacts of climate change and have identified many of the major remaining unknowns. Many of the unknowns, such as the effects of climate change on local weather, are common to several of the sectors. Recent regional studies such as Smith and Tirpak (1989) and Rosenberg et al. (1991) have revealed that physical and economic interactions between sectors (such as water and agriculture) and between regions (e.g., through world grain markets) are as important for estimating impacts of climate change on individual sectors in specific regions as are the direct impacts of climate on those sectors. This section summarizes what has been learned in the key climate-sensitive sectors.

2.4.1 Energy

The state of knowledge regarding the sensitivity of energy systems to climate change is primitive. Jaeger (1983) surveys the subject of climate effects on energy systems in a short chapter, the EPA (Smith and Tirpak 1989) reviews potential effects of climate change on U.S. electric utilities, and the IPCC (1990) reviews the findings of available international work. In general, the field is still in the process of cataloging the nature of CO_2/climate sensitivities and developing crude measures of sensitivity, with most of the impact work having been done in temperate-zone

Table 2.2. Summary of Human Reaction Research

Issue	Methods	Findings
How do human reactions to climate change affect the impact of changing climate? Will these reactions occur in a timely fashion without policy stimulus?	Incorporate feedback reactions through expert opinion; through analysis of analogous historical reactions; through behavioral models	Reactions may be as important or more important than the effect of climate itself. Current methods are ad hoc. Research needs to be done to adequately understand human reactions that occur without significant external stimulus.

developed countries (the United States, United Kingdom, Japan, Germany, and Australia all have studies). A significant question in this regard is the trend in the use of market fuels in developing countries--Meyers and Sathaye (1988) and Sathaye et al. (1989) were quoted by the IPCC, and Reilly et al. (1987) discussed this as one of the significant uncertainties in future energy emissions. Table 2.3 summarizes energy sector research.

Statistically derived measures of *weather* sensitivity, generally in existing energy models, depend on heating-and cooling degree days and vary from small (DOE/EIA 1989), to relatively large (Klan et al. 1989). Almost all quantitative estimates are based on sensitivity analyses of energy models derived for a condition of no climate change (e.g., Parry and Read 1988; Gertis and Steimle 1989; Smith and Tirpak 1989; Nishinomiya and Kato 1989[a]). Typically, changes in incremental energy demand resulting from climate change are shown to be in the range of 5% to 15% for temperate zone developed countries and probably less than 10% for developing countries. In both cases, change in demand that would prevail in the absence of climate change is expected to be several times larger (IPCC 1990). However, today's energy demand models generally do not capture the long-term response of energy consumption patterns to climate. In the long term, residential and commercial winter heating demand likely would decrease with higher average winter temperatures, reducing oil, gas, and electricity consumption, while summer electricity demand would likely increase. While the energy infrastructure might have to be modified to account for changes in the climate, the incremental investments are likely to be much smaller than those required by ordinary demand growth (IPCC 1990). In the agricultural sector, higher temperatures would likely result in increased energy demand for irrigation pumping, but reduced demand for crop drying (Coulter 1989; Darmstadter 1990). Industrial energy demand has been found largely insensitive to either weather or climate, although selected industries such as construction, soft drink manufacture, clothing manufacture, and outdoor recreation might have their activity levels influenced (IPCC 1990). The resulting energy shifts are likely to be inconsequential. Direct effects on transportation energy use are unclear (IPCC 1990).

Most current work on the topic of production of conventional oil, gas and coal is confined to particular localities, or makes very general statements concerning activities at risk. For example, Arctic costs could be increased by permafrost decay, which could create problems for infrastructure such as pipelines (e.g., Maxwell and Barrie 1989; Brown 1989), but sea ice problems might be reduced for production platforms

(a) S. Nishinomiya and H. Kato. 1989 (in press). *Potential Effects of Global Warming on the Japanese Electric Industry -- Event Tree of Impacts on the Electric Utility Industry Stemming from Climate Induced Changes in The Natural Environment, Ecosystems and Human Society.* Central Research Institute of the Electric Power Industry (CRIEPI) Report, Tokyo.

Table 2.3. Summary of Energy Sector Research

Issue	Methods	Findings
What are the effects of climate change on the demand and supply of energy?	Calculate sensitivity of existing energy models to changes in weather; calculate effects on water supply for hydropower; calculate derating of fossil powerplants for less effective cooling water.	Models of today's energy system do not take into account climate-driven changes in infrastructure; supply of hydroelectric energy is dependent on the quality of the runoff estimate; studies of restrictions on or enhancements of potential fossil, renewable, and unconventional energy resource availability are at a very early stage.

(Stokoe 1988) and high arctic transportation corridors (Lonergan 1989). More severe hurricanes (Emanuel 1987) could affect production areas like the Gulf of Mexico. Analyses of river operations models for changed climatic conditions suggest that the availability and operation of hydroelectric power could be indirectly affected by climate through precipitation and evaporation patterns, which affect both the total volume and the timing of river runoff (Smith and Tirpak 1989; Coulter 1989; Lettenmaier et al. 1990; Singh 1988). Changes in hydrology and average climate could similarly affect the availability and design of water-dependent powerplant cooling systems (Nishinomiya and Kato;[a] Smith and Tirpak 1989; Coulter 1989), although dry cooling is an option.

The production potential of renewable energy supplies such as solar, wind, ocean thermal energy conversion (OTEC), and biomass are considered to be more sensitive to climate change than fossil and nuclear energy supplies. Biomass as an energy source could be affected by climate-affected productivity of forests, which may either increase or decrease (e.g., Bowes and Sedjo 1990.) Average temperature and atmospheric pressure conditions can also affect the availability of recoverable methane from landfills, but the effect is likely to be small.

(a) Ibid.

2.4.2 Water Resources

Global warming is expected to accelerate the global hydrologic cycle with a resulting increase in average global precipitation and evaporation estimated at between 7% and 15% percent (e.g., Bolin et al. 1986). However, because climate models may not simulate future global oceanic and air circulation patterns and do not agree even on the direction of change in annual precipitation for many regions (Grotch 1988; Cushman and Spring 1989), the impacts on regional water supplies are highly uncertain (Frederick and Gleick 1989). In the absence of authoritative scenarios, analysts have turned to hypothetical scenarios built from current weather patterns and GCM control conditions, and historical and paleoclimate analogues. A key relationship that must be specified is that of precipitation to runoff. Approaches include rainfall/runoff curves, water balance methods, atmospheric GCMs, and deterministic hydrologic models for specific basins. Results of several studies appear in IPCC (1990) and in Waggoner (1990). Runoff often has been found to be two to four times more sensitive than precipitation to climate change (Revelle and Waggoner 1983; Fitzgerald and Walsh 1988). In areas such as the western United States, where precipitation is currently dominated by winter snowfall and runoff is dominated by spring snow melt, warmer temperatures could produce dramatic relative increases in winter

rain, earlier spring melting, and changes in seasonal runoff patterns, even with constant annual precipitation (Gleick 1987a, 1987b; Lettenmaier et al. 1990). Table 2.4 summarizes water research.

Water use in urban and suburban areas would likely increase with increasing temperature. In agriculture, irrigators would tend to use more water to compensate for higher transpiration rates, although higher CO_2 levels reduce transpiration by increasing the plant's resistance to vapor transfer into the air (Rosenberg 1981; Stockle et al. 1990a), and rising precipitation could reduce irrigation demand in some areas (Close 1988). Transpiration rates may also be raised or lowered as a result of changes in cloudiness, humidity and windiness (Martin et al. 1989; Rosenberg et al. 1989). Rosenberg et al. (1991) have adjusted their water use estimates for cloudiness, CO_2 effects on water use efficiency, windiness, and humidity, the only study to date to do so. This study showed increased efficiency in water use, but also overall increased demand for water at higher temperatures.

The relative values of water for alternative uses will likely change. For example, despite potential supply problems, hydroelectric power might become more attractive as a means of both abating the

Table 2.4. Summary of Water Research

Issue	Methods	Findings
What is the effect of global warming on water supply and demand and water quality?	Water balance models, water supply and demand models, runoff models, reservoir management models, correlation of runoff to precipitation, deterministic hydrologic models.	Forecasts of precipitation and seasonal levels of water supplies are highly uncertain. Where snowmelt now dominates, hydrography would be shifted in time, requiring greater storage capacity, revised water allocation schemes, or both. GCMs agree that equilibrium climate change for doubled CO_2 leads to increased evaporation as well as precipitation, and, on average, reduced soil moisture. There is an expectation of a general trend toward increased water use in agriculture, residential, and commercial sectors from climate change despite increased water use efficiency by crops. However, because regional patterns of climate change are highly uncertain for doubled CO_2 scenarios, water supply results for individual regions are uncertain. Water quality effects are site-specific.

greenhouse effect and adapting to increased power demands for irrigation and air conditioning that might accompany it (Frederick and Gleick 1989; Gleick 1989). Due to uncertainty, techniques that improve the operation of existing water supply infrastructure may take precedence over development of new storage structures or exotic supplies (e.g., through desalinization). The prospect of future climate change might hasten such investments, allowing for easier future adaptation (Frederick and Kneese 1989).

2.4.3 Agriculture

One of the more difficult problems in analyzing the effects of climate change on regional agriculture is estimating the demand and supply of food and fiber of the world agricultural system taken as a whole. Current projections of world population and income suggest that in the 50 years to 75 years expected for greenhouse gases to accumulate to the point where their combined effect is equivalent to doubling the preindustrial concentration of carbon dioxide (Bolin et al. 1986), global demand for food and fiber will grow at an annual percentage rate about half that of the last 30 years to 40 years (World Bank 1984). If changes are as gradual as most studies suggest, the negative impacts would not overwhelm the prospective gains in worldwide productivity of even modest rates of technical advance (Easterling et al. 1989; Crosson et al. 1990; Crosson and Rosenberg 1989). This would be especially true if increased atmospheric CO_2 proves to be as effective a fertilizer in the field as it has in laboratory experiments.[a] Table 2.5 summarizes agriculture research.

(a) CO_2 concentrations would actually increase by about 80% while increases in other greenhouse gases would cause the rest of the equivalent doubling usually discussed. This is important to note, since CO_2 fertilization studies have often used doubled CO_2 concentrations.

Table 2.5. Summary of Agricultural Research

Issue	Methods	Findings
What is the direct effect of climate on agricultural yields and costs? How is the direct effect modified by the world agricultural system, by human reaction, by expected technological change?	Crop yield/farm economics models; expert opinion on yield changes from experimental plots and historical analogues; food vulnerability calculations; technical trends analysis.	Crop yield models must be adjusted for future technology and CO_2 fertilization effects; estimates of effects must account for world agricultural demand and prices; weather derived from climate must be incorporated in a realistic manner. Water supply changes resulting from climate change are a potential critical constraint on future agricultural production in some important agricultural regions. In others, generally less important, low temperature constraints may be removed.

The nature of changes in regional biophysical agricultural capacity is uncertain in part because GCMs disagree about the effects of warming corresponding to doubled CO_2 concentration on regional climates (Schlesinger and Mitchell 1985). IPCC (1990) notes that there would be effects on thermal limits to agriculture, effects of extreme events such as drought or temperature extremes, and effects on the distribution of agricultural pests, diseases, and weeds. Some of the most recent work that models agricultural impacts has taken CO_2 fertilization into account (e.g., Adams et al. 1990; Stockle et al. 1990a, 1990b; Easterling et al. 1990), although much needs to be done in areas including the effect of extreme heat on plant processes such as reproduction and the effects of weeds, pests, and disease on crop and livestock productivity. Regional modeling of physical crop yields and farm economics (Blasing and Solomon 1984; Crosson et al. 1990; Crosson and Bowes 1990; Stockle et. al. 1990a, 1990b; Parry et. al. 1988a, 1988b) and national (Parry et al. 1988a, 1988b; Adams et al. 1990) and international modeling of crop markets (Bucklin et al. 1991) using models such as the IIASA LINK system (International Institute for Applied Systems Analysis Basic Linked System World Commodities Trade Model) suggest that, although the overall effects on world food security might be modest, shifts among regions in agricultural comparative advantage could present some affected regions and countries with difficult adjustment problems, while some northern areas might benefit directly from warmer weather (Kettunen et al. 1988; Yoshino et al. 1988), and still others such as Canada might benefit from comparative advantage (Smit 1989). In the absence of world agricultural market and production analysis, food supply security or vulnerability is frequently calculated for the developing world (Downing and Parry 1990a, 1990b). Particularly vulnerable may be poorer tropical or subtropical and semiarid regions with expanding populations that are already dependent on agriculture, but have marginal climates for agricultural production (Liverman 1991). In several regions believed to be vulnerable to drought, irrigation water supplies under climate change may not be adequate, or not adequate without some (possibly painful) adaptation (Adams et al. 1990; Frederick 1990; Turner and Weinmann 1989).

Countries losing agricultural comparative advantage because of climate change can be expected either to 1) protect their agriculture by restricting imports from newly advantaged producers (despite the economic cost); 2) support research to develop appropriate technologies including better adapted crop varieties and animals; or 3) import more of the needed food and fiber while diverting investment from agriculture to other more productive sectors (Easterling et al. 1989).

Under the extreme conditions of warming greater than that predicted to result from doubled CO_2 or occurring in a much shorter timeframe, increasing the global agricultural capacity to meet rising demand might come with higher economic and environmental costs (Easterling et al. 1989). Limiting worldwide emissions of greenhouse gases may postpone the time at which this would occur.

2.4.4 Forests, Unmanaged Ecosystems, and Biodiversity

No definitive methods at present exist for forecasting the effect of climate change on ecosystems. The effects of climate change on natural ecosystems are currently analyzed in several different ways, including analysis of the current distribution and potential distribution of vegetation types; reconstruction of historical or paleo communities; computer modeling of ecosystems as they compete for light, water, and nutrients at the stand level, analysis of the physiological requirements of species; and effects of growth chamber experiments (IPCC 1990). Studies such as Emanuel et al. (1985) have related changes in climate-biome classifications to changes in climate using systems such as the Holdridge Life System (Holdridge 1964); however, smooth migrations of species communities are believed to be unlikely because different species migrate by different mechanisms and at different speeds. In the case of plants, for example, some might be temperature-limited, others nutrient-limited or soil-limited (Kellison and

Weir 1987; Harte et al. 1990), and others water-limited (Woodward 1990; Pain 1988). The interactions between habitat, predators, and prey may also be critical (Topping and Bond 1988; Kushlan 1986; Lester and Myers 1989). The expected speed of climate change is itself a matter of concern for natural ecosystems because the rate is potentially 15 to 40 times that from past natural changes (Schneider 1989; Gleick et al. 1990). IPCC (1990) notes that the species most at risk are those at the edge of their "optimal" range; those geographically localized on islands, mountains, and reserves; those that are too highly specialized, poor dispersers, or slow reproducers, and those that are localized populations of annual species (where loss of a year's reproduction could result in local extinction) (IPCC 1990). Table 2.6 summarizes research on forest and econysterns.

Anticipated global warming could occur in a matter of decades, possibly outrunning natural rates of migration and species dependent on them, which occur on millennial time scales (Batie and Shugart 1989). If so, many existing forests will become increasingly temperature or water stressed and more susceptible to pest infestation, disease, and eventually, fire (Street 1989; Clark 1988; Fosberg 1988). Existing forests may die back slowly or rapidly, depending on the type of forest and stress, later to be replaced by other forms of vegetation or by forests with a different species mix (Sedjo and Solomon 1989). Even for widely distributed species, there may be significant reductions in ecotypes and genetic material (Davis and Zabinski 1990).

Simulations (Solomon 1986; Pastor and Post 1988) indicate that the greatest transitions occur at the boreal/cool temperate border, with some species moving to higher elevations in mountainous regions (Sedjo and Solomon 1989). Some mid-latitude forests could disappear, especially if the projected increases in tree growth and moisture-saving effects of high CO_2 and improved plant water use efficiency (Graham et al. 1990) do not materialize, and migration routes are blocked by development. Leemans (1989) notes that despite the general expectation, based on GCM results, that temperature changes in tropical latitudes will be relatively smaller than at mid- or polar latitudes, tropical forests, due to their narrow physiographic limits, would also be susceptible to climate change and tropical savannas and

Table 2.6. Summary of Forest and Ecosystem Research

Issue	Methods	Findings
What is the effect of global warming on forest health and succession, on ecosystem survival and function, and on biological diversity?	Forest succession models; ecosystem models; paleoecological studies; analysis of vegetative life zones, soils, reproductive and dispersal mechanisms; migration routes and other physical requirements.	Forest and other species may not migrate smoothly in response to climate change; problems are particularly likely where 1) the projected rate of climate change is rapid, 2) species do not have rapid dispersal mechanisms; and 3) potential migration routes are blocked. Arid lands are considered sensitive to desertification. Biodiversity could decline due to uneven migration and fragmentation of ecosystems.

warm deserts would likely increase. A significant concern is that some alpine species are in "island" environments where no migration routes are available.

Rapid change in climate could reduce ecosystem biodiversity (Batie and Shugart 1989). Some existing species of plants and animals would be unable to adapt because they are not sufficiently mobile to migrate at the rate required for survival (Davis 1989a, 1989b) and might be replaced with economically unproductive species (Botkin 1991). Some of the existing studies have discussed disturbance regimes (such as fire or logging) and their effect on established forests, which may persist in climates unfavorable to their long-term survival. Although some attempts have been made (e.g., Bowes and Sedjo 1990 for forests), no study has convincingly addressed the effects of elevated CO_2 on ecological succession. While the economic value of biodiversity is difficult to quantify, nations devote considerable resources to heritage sites and parks designed to preserve natural areas and endangered species, and these could be threatened by climate change (e.g., Soule 1987).

Adaptation of the forest sector to changing climate will not be simple, but would likely include earlier harvests of unsuited species and salvage operations in older stands, seeding and thinning (which are costly) in younger stands, and active planting of trees adapted to hotter and drier (or wetter--it is not clear which) climates in harvested stands (Sedjo and Solomon 1989). Active management may improve productivity in some regions.

Other unmanaged terrestrial and freshwater ecosystems have high value to humans because of their uniqueness (e.g., they may be protected in national parks), their value in maintaining genetic and biotic diversity (Wilson 1988; Peters and Darling 1985; Graham 1988; Botkin 1991), and the general ecological context they provide for natural resources exploited by humans (perhaps through grazing and hunting-gathering activities). Analyses have suggested that greenhouse warming may affect worldwide distribution of vegetative life zones and biotic communities, including not only forests (Pickett and White 1985; Overpeck et al. 1990), but also grasslands and tundra (Emanuel et al. 1985), and arid communities (Neilson 1986, 1987). Arid lands are considered particularly sensitive to abuse resulting in desertification and lack self-cleansing processes (Adams et al. 1978; Dregne 1983). In paleoecological studies, changes in past climates have been found to strongly influence vegetative patterns (Woodward 1987; Prentis 1986; Webb 1986; Davis and Botkin 1985; Davis 1989a, 1989b). Concern is growing over the effects of global warming on highly specialized terrestrial species, species with poor dispersal mechanisms, and alpine and arctic communities (Peters and Darling 1985). Effects of global warming on aquatic communities are currently unknown, but because these communities are strongly tied to their terrestrial settings through energy, nutrients, and water (Likens 1985; Minshall et al. 1985), changes in terrestrial vegetation could have pronounced effects on freshwater systems (Minshall et al. 1983).

2.4.5 Air Quality

Global warming is expected to affect regional and global air quality by action of a number of primary and secondary mechanisms. Primary interactions such as direct surface warming and the resultant off-gassing of pollutants are not as important from an air quality standpoint as secondary interactions. Secondary interactions include alteration of the wind patterns; modification of stagnation periods and associated changes in pollutant levels; changes of the hydrological cycle and associated storm climatology and corresponding changes in pollutant wet-removal; climatological modifications in levels of the solar actinic flux and photochemical conversion rates of many key pollutants; and modification of climatic regimes, associated vegetation, and dry-deposition rates of key pollutant species.

Although there is a consensus that these features are apt to affect ambient air quality profoundly under the scenario conditions suggested by current GCM outputs, few direct or substantive predictions to this effect have appeared in the literature. Most results are qualitative. Tropospheric ozone production has been studied in relation to temperature, with some

studies showing increases of 1.4 or minus 0.5% per °K (Gery et al. 1987). Large increases in local atmospheric concentrations of trace gases have been noted at specific locations (IPCC 1990). A number of stochastic models of wet-removal have been published (e.g., Rodhe and Grandell 1972) that demonstrate the strong general dependency of pollution residence times and concentrations on rainfall statistics. A variety of low-dimensional chemical models (e.g., Bruhl and Crutzen 1988) have provided some indication of this effect under clear-air conditions. Table 2.7 summarizes air quality research.

Major barriers to more detailed and quantitative evaluations include our present inability to execute comprehensive global chemical models within the computational constraints that currently exist and the coarse spatial resolution of the current GCMs. The first of these problems can be expected to be alleviated with faster computers and the coming generation of computer codes in chemical models. The second barrier is particularly important because many of the meteorological phenomena in the above list occur on scales that are too small to be resolved within this structure. Without the appropriate-scale GCM outputs, which will not be forthcoming for several years, one can expect correspondingly high levels of uncertainty in estimates of related air quality. Use of limited area models, which provide physical interpolations of GCM output (Giorgi et al. 1989), may reduce uncertainty somewhat earlier.

2.4.6 Fisheries

There have been a number of studies of the relationship between past climatic variations and specific marine fisheries (e.g., Southward et al. 1988; Sutcliffe et al. 1977; Crecco and Savoy 1984). Meisner et al. (1988) described how increased groundwater temperatures could affect survival and growth of salmonids (salmon, char, and trout). One symposium on climate change and fisheries (Regier 1988) explored a wide array of methodologies for forecasting the effects on marine and freshwater fish species and communities, including fish thermal tolerances, bioenergetic models, indicator species, and large-scale experimental studies. The long and complex causal chains linking climatic change with ultimate effects on fisheries stocks make a general study of the effects on fisheries problematic. A discussion of the numerous complexities involved in linking fisheries production to climate appears in DeAngelis and Cushman (1990). According to Sibley and Strickland (1985), the distributions of most fish species are expected to move poleward, but the magnitude of the shift and implications for yields are not known. The effect of

Table 2.7. Summary of Air Quality Research

Issues	Methods	Findings
Would global warming make air quality any worse than it would be from other causes?	Study of atmospheric concentrations in relation to temperature; stochastic models of pollutant removal; low-dimensional chemical models of the atmosphere.	Most findings with respect to climate change effects are qualitative in nature. Some evidence exists that tropospheric ozone will be more concentrated at higher temperatures and that inversion periods with high pollution may be more common. But such findings are highly uncertain.

abiotic factors on the food supplies of immature fish was seen as a major source of uncertainty. Table 2.8 summarizes fisheries research.

The report to Congress by the EPA (Smith and Tirpak 1989) included an analysis of potential effects of global warming on temperature, water quality and habitat affecting fisheries. Effects were estimated for the Great Lakes (on balance, the effects were favorable), California (where marine species were favored and fresh water species damaged), and the Southeast (where the effects on Gulf of Mexico fisheries were deleterious due to loss of habitat).

The prediction of climate change impacts on fisheries (especially marine fisheries) is crude at this time, relative to more well-studied sectors such as agriculture, for several reasons: the physical changes in habitat (e.g., water temperature and circulation patterns) are less predictable at this time than are air temperature and precipitation; fisheries other than aquaculture combine elements of both managed resources (i.e., economics, catch limits, and harvest technology are all important factors) and unmanaged ecosystems; and basic life-history and population-dynamics information is often inadequate because of the vastness of the seas and sampling difficulty. It is also difficult to anticipate how abiotic conditions in inland waters could be affected by global climate change because it is not yet possible to relate the output from GCMs, with their coarse spatial resolution and crude approximation of surface hydrology, to the flow, water temperature, and water quality information needed for fisheries assessment.

2.4.7 Coastal Zone

Sea level rise is projected to be one of the more certain impacts of global warming. Reducing emissions is likeliest to have a positive impact on the coastal zone. However, the impact in the coastal zone would depend very much on the amount by which sea level changes. The IPCC states that sea level is likely to rise 0.3 meter to 0.5 meter by the year 2050 and 1 meter by the year 2100 (IPCC 1990). This is about half the rate of increase that had been assumed as little as 2 years ago, meaning that most impact studies have assumed a sea level increase of at least a meter. Most studies have not considered future levels of development on coastlines in the absence of climate change but have assumed today's level of development. A general analysis of the effects of sea level rise on all affected resources has not been done. Early assessments of coastal zone impacts focused on rising sea level were based on relatively simple analyses of topographic data [Schneider and Chen (1980) for the United States, Henderson-Sellers and McGuffie (1986) for the world]. European and North American sites have provided most sea level data with which these analyses have been done (Robin 1986), although much is now being done to improve data elsewhere (IPCC 1990). The kinds of resources at

Table 2.8. Summary of Fisheries Research

Issues	Methods	Findings
What would be the effects of climate change on the survival of fish and shellfish species of importance?	Studies of the relationship of past climate variations to specific fisheries (e.g., El Nino effects); studies of thermal tolerance; bioenergetic models; indicator species; large-scale experimental studies.	Causal chains and geographic distribution of future climate are too complex to provide more than general types of potential vulnerabilities for marine fish; effects on freshwater species depend largely on water temperature and runoff. Results are mainly qualitative.

risk from rising sea level include both natural ecosystems such as wetlands (e.g., Armentano et al. 1986) and coastal structures (e.g., Kyper and Sorensen 1985). While elevated CO_2 appears to make crops more tolerant of increased salinity (Acock and Allen 1985), increased salinization of ground- and surface-water supplies (e.g., Hull and Titus 1986) could be aggravated by precipitation and runoff decrease and threats to the operation of coastal sewage and drainage systems (e.g., Titus et al. 1987; Wilcoxen 1986). Attempts to protect developed areas may exacerbate the loss of some kinds of shoreline, wetlands, and even structures (Leatherman 1991). Table 2.9 summarizes coastal zone research.

Coastal storms, such as tropical and extratropical cyclones and monsoons, can cause loss of life and considerable damage to coastal structures. The intensity of tropical cyclones has been linked to sea surface temperature, which is expected to rise during a global warming. Although the effect of climate warming on storm frequency and severity is highly uncertain (Broccoli and Manabe 1990), there is concern that sea surface warming could increase the maximum severity (but not necessarily average intensity or frequency) of such storms as climate changes (e.g., Emanuel 1987; Holland et al. 1987; Idso et al. 1990).

In Smith and Tirpak's (1989) study of sea level rise (which did not account for the accretion rate of wetlands), it was concluded that a sea level rise of 1 meter by the year 2100 could drown from 25% to 80% of the nation's coastal wetlands and could cost the United States about 7000 square miles of dry land. Based on calculations by Park et al. (1989) and Yohe (1990a), the IPCC (1990) estimates the U.S. loss associated with a 1-meter rise at 20,000 square kilometers valued at $650 billion. Even a 0.3 meter rise is expected to eliminate many recreational beaches and ocean-front property worth tens of millions of dollars per kilometer (Titus 1990). Other locations where a sea level rise of 1 meter would be of concern include the Netherlands, Bangladesh, the mouth of the Nile River in Egypt, coastal areas of Japan, the coastal mangrove swamps of Indonesia and Malaysia, the area of Thailand around Bangkok, and Vilan Plain in northeast Taiwan (Hekstra 1989). Also included are several low-lying island nations such as the Maldives, Kiribati, and Tuvalu, South Australia, and the Caribbean, for which even lesser increases may be a problem. Calculations of the probable cost to society have been done in a few instances. For example, structural adjustments to dikes, harbors, etc., for a 1-meter increase in sea level in the Netherlands would cost about $10 billion guilders (US$5 billion) over about 100 years (de Ronde 1989). Delft Hydraulics Laboratory (1990) has calculated costs of protection for 181 countries and territories. For ten of the countries, several of which are islands, costs of preventing inundation from a 1-meter rise

Table 2.9. Summary of Coastal Zone Research

Issues	Methods	Findings
Would sea level rise, coastal erosion, and storm surge pose a serious threat to coastal resources if the climate warms? Can the threat be quantified?	Calculations of ocean thermal expansion, snowfall, and glacial melting and shoreline dynamics; relationships of hurricane frequency and severity to sea temperature; historical changes in wetlands and shores.	Several low-lying nations and coastal areas are at risk from projected sea level rise of less than 1 meter before 2100. Calculations of wetland functioning, vulnerability and value are a major source of uncertainty in quantifying impacts.

would be more than 5% of their Gross National Product (GNP), with values rising to as much as 34% of the GNP.

There are major uncertainties in most of the available studies concerning the impacts on the ecological systems in estuaries and at coastal margins. The rate of net measures is unresolved, depending in part on the value assigned to wetlands. Based on a portion of the environmental functions that they provide (sinks for pollutants, flood protection, nurseries for various species, and support for birds, mammals, fish and shellfish) one study assigned values of $13,600/ha to salt marshes (Thurman 1983).

Uncertainty limits our ability to predict the magnitude and rate of rising sea level from global warming. In particular, it is known that coastal wetlands (Stevenson et al. 1986) and coral (Grigg and Epp 1989) can keep up with rising sea level if the rise is not too rapid; beyond a critical rate, these systems would be inundated and destroyed. If the rise is not too rapid, the location, planned lifetime, and maintenance of coastal structures can be adjusted (National Research Council 1987). However, a variety of coastal processes and coastal ecosystem dynamics must be better understood before it is possible to predict the response of the coast to rising sea level (Mehta and Cushman 1989). For example, in recent decades, 28% of the mid-Atlantic coast has actually been *accreting*, rather than eroding (Dolan et al. 1989).

Gornitz and Kanciruk (1989) have described a project to identify those areas of the world at highest risk, while efforts continue to quantify the current rate of global sea level rise and underlying processes (e.g., Peltier and Tushingham 1989; National Research Council 1985).

2.4.8 Infrastructure

No credible estimates exist for the overall infrastructure requirements related to climate change. IPCC (1990) includes a number of examples from very limited studies that discuss the types of effects on infrastructure that may be expected. Most currently existing infrastructure will be outdated and will have to be replaced, refurbished, or modified over the next 50 years, regardless of whether climate changes. If climate changes systematically, then modifications to new infrastructure can be designed accordingly, and the impact of climate change on infrastructure cost would be a small fraction of the total investment in most cases. However, some structures may have to be moved to avoid rising seas or to serve migrating markets and populations or else they may have to be modified and maintained differently (e.g., storm drains may have to be enlarged if rainfall intensity or snowmelt increases, or river channels may have to be dredged more frequently). New infrastructure may be required--only some of which might be based on technologies that already exist.

In all of these cases, changes in infrastructure may have to be designed more flexibly than in the past to anticipate and reduce social, economic, and political displacements that could result from changing climate. Long-lived capital investments will require creative reaction well in advance of climate change and will therefore be possible only if we develop decision making structures that can cope with enormous uncertainty, large expense, and lengthy time periods. A new understanding of intertemporal decision processes is thus required, supported by research directed toward uncovering information that is most valuable (Yohe 1990b, 1990c).

2.4.9 Health Effects

Potential effects of climate change on human health have been inferred from correlation of health conditions with weather variables or seasonality. Studies include White and Hertz-Picciotto (1985), Wiseman and Longstreth (1988), Haile (1988), Kalkstein (1988), Smith and Tirpak (1989), Longstreth (1989), Dobson and Carpenter (1989), and Kalkstein (1989). No definitive estimates have been done of either the overall effects of climate change on human health or of the health costs associated with these effects.

It is currently believed that effects on human health could occur through 1) the direct impacts of

temperature (heat stress and cardio- and cerebrovascular conditions); 2) climate-related chronic, contagious, allergic, and vector-borne diseases and mosquito and tick-borne diseases, such as encephalitis and Lyme disease; 3) premature birth; and 4) pulmonary conditions such as bronchitis and asthma related to photochemical smog (Raloff 1989). Although the ozone-depletion issue also comes up in agriculture and fisheries, stratospheric ozone depletion and climate impacts on human health may reinforce each other. Human populations with natural immunities weakened by increased UV-B radiation as a result of stratospheric ozone depletion might be more vulnerable to vector-borne diseases and other climate-related health insults (IPCC 1990).

Climate-induced impacts on agriculture, fisheries, water and coastal resources, and social and economic conditions might also affect human health. Decreases in food production might result in poorer diets; or rising sea levels and changed precipitation patterns might result in the deterioration of water supplies or drainage systems, with significant health and economic consequences (Harrington et al. 1989). The IPCC (1990) notes that greater numbers of humans may migrate from one area to another as "environmental refugees" associated with climate change, changing the geographic ranges of susceptibility of human populations to many diseases, and causing a breakdown in sanitation and medical services in some cases. In general, any event that reduces standards of living will have an adverse impact on human health (Chappie and Lave 1982).

A number of issues have yet to be resolved. Predictions of the health effects cannot be made without good predictive data on local temperatures, humidities, levels of precipitation, and other climate influences on human health. We do not have the information required to accurately assess all the synergistic and offsetting effects of confounding factors, nor on the social and economic impacts that climateor ozone-induced changes in mortality and morbidity might, in turn, generate. Nor do we have much information on the social and economic costs of such impacts. Information on the out-of-pocket medical costs and the productivity losses associated with increases in morbidity, in particular, is not readily available. If in fact the major pathway for reduced human health is indirect; e.g., through the cost and availability of food and general levels of income, an adequate understanding of the full costs awaits the development of a global, general equilibrium model of the consequences of atmosphere/climate change. Table 2.10 summarizes health effects research.

2.5 REGIONAL STUDIES AND FINDINGS

The "state of the art" in regional climate impact assessment has some significant methodological limitations, even though it has been advanced recently for developed regions in a major study for DOE (Rosenberg et al. 1991) that linked the directly affected sectors through an input-output model of the regional economy. In the DOE study, an analytical framework was developed that provided baseline information on the current functioning of a region's economy and how it might develop in the future in the absence of climate change, analyzed how various kinds of climate change and elevated atmospheric CO_2 might alter baseline activity in all the major climate-sensitive sectors (first-order effects), studied the ways in which the primary natural resource-related enterprises and institutions may respond (second-order effects), and then studied how the responses of these enterprises might feed back on economic activity in the regional economy as a whole. Table 2.11 summarizes regional effects research.

A number of other studies have attempted to produce an overall assessment of the effects of significant aspects of climate change on regional economies and societies, but few have been integrated studies. The EPA report to Congress (Smith and Tirpak 1989), for example, focused on four regions of the United States: California, the Great Lakes, the Southeast, and the Great Plains. In the DOE study, separate (and somewhat independent) studies examined the response of different sectors to climate change. Common climate projections were taken from the GCMs of the Geophysical Fluid Dynamics Laboratory, Goddard Institute for Space Studies, and Oregon State University; sea level rises of

Table 2.10. Summary of Health Effects Research

Issues	Methods	Findings
Would global warming be a threat to human health, either by itself or in combination with other factors?	Correlations of health conditions with weather variables in historical record. Models of vectors and hosts for vector-borne diseases. Analysis of epidemiological and experimental data on health conditions and influences such as exposure to UV-B.	Human populations appear potentially vulnerable to the spread of some tropical diseases due to expansion of geographic ranges of some insect hosts. Malnutrition and lowered living standards are potential threats, as is reduced immunity due to greater UV-B exposure. Quantitative effects are not known, due to the prevalence of confounding factors.

Table 2.11. Summary of Regional Effects Research

Issues	Methods	Findings
What are the additional effects of global warming when all the climate-sensitive sectors in a region are considered? How are these sectors influenced by events outside of the region? How should a region be defined?	Regional economic models; models of individual sectors; analyses linking individual sectors to global markets (comparative advantage) and to resources in other regions.	Total climate change impacts within regions are sensitive to 1) interactions between sectors (e.g., agriculture and water resources), 2) resource interactions between regions (as with upstream decisions regarding surface water withdrawals), and 3) international market interactions within particular sectors. These effects could be larger than the direct effects of climate.

50 centimeters to 200 centimeters by the year 2100 were assumed. Some regions of the United States have been examined by other researchers in studies of particular resource sectors. For example, Flaschka et al. (1987) studied the response of the Great Basin to climatic change, while Idso and Brazel (1984) and Callaway and Currie (1985) studied basins in the Lower Colorado region. Linder and Gibbs (1986) analyzed how electric utilities in New York State could be affected by climate change.

One typical limitation of special significance to the regional studies is that the regional interactions between sectors are not fully accounted for. Therefore, the findings of these studies should be interpreted as a statement of the **possible responses or vulnerability** of some resource sectors to climatic change, rather than as a prediction. Even in the DOE study, the range of enterprise and institutional adjustments was somewhat limited. Ideally, a regional study should incorporate the many interactions and

feedbacks that link the various sectors within the region. In many regions, assessment of neither the impacts nor the responses would be possible in a conventional economic model. Indeed, in several of the developing countries, the most important impacts could be on human health and nutrition, migration, land degradation, or changes in institutional structures. A number of references, including Turner et al. (1990), have been cited by Riebsame and Magalhaes (1990) as beginning to deal with the coevolution of social and ecological factors along with economic ones.[a]

Potential effects of global climate warming also have been studied outside of the United States, most particularly in the Netherlands, Canada, and the Soviet Union. The impacts on agriculture, forestry, and sea-level rise have received the most attention.

Most international climate effects studies have emphasized agriculture (which has in some cases included forestry). A 1988 IIASA project pursued 11 agricultural case studies in temperate, high-latitude, and semiarid regions (Parry et al. 1988a, 1988b), while IPCC (1990) has documented the results of a number of further studies. Some of the agricultural case studies were integrated into studies of the surrounding regional economies. The most complete study of this to date is Rosenberg et al. (1991). The case studies examined the impact of variations in climate using both climate anomalies (e.g., historical single-year droughts or historical series of several cold or warm years) and synthetic estimates of climate warming from GCMs. In general, the case studies of cooler regions such as Saskatchewan, Iceland, northern agricultural areas of the Soviet Union, Finland, and Hokkaido in Japan showed some benefits to agriculture from warmer growing season weather in cold-limited areas. If, however, precipitation also decreases, production in some of these areas (such as southwestern Saskatchewan) would be damaged by lack of moisture, moisture deficits over several years, or moisture at the wrong time. In general, the IIASA studies of semiarid regions showed that interannual and intraseasonal variability in precipitation are extremely important factors in the productivity of agriculture, both in subsistence agricultural areas such as Kenya, northeast Brazil, and Ecuador and in commercial agricultural areas such as the southern U.S.S.R. and Australia.

The Canadian Climate Centre of Environment Canada has published a series of regional studies of the effects of climate change on various individual resource sectors in the Canadian economy, together with an assessment of sector interactions in Ontario (DPA 1988) and multiple resources in Quebec (Singh 1988). A $2xCO_2$ climate change forecast from the Goddard GISS GCM was used to drive the analyses. Almost all components of the climate system and resource use in the province were affected, including municipal water use, hydroelectric power, tourism anld recreation, food production, forest resources, health, and residential heating and cooling requirements. The Canadian studies also examined agricultural impacts in Ontario and the prairie provinces, sea-level rise in the maritime provinces, and the skiing industry in Ontario. None of the regional studies was a fully integrated regional analysis, and none directly linked the impacts to emissions of greenhouse gases.

2.6 ANALOG STUDIES AND FINDINGS

Another approach has been to examine the actual response of the human environment to actual past climatic variation, the so-called analog approach. It is not known whether past climate patterns are a good proxy for greenhouse-induced changes in the future, and because of data limitations, such studies are usually very restricted in their temporal and spatial extent.

A number of studies have been conducted to learn the effects and responses of global climate change on

(a) The Interlaken Workshop participants emphasized the need to look carefully at regional systems that do not integrate through advanced Western-style market mechanisms. The same point was made recently by several developing country participants at the 1991 Woodlands Conference at The Woodlands, Texas.

human and natural systems. Early studies by historians have provided assessments of the impact of climate on human societies; for example, Wigley et al. (1981); Rotberg and Rabb (1981); and Lamb (1982). A fairly lengthy list of early analog climate impact studies is provided by Kates et al. (1985). Properly qualified, these "semidescriptive" case studies may shed useful light on the relationships between society and climate change. Some of the most thorough and interesting recent assessments of human institutional response have been provided by (Glantz et al. 1987; Glantz 1988), and by the IIASA study on the impacts of climate variations on agriculture (Parry et al. 1988a, 1988b). Table 2.12 summarizes analog research.

Some human institutional responses include relatively successful risk-minimizing cropping patterns and other institutional adaptations of indigenous peoples to climate variability of the Ecuadorian Andes, the successful food purchase programs of the Kenyan government in response to drought, and the reliance of Icelandic farmers on fodder reserves to guard against cold summers (Parry et al. 1988a, 1988b). In some cases, such as India, ad hoc or emergency responses have themselves been institutionalized to the point where the population has come to expect them (Gadgil et al. 1988). In other cases, such as the Colorado River Compact, the institutions are rigid to the point that surface water is used to grow low value crops while cities in the region are mining groundwater at a high cost (Brown 1988).

In general, case studies have demonstrated how societies can respond to climate variability. For example, coalition-building among governments and interest groups has been shown to be important if action is to be taken in the face of uncertainty (Glantz 1988). All of the case studies raise the issue of intergenerational equity. The studies show that ad hoc responses and traditional approaches usually have been the preferred initial mode of adaptation, which in turn often added an element of rigidity to further response. Some of the studies show that once the regional winners and losers from environmental change have been identified, the winners have little incentive to compensate the losers. The advantage of the analog studies is that they contain a wealth of detail (particularly on the capacity of humanity to adapt), integrate a broad range of knowledge, provide a multiplicity of perspectives, and are easy to communicate and use. The disadvantages of analog studies include lack of definite causes for environmental change that can be related to greenhouse warming (the cause is

Table 2.12. Summary of Analog Research

Issues	Methods	Findings
What can past climate anomalies tell us about the impacts of future climate change?	Qualitative and quantitative historical assessment of the impacts of past anomalous climate periods on institutions, markets, and group behavior.	Human institutions are quite adaptable to climate change, provided that the nature of the change is understood. Intergenerational equity and compensating the losers has proved challenging. Analysis tends to be local in nature. No good analogues exist for long-term climate change experienced on a global basis.

not always known) and simple failure of the analogy to be apt for a warmer world with elevated CO_2 (many of the studies concern cooling and none is concerned with elevated CO_2).

2.7 UNCERTAINTIES AND INFORMATION NEEDS

This section deals with limitations on effects estimation that are posed by uncertainty or lack of information concerning biophysical and socioeconomic relationships, models, and data required to estimate the effects of climate change on the human environment. Both limitations in existing methodologies and problems with available data are addressed.

2.7.1 Limitations and Methodology

In the past, climate problems dominated by enormous uncertainty have been handled by sensitivity analysis (Smith and Tirpak 1989) and Monte Carlo simulation techniques (Reilly et al. 1987; Nordhaus and Yohe 1983). Structural uncertainty has usually been handled by examining the outputs of alternative model structures (Bolin et al. 1986). The climate change system is so complex that "brute force" application of any of these techniques is not likely to be productive. Methods based on analysis of the hierarchical model structure are one possible approach (Liebetrau and Scott 1990a). Methodological literature on creating reduced form models includes Brainard (1967), Fair (1980), and Box et al. (1987). Input designs to meet specific modeling objectives are being developed and may prove useful for sorting or ranking input variables (Sacks et al. 1989). Similar methodologies are being developed in other areas that may be useful in the global modeling arena [Chapter 6 of Reimus et al. (1989) for geologic storage of nuclear waste; Gilbert et al. (1990) for an application to radioactive dose estimation].

In addition, uncertainty about some other variables may not be important even though their future trajectories are not well known; median or mean values of their trajectories can thus be assumed with little cost. Also, practical methods have been developed to bring outside information to bear on the problem of uncertain outcomes for sea level rise, for example (Yohe 1990b), and for agricultural response (Yohe 1990d).

2.7.2 Limitations and Information

Environmental assessments of impacts from climate change have focused on individual resource sectors in selected regions of the United States. A major reason is that regional studies require a major commitment of time and money, and a "truly integrated assessment" requires a very significant commitment, such as that devoted to the National Acid Precipitation Assessment Program (NAPAP 1989).

This section focuses on the general limitations in information available for environmental assessments at the regional and national scales; detailed lists of data needs have been prepared for individual resources (White 1985). Numerically and geographically integrated data sets for environmental data do not generally exist for large regions (Olson 1984)--let alone economic data sets that are geographically aligned with environmental data. No standard methods exist for integrating data collected for different spacial units or for defining study regions to minimize uncertainties caused by boundary heterogeneity. Large, integrated database systems that provide data stored in compatible spatial and temporal formats, with associated analysis and mapping capabilities to conduct integrated studies, are rare in the developed world and even rarer in the developing world (Riebsame and Magalhaes 1990).

Examples of existing integrated data systems in the United States include the DOE's GEOECOLOGY and SEEDIS, the Council of Environmental Quality's UPGRADE, the Environmental Protection Agency's GEMS and ADDNET, and DATAGRAF (Merrill 1982; Olson et al. 1987). A compilation of U.S. data sources and agencies dealing with climate change has been compiled by the DOE national laboratory system. Typically, one-third to one-half of the effort spent on regional studies is devoted to developing an integrated and quality-assured database.

Although regional studies have been performed for many years, the ecosystem properties that are important for establishing regional scales are still poorly understood (Hunsaker et al. 1989). Few regional-scale biological models exist. In most instances, either local models will have to be scaled up with attendant scale-effect risks (Solomon 1986), or entirely new models will have to be built (Emanuel et al. 1985). The number of available models for physical processes is limited and not easily integrated with resource use and economic models.

Data manipulation and extrapolation can contribute to uncertainty because of inadequate spatial or temporal resolution, or both. Computerized, digital terrain data that are of sufficient spatial resolution to be useful for coastal studies (such as land inundation from a sea level rise of 1 meter) are only available for limited areas (Durfee et al. 1986; Bright et al. 1988). The classification of geographic areas according to the relative homogeneity of one or more environmental attributes can be useful in reducing uncertainty. Some of the more recent technological tools--such as geographic information systems, satellite sensors that capture biologically significant spectral patterns, and supercomputers that can process large spatial arrays--will be useful for addressing the theoretical and applied research challenges that the regional scale poses (Hunsaker et al. 1989).

2.7.3 Dependence on Forecasting Future Developments and Interactions

Understanding the potential effects of climate change is based on subjective views of the likely distributions of a myriad of random variables by individual researchers. Our ability to foresee future developments is dependent upon both temporal changes in these distributions and the "general equilibrium" interactions among them, which work across the entire system. We need to understand that learning process as well as we understand the system itself.

Some of our learning will be Bayesian in nature--simply improving our understanding of possible ranges of critical state variables by observing how they move into the future. We will learn more quickly about some variables than others, and we will need to assess the value of resources devoted to the process, weighing the relative ease of learning about each variable against its relative importance in affecting human existence. Other learning will be derived by improved understanding of underlying driving variables and the processes by which they affect the critical state variables. Investigation into the processes of learning in the context of the type of long-term uncertainty of climate change effects is under way as part of the DOE effort described in Edmonds et al. (1989). Two applications to particular learning situations are shown in Yohe (1990c, d).

2.8 DISCUSSION AND SUMMARY

The state of science with respect to the effects of global climate change on the human environment is still in its early stages. Research to date has revealed probable qualitative effects of climate change in specific sectors and regions, climate vulnerabilities, and in a few cases, quantitative effects for selected historical and synthetic climate patterns thought to be illustrative of future climate change. There are methodological and data-related problems of quantitatively characterizing the complex underlying interactions between humans and the environment. More important, the current capability of climate models is limited to continental-scale effects, while events important for impact on humans occur at much smaller regional levels and bridging mechanisms are still problematic, although some progress has been made. Table 2.13 summarizes the general state of the science or "knowns," as well as the significant uncertainties, based on Scott et al. (1990). In a recently released study, the U.S. Committee on Science, Engineering, and Public Policy, a joint committee of the National Academies of Science and Engineering and the Institute of Medicine discussed the impacts of climate change on natural and human resources as well as potential adaptive responses (Committee on Science, Policy, and Engineering 1991). Resources

Table 2.13. Summary of State of the Science and Uncertainties in Effects of Global Climate Change on the Human Environment

Parameter or Area of Inquiry and Sensitivity Rating[a]	Knowns	Uncertainties
Findings of Sectoral Studies:		
1) Energy (A)	Probable general direction of effects on conventional energy supply (except hydro) and demand, given a level of average temperature increase. Models and methods for short-term weather variations.	Regional effects of climate change on weather variables. Effect of climate change on hydroelectric supply. Effect of climate change on biomass supply and productivity of wind energy, ocean thermal, and other unconventional resources, as well as environmental impacts on conventional sources (e.g., permafrost changes).
2) Agriculture (B)	Mechanisms of climate change. Physical/economic crop models with some CO_2 fertilization from laboratory experiments, which show significant fertilization benefits of CO_2 in some crops. Some effects of selected production scenarios on national and international markets and processing firms, indicating that world food supplies are probably not jeopardized by modest climate change.	Necessary detailed regional climate forecasts and effects on regional crop production are very uncertain. Actual farmer responses to weather and world prices (and possibly changed incentives) under changed climate are not clear. Because of these and other considerations, even the direction of effects on specific crops in given locations is uncertain. Effects of elevated CO_2 on photosynthesis, water-use efficiency, resistance to drought and salinity have not been fully incorporated in analyses.
3) Water Resources (B)	Models of watersheds, ground water supply and some river basins. Relationship of precipitation to run-off and water supply for today's climate. Some relationships between agriculture, available irrigation water, and instream needs.	Necessary detailed regional and temporal forecasts of temperature, precipitation, and other weather variables. Relationships between small area precipitation and large basin water supply. Effects of changed seasonality of precipitation. Water supply institutional response to changed water supply conditions (water markets, allocation rules, storage) are uncertain. Changes to agricultural water demand due to elevated CO_2 have been considered in some analyses, but the size of this effect remains uncertain.

Table 2.13. (contd)

Parameter or Area of Inquiry and Sensitivity Rating[a]	Knowns	Uncertainties
4) Forestry (B) and Unmanaged Ecosystems (C)	Some mechanisms of climate impacts. Physical models of forest succession for small plots. Estimates and models of world products markets. Vegetation change based on fossil record.	Regional weather inputs for forest succession models. Existence of a CO_2 fertilization effect and water-use efficiency improvements. Response of the forest industry and ecosystems to high rates of climate change. Changes in terrestrial-aquatic linkages. Role of disturbances like drought and wildfire. Time sequences and species mix of changes in communities.
5) Air Quality (A)	General effects of temperature on severity of inversion episodes, changes in wind field patterns, and other features of air quality.	Likelihood of inversions (requires weather forecasts). Synergistic and offsetting effects of pollutant emissions. Sufficient spacial resolution of meteorology.
6) Fisheries (C)	General movement of marine fisheries poleward. General influence of temperatures on freshwater species.	Quantitative influence of warming on currents and abiotic processes. Influence of warming on precipitation, ground and surface water.
7) Coastal Zone (B)	Probable rates of shoreline inundation in many locations, given a scenario of sea level rise resulting from temperature change. Costs of coastal defense for some areas.	Impact on, and value of, coastal wetland resources. Effects on land subsidence and coastal fresh groundwater. Effects of coastal processes such as sediment transport.
8) Infrastructure (B)	Some data on the influence of weather phenomena on road and building maintenance requirements, utility demand, hydroelectric supply, irrigation works. Influence of sea level on coastal infrastructure. Requirement to replace today's infrastructure within the next 50 years, independent of climate change.	Relationship of global warming to local weather. Quantitative estimates of infrastructure requirements.

Table 2.13. (contd)

Parameter or Area of Inquiry and Sensitivity Rating[a]	Knowns	Uncertainties
9) Human Health (A)	Some inferential data on the relationship of health conditions to weather episodes, disease vectors, and climate.	Influence of global warming on proximate causes of disease and health conditions. Influence of synergistic (e.g.,UV-B) and offsetting (e.g., acclimatization) factors. Impact of migration and social service breakdown.
Findings of Regional Studies	Impact of global warming scenarios (usually $2xCO_2$) on individual regional resources, given current technology. Some discussion of intersectoral links (CO_2 fertilization) and sensitivity of impacts to human adaptation. Some intersectoral and interregional linkages.	Realistic warming scenarios. Scientific basis for resource effects (e.g., open-air fertilization). Influence of human adaptation and technological change on impacts. Effects of realistic intersectoral and interregional economic and social linkages.
Findings of Analog Studies	Impact of institutional adaptation on environmental impacts. Reaction of human institutions to complex environmental problems with interregional, intersectoral, and intergenerational implications.	Appropriateness of the analogues studied to global climate change situation.

(a) Ratings: A = Low sensitivity; B = sensitive, but adaptation at some cost; C = sensitive, adaptation problematic.

were rated according to how "sensitive" each resource was considered to be (sensitivity being defined as the degree of change in the subject resource for each "unit" change in climate). Sensitive resources were also rated as to whether 1) adaptation could take place at a cost or 2) adaptation was problematic. The committee noted that sensitivity depends on, among other things, intentional adaptation and natural and social surprises (to which could be added strength of technological base and institutions). The ratings given in the individual sectors in Table 2.13 for the United States and similar industrialized countries are for current conditions, not those that might prevail in the middle of the twenty-first century. In the table, A = low sensitivity; B = sensitive, but adaptation at some cost; C = sensitive, but adaptation problematic. Air quality was not rated by the committee; it is largely similar to Health in its mechanisms and probable rating.

Many of the uncertainties in the area of effects on human society are still at the conceptual or process level and are site-specific. For example, in the area of agriculture, where some of the most extensive work has been done, only the basic models of the physical mechanisms of climate change have been worked out. It is not yet clear how significant the timing of weather events and CO_2 fertilization will be. In

addition, it is not yet clear what the reactions of the agricultural sector (e.g., choice of crops, irrigation, pesticide and herbicide use, planting dates) will be to weather events, although progress has been made in clarifying some of the impacts of responses of particular types (Easterling et al. 1990; Rosenzweig and Parry 1990). The lack of detailed regional climate forecasts is a major source of uncertainty; nevertheless, there is still major uncertainty that needs to be resolved within the models themselves.

According to the IPCC Work Group III report on Resource Use and Management, the impacts of human-induced climate change will take place against a backdrop of population growth, technological change, economic progress, and natural climatic variability. In many instances, the IPCC believes that the impacts of human-induced climate change could be relatively small, compared to the much larger effects of population growth and other factors. In other instances, the climate effects could be significant. In some cases, climate change may exacerbate the other pressures, but in some cases, it may help relieve them. There does not yet exist a sufficient knowledge base concerning effects to permit evaluations of the costs and benefits of adaptation versus emissions reduction.

Several key issues must be addressed in any reference methodology designed to examine climate change effects:

- Time. Resource effects of climate change will take place in a world with tomorrow's technology where climate is an evolving state. Any analysis must be ***future-oriented***. The pace and timing of CO_2/climate change and the response technology may be as important to determining consequences as the characteristics of any eventual CO_2 concentration and climate.

- Multiple resources are affected. Methods must be developed to address the interactions of human and natural systems, including methods to simultaneously analyze the interaction of multiple resources within a systems framework, quantify the combined CO_2/climate change interactions, and forecast trends in exogenous system variables such as technological change and population growth. Because many economic agents in a region may compete for the same regional resource (e.g., surface water), the indirect market effects of climate change may either exacerbate or mitigate the direct effects. This implies that the analysis of impacts in a region ***must integrate all the significant environmental, economic, and social interactions***. The relative emphasis of economic, environmental and social effects will vary by region.

- Geographic disaggregation and integration. To be meaningful, effects studies must select appropriate geographical entities for analysis--site, region, global--and because of the interactions between regions, studies ***must take into account the world context***. Interregional effects occur either through interregional trade and market responses, through human migration, or through natural resource flows such as transboundary river flows or transboundary air pollution. It may not be always computationally feasible to directly link individual regions into a grand "world model," but regional analyses must be conducted with awareness of the potential impacts on competing and neighboring regions.

- Uncertainty. Studies must develop and apply appropriate uncertainty analysis techniques. First, we will be uncertain of future climate, which implies the use of multiple climate scenarios. Second, future economic growth, populations, and technologies are also uncertain, so any analysis of the environmental consequences of climate change will have to deal explicitly with human behavioral uncertainty, learning, and institutional change. It is likely that this work will require advances in analytical and computational techniques.

- Networking. Many of the interesting questions in climate effects are at the regional level and require regional expertise for proper analysis. Especially in the developing countries, much of the actual analytical work may have to be done in-country, with technological expertise for conducting such

studies being transferred from the developed world. A system will have to be developed for doing this.

To summarize, an optimal greenhouse gas emissions policy must equate the marginal cost of the last tonne of carbon dioxide equivalent emissions reduction to the value of the benefits derived from that last tonne of emissions reduction. However, while the numerous studies cited in this chapter (and others) have provided us with considerable knowledge concerning the impacts of global atmospheric/climate change, the comprehensive models and data required to assess the consequences of such changes in terms of the "damage" to society do not yet exist. This problem is compounded by the fact that critical problems still exist in predicting and assessing the nature and timing of global atmosphere/climate change, especially at the local and regional scale. However, even if the GCMs were capable of accurately forecasting future patterns of local and regional atmosphere/climate change for alternative emissions scenarios, we would still be faced with problems with depicting and predicting local and regional physical and human response functions, lack of appropriate data, and problems with linkages between regions. Thus, while it is possible to describe the type of effects that can be expected from global atmospheric/climate change, and in some cases to quantify them, the comprehensive damage functions required to achieve optimal national policy remain a goal for the future.

In the chapters that follow, we will assemble information regarding the emissions of radiatively important gases and potential future emissions of these gases by the United States and the rest of the world during the period to the year 2030 under both Current Policies and National Energy Strategy (NES) Actions. We will evaluate the feasibility and cost of reducing potential future emissions beyond the levels achieved through the NES Actions by employing a variety of policy instruments, and finally compare the results reported here to those obtained by other researchers.

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3.0 U.S. GREENHOUSE GAS EMISSIONS PAST AND PRESENT

3.1 INTRODUCTION

The purpose of this chapter is to provide a frame of reference for discussions of national policy implications of greenhouse gas control and mitigation in terms of:

- the principal greenhouse gases and their relative contributions to global warming
- the current levels of emissions, especially as they compare with pre-industrial levels
- the portion of total emissions influenced by human activities
- the U.S. relative contribution to the total and, where applicable, the regional activities that are the most important contributors.

Discussions of global climate change generally focus on a dozen or so (depending on level of aggregation) trace gases that either directly affect the vertical temperature profile of the atmosphere (radiatively active gases) or affect atmospheric chemistry interactions, which in turn affect the concentrations of temperature forcing gases. Table 3.1 summarizes characteristics of many of those gases whose atmospheric concentrations are affected by human activities.

These gases vary greatly in their concentrations in the atmosphere and in their radiative absorption per molecule. This has led to confusion regarding the relative importance of various gases. To date, no convention has emerged that provides a satisfactory measure of the relative importance of radiatively active gases. One index of effectiveness, the Greenhouse Warming Potential (GWP), attempts to relate the various gases in terms of their importance. A discussion of GWP is included at the end of this chapter.

Manufactured emissions of these gases occur against a natural background of emissions and removal processes that range from nonexistent for the CFCs to enormous for CO_2. CO_2 is generally considered to be the most important of these gases, accounting for about half of the current and anticipated radiative forcing. Fossil fuel use is the most important present and anticipated source of CO_2 emissions, though land-use change, especially deforestation, is another important source of net release to the atmosphere.

The quality and detail of the state of knowledge of historical emissions of greenhouse gases varies considerably among gases and sources. Fossil fuel CO_2 emissions and release of CFCs to the atmosphere are among the best known of greenhouse gas emissions. CO_2 emissions from land-use changes are less well understood. Emissions budgets for CH_4 and N_2O are also uncertain, and the global emissions budget for CO, which affects climate indirectly by perturbing the atmospheric composition, is highly speculative. Fluxes of carbon between oceans and the atmosphere and between the biosphere and the atmosphere are much larger than emissions from fossil fuel use and land-use change. These exchanges are discussed briefly in Chapter 1 in this report as part of the natural carbon cycle.

In the sections that follow, we will review for five of the principal greenhouse gases (CO_2, CH_4, CO, N_2O, and CFCs) the available information regarding historical and present-day atmospheric concentrations, the sources of emissions along with the attendant uncertainties, and the U.S. contributions to the emissions totals. (Appendixes A through I, available from the DOE, contain detailed information on emissions coefficients used in the analysis and some extensive state-by-state historical estimates of emissions.) Nitrogen oxides (NO and NO_2) and sulfur dioxide (SO_2) are also considered

Table 3.1. Characteristics of Key Greenhouse Gases[a] (values based on mid-1980s)

Gas	Common Name	Surface Concentration (ppm)	Atmospheric Trend (%/yr)	Atmospheric Lifetime[b] (year)	Primary Human-Related Sources
CO_2	Carbon dioxide	350	~0.4	~250*	Fossil fuel burning; deforestation.
CH_4	Methane	1.7	~1	~10	Domestic animals; rice paddies; biomass burning; natural gas and coal mining.
CO	Carbon monoxide	0.12	~1-2	~0.4	Energy use; agriculture; deforestation.
N_2O	Nitrous oxide	0.31	~0.3	~150	Cultivation and fertilization of soils.
NO_x	Reactive odd nitrogen	20×10^{-5}	unknown	<0.02	Fossil fuel burning; biomass burning.
$CFCl_3$	CFC-11	2.0×10^{-5}	~5	~60	Chemical manufacture.
CF_2Cl_2	CFC-12	2.0×10^{-4}	~5	~75	Chemical manufacture.
$C_2Cl_3F_3$	CFC-113	3.2×10^{-5}	~10	~90	Chemical manufacture.
CH_3CCl_3	Methyl chloroform	1.2×10^{-4}	~5	~6	Chemical manufacture.
CF_2ClBr	Ha-1211	1×10^{-6}	~10-30	~12-15	Chemical manufacture.
CF_3Br	Ha-1301	1×10^{-6}	unknown	~110	Chemical manufacture.
SO_2	Sulfur	$1\text{-}20 \times 10^{-5}$	unknown	~0.02	Coal and oil burning.
COS	Carbonyl sulfide	5×10^{-4}	<3	~2-2.5	Biomass burning; fossil fuel burning.

(a) Wuebbles and Edmonds 1988; Wuebbles et al. 1989. More sophisticated models of ocean uptake (e.g., Maier-Reimer and Hasselman 1987) show variable removal rates from the atmosphere (lifetimes) depending upon the period of analysis; see Chapter 1, this volume.
(b) Computed as the ratio of the atmospheric burden to net annual removal. Net annual removal is estimated emissions less atmospheric accumulation.

important greenhouse gases, though far less is known about these gases with regard to global climate change, as neither is an important radiatively active gases.

3.2 CARBON DIOXIDE EMISSIONS

Accounting for about half of the total greenhouse warming effect observed during the post-World War II period (Raynaud et al. 1988), CO_2 is principally the result of combustion of fossil fuels; however, land-use changes and to a small extent, the manufacture of cement also make contributions. Table 3.2 provides an indication of the current knowledge of CO_2 sources.

Table 3.2. Historic CO_2 Emissions

Sources	Quality of Emissions Data	Uncertainty	Notes
Fossil fuel use	Good	± 10-20% available by country by fuel	1988 = 5.7 PgC/yr 1850-1986
Cement manufacture	Good	± 10-20%	Minor importance (0.2 PgC/yr in 1988)
Land use	Fair/Poor	± 50-100%	1980 = 0.4-2.6 PgC/yr Primarily tropical deforestation

Sources: Wuebbles and Edmonds 1988; Edmonds and Barns 1990; also Wuebbles and Edmonds 1991.

3.2.1 Historic Fossil Fuel CO_2 Emissions

The average annual concentration of CO_2 in the atmosphere has risen from approximately 315 ppm in 1958 to approximately 350 ppm in 1988. This rise is thought to result principally from emissions of CO_2 by fossil fuel use and from deforestation. There is a longer record of emissions of CO_2 from fossil fuels than for any of the other gases. Since 1860, global annual emissions of fossil fuel CO_2 have increased from 0.1 PgC/yr to approximately 5.7 PgC/yr in 1988 (1 PgC = 1 petagram carbon = 10^{15} grams). During the period 1945 through 1979, the rate of CO_2 emissions from fossil fuel use grew at 4.5%/yr. Emissions declined from 1979 until 1983, but have risen subsequently. The United States, the Soviet Union, and the People's Republic of China account for half of the world's fossil fuel CO_2 emissions (Boden et al. 1990).

Carbon content varies by fuel. Of fossil fuels, natural gas has the lowest (13.74 TgC/EJ) (TgC = teragram carbon = 10^{12} grams; EJ = exajoule = 10^{18} joules), coal has the highest (24.12 TgC/EJ), and oil falls between the two (19.94 TgC/EJ). The mining of oil shales in carbonate rock formations would add an additional stream of CO_2 to the atmosphere. The transformation of primary fossil fuel energy, for example, from coal to electricity or from coal to synoil or syngas, releases carbon in the conversion process. Energy technologies such as hydroelectric power, nuclear power, solar energy, and conservation (including energy efficiency improvements) emit no CO_2 to the atmosphere (unless a full fuel cycle accounting is made). It should be noted that more efficient fossil energy technologies can also reduce greenhouse gas emissions, relative to conventional technologies. Traditional biomass fuels such as crop residues and dung release CO_2 to the atmosphere, but are in a balanced cycle of absorption and respiration whose timeframe is short. The use of other biomass fuels such as firewood may provide either a net annual source or sink for carbon, depending on whether the underlying biomass stock is growing (sink) or being exhausted (source).

3.2.2 Historic CO_2 Emissions From Land-Use Change

There are approximately 560 PgC in the form of terrestrial biomass, principally stored in forests. This is estimated to vary by less than about 10 PgC/yr on a global basis (Trabalka 1985) through the seasons as leaves and grasses grow and die.

Estimates of the net annual emissions of carbon from land-use changes are far less certain than emissions estimates for fossil fuel use. Emissions of net annual CO_2 release from land-use changes have been estimated for the year 1980 by various researchers. Net release is calculated as the difference between annual gross harvests of biomass, plus releases of carbon from soils, less biomass carbon whose oxidation is long delayed (e.g., stored in forest products such as telephone poles, furniture, and housing) and additions to the stock of standing biomass. Houghton et al. (1985) estimate 1980 land-use emissions to be between 0.5 PgC/yr and 4.5 PgC/yr. This range is narrowed in Houghton et al. (1987) to between 1.0 PgC/yr and 2.6 PgC/yr. Detwiler and Hall (1988) estimate 1980 emissions from the tropics to be in the range 0.4 PgC/yr to 1.6 PgC/yr. Net emissions from land-use change are dominated by tropical deforestation. Houghton et al. (1987) estimate that all but 0.1 PgC/yr of net release is from tropical forests. Estimates of deforestation in 1980 are greatest for Brazil, Columbia, the Ivory Coast, Indonesia, Laos, and Thailand.

Estimates of net CO_2 emissions from land-use change have increased for recent decades. Prior to 1950, significant deforestation is estimated to have occurred in the temperate latitudes as well as in the tropics. It has been suggested that increases in the atmospheric concentration of CO_2 could act to accelerate the rate at which plants store carbon, although this is a matter of heated debate. Estimates of net CO_2 release from land-use change do not take into account the possibility of a CO_2 fertilization effect. As discussed in Chapter 1, this refers to the controversial proposition that higher concentrations of CO_2 in the atmosphere may accelerate the rate at which the terrestrial biosphere stores carbon.

3.2.3 U.S. Share of Carbon Dioxide Emissions

U.S. fossil fuel CO_2 emissions accounted for more than 40% of global emissions in 1950. This share has steadily declined to less than 25% in 1988. U.S. CO_2 emissions peaked in 1973 (1.27 PgC/yr) and again in 1979 (1.30 PgC/yr) and had risen to 1.31 pgC/yr in 1988, the last year for which global statistics are available. However, U.S. fossil fuel CO_2 emissions have increased since 1983. Figure 3.1 shows the U.S. emissions from fossil fuel combustion as a share of the world total, along with the fuel source. (For the purposes of this analysis, CO is accounted for separately in a later section; however, because is virtually all of it is transformed to CO_2 within a few months, the fraction of CO_2 that originated from CO is shown separately in Figure 3.1.) Global average per capita emissions of fossil fuel CO_2 to the atmosphere are approximately 1 tonne C/capita/yr (1 tonne = 10^6 grams). U.S. emissions exceed 5 tonnes C/capita/yr.

U.S. emissions from fossil fuel sources were computed from energy consumption data contained the State Energy Data System (SEDS) (DOE/EIA 1989a) by application of suitable emissions coefficients (see Appendix A; tabular data are presented in Appendix I). This database contains detailed energy usage information broken down by fuel type and economic sector. For the purposes of this study, all fuel consumption listed for each state in the SEDS Report is assumed to be used entirely within that state, and the total quantity of emissions from that amount of fuel is assigned to that state. No attempt has been made to correct for such things as interstate sales of electricity or jet fuel delivered in one state but consumed in transit over several states. In addition, there are certain vagaries in the accounting for fuel usage, as described in detail in the appendix to the SEDS Report, that may impose other distortions on emissions calculations.

Figures 3.2 and 3.3 graphically portray U.S. emissions totals for the period 1960 to 1987, distributed between fuel type and economic sector. Table 3.3 lists emissions by sector. Note that these sectors represent the point of actual fuel consumption. Thus, the reduction in the residential, commercial, and industrial sectors is due, in part, to a shift to electricity, with a corresponding rise in utility energy consumption. Figure 3.4 gives total fossil fuel CO_2 emissions rankings by state. Appendix B

Table 3.3. U.S. CO_2 Emissions from Combustion of Fossil Fuel by Economic Sector (millions of metric tonnes)

Year	Residential	Commercial	Industrial	Transportation	Utility	Total
1960	102	55	273	167	145	742
1961	105	55	269	169	150	748
1962	110	57	277	177	159	780
1963	110	55	287	185	173	810
1964	111	55	303	191	185	844
1965	114	59	314	197	198	882
1966	117	62	326	209	218	932
1967	120	67	323	221	227	957
1968	125	68	329	240	250	1012
1969	129	71	337	250	269	1057
1970	130	72	340	259	287	1089
1971	130	73	328	269	298	1100
1972	136	74	337	285	324	1156
1973	131	74	352	300	348	1205
1974	125	70	334	292	339	1160
1975	124	69	303	290	337	1123
1976	131	72	316	308	366	1192
1977	127	70	316	231	390	1224
1978	126	71	307	336	392	1233
1979	117	71	321	335	408	1252
1980	107	67	291	324	420	1208
1981	100	62	282	320	422	1186
1982	100	62	249	313	400	1123
1983	94	62	232	312	411	1112
1984	98	64	254	327	429	1172
1985	98	60	245	331	440	1174
1986	96	58	237	342	436	1170
1987	96	60	245	353	454	1207

Source: DOE/EIA State Energy Data Base 1960-87.

provides graphic displays of individual state emissions from combustion of fossil fuels for the period 1960 to 1987 (tabular data are presented in Appendix I).

3.3 METHANE EMISSIONS

Atmospheric methane emissions stem from a variety of sources. Figure 3.5 gives an indication of the currently known sources along with a range of the estimates of annual emissions from each source. If we accept these estimates as a basis for discussion, we note that about two-fifths of the total comes from natural sources such as wetlands and wild animals, leaving about three-fifths resulting from some form of human activity. Within the latter category, an estimate of the U.S. contribution is shown in Figure 3.6. Landfills may constitute as much as one-half of the U.S. total.

3.3.1 Historic Methane Emissions

Annual estimates of emissions sources are not generally available for CH_4. Source strength uncertainties are so high that emissions budgets are typically referenced to an average annual rate over a decade rather than to an individual year. Whereas emissions of fossil fuel CO_2 are developed for specific years based on databases for a small number of human activities, the sources and sinks for CH_4 are developed using an observed globally averaged atmospheric burden of CH_4 (approximately 4800 $TgCH_4$), an average annual rate of increase (approximately 0.9%/yr), and an atmospheric lifetime (12.5 years) derived from an atmospheric chemistry model to calculate a global emissions budget constraint (approximately 400 to 640 $TgCH_4$/yr). Information about the changing isotopic ratio of carbon (i.e. $^{14}CH_4/^{12}CH_4$) is used to estimate relative source strengths of methane emissions by broad period of origin, and, by inference, to bound the contribution of fossil fuels to total emissions. A summary of the best current understanding of the sources and sinks of CH_4 is given is Table 3.4.

At this point, it is not clear that all of the major sources of CH_4 have been identified, and the emissions rates of those that have been identified are subject to significant uncertainty. The principal human activities that have been identified as emissions sources are cattle raising, rice production, and energy production and use, as well as other combustion of biomass and disposal of waste in land fills. While human activities have been identified as major sources of atmospheric emissions, there remains great uncertainty surrounding emissions source estimates and the time profile of those emissions.

Roughly one-quarter of the total atmospheric methane emissions are attributable to the production, transfer, conversion, and consumption of energy. These include the mining of coal, as well as the gathering, transmission, distribution, venting, and flaring of natural gas. Landfill material representing the residue of the consumption process, is a rich source of methane that is currently only very slightly exploited as a source of energy. Burning of biomass can occur naturally, as in forest fires, or can be initiated by human activity, such as the clearing of land for agriculture. Some fraction of the human contribution is for direct energy consumption such as the burning of fuelwood. Finally, each of the combustion processes associated with the conversion of fossil fuel to thermal energy may be attended by the emission of some quantity of methane, depending on the constituents of the fuel, the temperature of combustion, and the efficiency of the process. Emissions from natural gas production, coal mining, and landfills currently appear to be more important sources of methane than are combustion process byproducts. The United States, the Soviet Union and the People's Republic of China account for the largest shares of fossil fuel methane emissions.

3.3.2 U.S. Share of Methane Emissions

Recalling Figure 3.6, this country is responsible for possibly one-seventh of the total CH_4 emissions caused by human activity. The likely dominant source in this category is the anaerobic decay of

Table 3.4. Historic CH_4 Emissions

Sources	Quality of Emissions Data	Uncertainty	Notes
Natural	Poor	Great	Global Emissions = Natural sources account for approximately 40% to 50% of global emissions. It is not clear that all sources and sinks for CH_4 have been identified. Total emissions are derived from atmospheric observations and calculations from atmospheric chemistry models. Current source estimates are (in $TgCH_4$/yr): enteric fermentation (wild animals) 4±3; wetlands 110±50; lakes 4±2; tundra 3±2; oceans 10±10; termites 25±20; methane hydrates 5±5(0-100); other 40±40.
Agriculture	Fair/Poor	± 40-50%	25-40% of global emissions. Current source estimates are (in $TgCH_4$/yr): rice cultivation 70±30; ruminant digestive systems of domesticated animals (cattle) 77±35; slash and burn agriculture/land-clearing 55±30.
Energy	Fair/Poor	± 40-50%	20-25% of global emissions. Current source estimates are (in $TgCH_4$/yr): deep coal mining 30±10; natural gas production, transport and distribution 40±15; incomplete combustion (e.g., automotive exhaust, fuelwood use)15±8; landfills 50±30.
Sinks			
Atmospheric chemistry/ terrestrial systems	n.a.	± 25-50%	Current sink estimates are (in $TgCH_4$/yr): Reaction with tropospheric OH 350±100; transport to and reaction with OH, Cl or O in stratosphere 50±20; microorganisms uptake by soils 32±16; and accumulation in the atmosphere 60±15.

Sources: Wuebbles and Edmonds 1988, 1991; Edmonds and Barns 1990.

organic waste in landfills, although the total is highly speculative. Current estimates are based roughly on regional population and degree of affluence, so the United States tends to be a leader in this emissions area.

Two agricultural activities are significant sources of CH_4 emissions--the production of rice and the raising of domestic animals--although U.S. rice production is a very small share of the world's total. The output of ruminant animals is generally far greater than for other animals, and in this country, cattle dominate the picture, as shown in Figure 3.7. Emissions are calculated as a function of animal population; hence, the downward trend over time reflects the reduction in cattle population over the years. Over half of the emissions from this source come from ten or so of the large cattle-producing states, as seen in Figure 3.8. Figure 3.9 ranks the individual states in this category; note that Texas is at the top, with more than twice the emissions of the second-ranked state. Although not addressed here, animal wastes are a potentially significant source of CH_4 if permitted to decompose under anaerobic conditions.

Only six states have significant rice production, and the estimated emissions from this source are indicated in Figures 3.10 and 3.11. Here the emissions are based on the number of acres of rice harvested each year. Note that the total emissions are about one-third of a teragram, which is probably a fraction of 1% of the world's total from this source.

The production, distribution, and consumption of energy is thought to be a major source of CH_4 losses in this country; however, the estimates are highly uncertain. [For the development of energy-related methane emissions factors used in this analysis, see Barns and Edmonds (1990).] Natural gas, the main constituent of which is CH_4, comes from over 250,000 wells and is distributed through thousands of miles of pipeline and gas mains of varying ages and conditions. Historically, losses have been important only from the standpoint of economics or safety, and significant atmospheric emissions can occur at levels well below the threshold of importance in these two categories. As a result, emissions estimates are very approximate. For the purposes of this study, production losses are estimated at 0.5% of production, and transmission and distribution losses are estimated at 1.5% of consumption. Venting and flaring are monitored in the aggregate by DOE and state conservation agencies, but no effort has been made to differentiate between venting, which results in CH_4 emissions, and flaring which yields mainly CO_2. Here, one-fifth of the total emissions vented and flared is assumed to enter the atmosphere as CH_4. Figure 3.12 shows the result of application of the above estimating factors to DOE natural gas statistics for the United States. In general, the profile follows the amount of gas consumed, but note the significant reduction in venting of gas in the early 1970s. Individual state charts are contained in Appendix C (tabular data are presented in Appendix I). For estimating purposes, venting and production emissions are assigned in proportion to the state's production of gas. Distribution and transmissions losses are in relation to each state's total consumption. Figure 3.13 gives a ranking of individual states on the basis of these estimates.

Coal seams contain significant quantities of CH_4, which is a byproduct of the coalification process. In the absence of any efforts to capture this gas, virtually all of it will be liberated to the atmosphere in the course of mining, transportation, and preparation for end-use combustion. The amount of CH_4 contained in the coal microstructure generally increases with the coal rank and depth; however, gas contained in the macrostructure and surrounding pockets and overlying strata is much more variable. For this study, the gas release factors used are related to coal ranking, which gives a production-weighted average of about 230 ft^3 per short ton of coal. Figure 3.14 shows the historical trend for coal mining emissions for the United States, and individual state charts are contained in Appendix D (tabular data are presented in Appendix I). Total emissions are seen to be increasing over time as coal production increases; however, the increasing proportion of lower-ranked

coals with lower emissions tends to slightly offset this growth. Figure 3.15 ranks the coal-producing states.

Combustion of fossil fuels emits small quantities of CH_4, probably less than one teragram total in this country. Figures 3.16 and 3.17 show the result of application of appropriate emissions coefficients to U.S. energy consumption as set forth in the SEDS. Table 3.5 lists emissions by sector. Appendix E provides these data for individual states (tabular data are presented in Appendix I). Burning of biomass--mainly fuelwood and agricultural waste in this country--produces methane at highly variable rate, depending in part on temperature and size of the fire. The U.S. contribution is again highly speculative but may be on the order of 2 teragrams.

Table 3.5. U.S. CH_4 Emissions from Combustion of Fossil Fuel by Economic Sector (thousands of metric tonnes)

Year	Residential	Commercial	Industrial	Transportation	Utility	Total
1960	14.4	11.1	39.2	348.7	3.3	416.7
1961	14.9	10.7	38.2	357.4	3.4	424.6
1962	15.5	11.0	39.0	368.2	3.6	437.3
1963	15.5	10.2	39.4	384.2	3.9	453.2
1964	15.1	9.7	40.4	391.9	4.2	461.3
1965	15.8	9.9	41.4	412.1	4.5	483.7
1966	15.8	10.3	41.6	432.2	5.0	504.9
1967	16.3	10.4	40.5	447.7	5.2	520.1
1968	17.0	10.2	41.2	474.4	5.7	548.5
1969	17.2	10.3	41.6	497.4	6.2	572.7
1970	17.4	10.1	41.6	526.7	6.7	602.5
1971	17.6	9.9	39.9	547.2	7.0	621.6
1972	18.2	9.7	39.9	580.2	7.8	655.6
1973	17.7	9.6	41.3	597.9	8.6	675.1
1974	16.4	9.3	39.1	580.4	8.4	653.6
1975	16.4	9.3	39.1	580.4	8.4	653.6
1976	17.4	9.6	36.3	598.7	9.2	671.2
1977	17.1	9.6	35.5	612.6	9.9	684.7
1978	16.9	9.9	33.7	631.9	10.0	702.4
1979	14.8	9.8	34.2	616.5	10.0	685.3
1980	12.7	9.4	31.6	588.5	10.1	652.3
1981	11.5	8.6	30.7	589.4	10.1	650.3
1982	11.1	8.6	26.8	579.0	9.5	635.0
1983	10.2	9.0	24.3	572.3	9.7	625.5
1984	10.6	9.4	28.2	584.3	10.3	642.8
1985	10.9	8.5	29.3	589.1	10.6	648.4
1986	10.6	8.9	28.2	603.3	10.7	661.7
1987	10.8	9.1	28.7	620.5	11.0	680.1

Source: DOE/EIA State Energy Data Base 1960-87.

3.4 CARBON MONOXIDE EMISSIONS

Although not radiatively interactive, CO_2 is discussed here because it competes with methane for OH radicals that act as a sink for both gases. Thus, increases in CO concentration in the atmosphere would tend to have the effect of increasing the concentration of CH_4 because of the reduced rate of disposal. In addition, CO will ultimately be oxidized, thus adding to the atmospheric CO_2 burden.

3.4.1 Historic Carbon Monoxide Emissions

Even greater uncertainty surrounds the atmospheric carbon monoxide (CO) budget than surrounds the CH_4 budget. The general global sources, along with the associated uncertainties in emission estimates, are shown in Figure 3.18. As indicated in Table 3.6, CO is generated by incomplete combustion processes (complete combustion yields CO_2 rather than CO), oxidation of anthropogenic hydrocarbons, the decomposition of CH_4, and other minor sources. Because of its relatively short lifetime in the atmosphere (0.4 years), the gas is poorly mixed in the global atmosphere. Annual emissions estimates range from 600 TgC/yr to 1700 TgC/yr.

3.4.2 U.S. Share of Carbon Monoxide Emissions

As indicated in Figure 3.19, the United States contributes somewhere around one-fifth of CO associated with human activities, and most of that is the result of incomplete combustion, principally from internal combustion engines. Figures 3.20 and 3.21 give two different perspectives on recent trends in CO emissions as derived from energy consumption patterns in the SEDS. Table 3.7 lists emissions by sector. The obvious conclusion is that use of liquid fuels in the transportation sector is by far the dominant source. Figure 3.22 shows emissions from fossil fuel combustion at the state level, with time series charts contained in Appendix F (tabular data are presented in Appendix I). Total U.S. combustion emissions are estimated to be about 70 TgC, with another 10 TgC from the oxidation of anthropogenic hydrocarbons and other minor sources.

3.5 NITROUS OXIDE EMISSIONS

3.5.1 Historic Nitrous Oxide Emissions

The sources of N_2O emissions are poorly documented, as indicated in Table 3.8. Emissions rates are small, relative to atmospheric stocks. Total emissions are estimated to be between 11 TgN_2O/yr and 33 TgN_2O/yr. Emissions studies are inconsistent with regard to their categorization of emission-producing activities. The chief sources of emissions are presently thought to be combustion activities and biogeochemical activities in soils. The biogeochemical activities include N_2O releases from both cultivated and uncultivated soils, and fertilized and unfertilized soils. Combustion activities include savanna burning, forest clearing, fuelwood use, and fossil fuel combustion. Other sources of emissions include oceans and contaminated aquifers. Figure 3.23 shows these general sources along with the range of uncertainties associated with emissions estimates.

The dominant human activities associated with N_2O emissions are agricultural savanna burning, soil cultivation and fertilizer application, wood burning, and fossil fuel use. Khalil and Rasmussen (1988) use ice core data to constrain the total human-related emissions to 10% to 30% of the total. Until recently, the dominant manufactured emissions source was thought to be fossil fuel combustion (Hao et al. 1987; Wuebbles and Edmonds 1988). This conclusion was based on flask samples taken from combustion experiments (Muzio and Kramlich 1987; Linak et al. 1989). This research has recently been shown to be subject to a sampling artifact that produced N_2O in the flask between the time the sample was taken and the time the flask was analyzed. It is possible that fossil fuel emissions are a relatively minor source of N_2O emissions, but this is by no means certain. It is also

Table 3.6. Historic CO Emissions

Sources	Quality of Emissions Data	Uncertainty	Notes
Natural	Poor	Great	Global emissions = 600 TgC/yr to 1700 TgC/yr. Natural sources are approximately 50% of global emissions. Current source estimates are (in TgC/yr): plants 55±35, wildfires 10±10, oceans 20 (10-200), oxidation of natural hydrocarbons 250±250, and oxidation of CH_4 260±190. It is not clear that all sources and sinks for CO have been identified. CO is highly reactive; therefore, global source/sink relationships are highly uncertain, even in aggregate.
Non-energy	Poor	± 50-100%	40-60% of global emissions. Current source estimates are (in TgC/yr): slash and burn agriculture/land-clearing 270±250.
Energy	Fair/Poor	± 40-50%	40-60% of global emissions. Current source estimates are (in TgC/yr): incomplete combustion (e.g. automotive exhaust, fuelwood use) 200±100; oxidation of anthropogenic hydrocarbons 40±40. U.S. energy-related CO emissions have been estimated within the NAPAP.
Sinks			
Atmospheric chemistry	n.a.	± 25-50%	Current sink estimates are (in TgC/yr): 820±300.
Soil uptake	n.a.	± 25-50%	Current sink estimates are (in TgC/yr): 110±30.

Sources: Wuebbles and Edmonds 1988, 1991; Edmonds and Barns 1990.

Table 3.7. U.S. CO Emissions from Combustion of Fossil Fuel by Economic Sector (thousands of metric tonnes)

Year	Residential	Commercial	Industrial	Transportation	Utility	Total
1960	550	375	2040	37,197	42	40,202
1961	505	383	1952	37,757	44	40,642
1962	486	397	1981	38,860	47	41,723
1963	426	391	1918	40,077	51	42,867
1964	378	393	1874	40,687	55	43,388
1965	356	406	1891	42,121	59	44,835
1966	347	416	1799	43,887	65	46,517
1967	303	435	1706	45,022	68	47,536
1968	279	433	1713	47,825	76	50,327
1969	263	435	1667	49,889	82	52,338
1970	232	445	1633	51,952	90	54,354
1971	221	433	1544	54,030	92	56,323
1972	179	445	1450	57,546	100	59,722
1973	171	442	1465	60,125	104	62,309
1974	167	423	1358	58,975	100	61,025
1975	143	420	1283	58,839	98	60,785
1976	141	487	1229	63,030	105	64,995
1977	142	504	1153	64,794	113	66,709
1978	143	533	1058	67,037	113	66,886
1979	126	521	996	63,777	118	65,541
1980	107	530	956	59,744	120	61,460
1981	117	457	961	59,663	119	61,319
1982	124	439	827	59,219	111	60,722
1983	123	509	697	60,059	113	61,503
1984	132	533	941	60,652	120	62,380
1985	115	478	1209	61,603	126	63,533
1986	115	526	1146	63,567	122	65,478
1987	110	544	1146	64,990	129	66,921

Source: DOE/EIA State Energy Data Base 1960-87.

Table 3.8. Historic N_2O Emissions

Sources	Quality of Emissions Data	Uncertainty	Notes
Natural	Poor	Great	Global emissions = 11 TgN_2O/yr to 33 TgN_2O/yr. Natural sources are approximately 45-65% of global emissions. Natural sources include (in=TgN_2O/yr): oceans and estuaries 3±1.5; natural soils 10±5.5; aquifers, wildfires, lightning, and volcanos 1.3±0.5. It is not clear that all sources and sinks for N_2O have been identified. While N_2O is, chemically, a highly stable gas in the atmosphere, the average lifetime uncertainty ranges from 100 years to 175 years, leading to a 100% uncertainty in the global emission rate.
Non-energy	Poor	± 50-100%	35-55% of global emissions. Current source estimates are (in TgN_2O/yr): natural soil cultivation 2.4±1.3; nitrogen fertilizer application 1.3±0.6; slash and burn agriculture, land clearing 1.1±0.6.
Energy	Poor	Great	3-15% of global emissions. Fossil fuel combustion estimated to produce 0 TgN_2O/yr to 3 TgN_2O/yr. Combustor studies originally showed high rates of release of N_2O from fossil fuel use in high temperature combustion. Later analysis revealed a sampling artifact that, when removed, greatly reduces the emission coefficient.
Sinks			
Atmospheric chemistry	n.a.	± 15-40%	Current sink estimates are (in TgN_2O/yr): photolysis and reaction with $O(^1D)$ in stratosphere 16.5±4.7; accumulation 5.5±0.8.

Sources: Wuebbles and Edmonds 1988, 1991; Edmonds and Barns 1990.

possible that the chemistry that occurred in the flask may also occur in nature. Wuebbles and Edmonds (1988) estimate that approximately 24% of the N_2O sources are human-related, if the combustion source contributes zero emissions.

3.5.2 U.S. Share Nitrous Oxide Emissions

Figure 3.24 gives an indication of the U.S. contribution to those N_2O emissions that are related to human activities. Most of these emissions are associated with agriculture and land-use changes. As shown by Figure 3.25, the use of nitrogen fertilizers has roughly quadrupled since 1960. Emissions from anhydrous ammonia fertilizer are far greater per unit applied than any other fertilizer. As a consequence, although the use of anhydrous ammonia has declined as a fraction of the total, the emissions from the source (see Figure 3.26) dominate the overall total. Figure 3.27 ranks the states in terms of consumption of anhydrous ammonia fertilizer.

As discussed above, previous studies of N_2O emissions from combustion processes are of questionable value because of the discovery of the possible sampling error. For the purposes of this report, emissions coefficients applied are substantially lower than those formerly used (order of magnitude of 10^{-1} of previous values). Application to energy consumption data from the SEDS gives highly speculative emissions information, as shown in Figures 3.28, 3.29, and 3.30, which are useful mainly for time trend indications and relative ranking (charts for individual states can be found in Appendix G; tabular data are presented in Appendix I). Table 3.9 lists emissions by sector. Credible emissions coefficients for these combustion phenomena are urgently needed in order to resolve not only the total amount of emissions from this source, but also the relative importance of the contribution to the total.

3.6 NITROGEN OXIDE EMISSIONS

3.6.1 Historic Nitrogen Oxide Emissions

Although they are rotatively interactive trace gases, the oxides of nitrogen (NO and NO_2) do not presently make a significant contribution to global warming. Because most sources are manufactured and because the lifetime is relatively short (a matter of days), the heaviest concentrations are in the lower atmosphere near populated areas. The major impacts of NO_x on overall greenhouse warming are twofold: 1) the concentration of NO_x strongly effects the reaction pathway for CH_4 oxidation, and 2) NO_x is a very active catalyst in the oxidizing reactions that form tropospheric O_3 (Wuebbles and Edmonds 1988).

Total annual emissions of NO_x are estimated to be in the range of 70 $TgNO_x$ to 300 $TgNO_x$. Table 3.10 and Figure 3.31 show the range of uncertainty for both natural and anthropogenic sources. By far the largest sources are combustion activities, which include savanna burning, forest clearing, fuelwood use, and fossil fuel combustion.

3.6.2 U.S. Share of Nitrogen Oxide Emissions

Figure 3.32 provides an indication of the U.S. contribution to global anthropogenic NO_x emissions, which is mostly in the form of fossil fuel combustion products. Figures 3.33 and 3.34 show U.S. fossil fuel NO_x emissions by fuel source and by economic sector as derived by application of appropriate emissions coefficients to the SEDS database. Table 3.11 lists emissions by sector. In this case, use of constant (over time) coefficients shows that emissions grow with increasing energy usage. In actuality, pollution control measures, principally in the transportation sector, have effected a net reduction since the early 1970s, when total fossil source

Table 3.9. U.S. N_2O Emissions from Combustion of Fossil Fuel by Economic Sector (thousands of metric tonnes)

Year	Residential	Commercial	Industrial	Transportation	Utility	Total
1960	7.93	8.13	7.89	6.85	10.12	26.47
1961	7.70	7.67	7.59	6.90	10.44	26.47
1962	7.78	7.75	7.70	7.27	11.09	27.60
1963	7.38	6.97	8.02	7.65	12.10	29.21
1964	7.06	6.37	8.53	7.92	12.91	30.70
1965	7.04	6.37	8.87	8.11	13.91	32.23
1966	7.10	6.58	9.05	8.57	15.12	34.12
1967	6.93	6.34	8.65	8.90	15.53	34.41
1968	6.91	6.11	8.60	9.83	16.94	36.66
1969	6.99	6.08	8.45	10.35	17.67	37.78
1970	6.81	5.77	8.40	10.79	18.02	38.47
1971	6.83	5.65	7.39	11.34	18.30	38.28
1972	6.68	5.27	7.51	12.25	19.65	40.60
1973	6.40	5.20	7.67	13.13	21.44	43.40
1974	6.14	5.06	7.30	12.87	21.04	42.33
1975	5.97	4.71	6.82	12.71	21.43	42.02
1976	6.20	4.91	6.90	13.58	23.56	45.15
1977	6.04	4.88	6.64	14.23	24.89	46.84
1978	6.04	4.99	6.36	14.91	24.92	47.29
1979	5.61	4.86	6.79	14.98	27.08	49.89
1980	5.08	4.43	6.03	14.30	28.91	50.19
1981	4.90	4.43	5.95	14.40	29.80	51.05
1982	4.94	4.32	4.95	14.10	29.27	49.24
1983	4.73	4.46	4.75	14.38	30.56	50.60
1984	4.95	4.67	5.30	15.04	32.28	53.65
1985	4.82	4.23	4.93	15.28	33.58	54.69
1986	4.71	4.23	5.03	15.79	33.14	54.85
1987	4.70	4.25	5.09	16.22	34.71	56.91

Source: DOE/EIA State Energy Data Base 1960-87.

Table 3.10. Historic NO_x Emissions

Sources	Quality of Emissions Data	Uncertainty	Notes
Natural	Poor	Great	Global emissions = 70 $TgNO_x$/yr to 300 $TgNO_x$/yr. Natural sources are approximately 12-30% of global emissions. Natural sources include (in=$TgNO_x$/yr): stratospheric oxidation of N_2O, 3.3±1.6; lightning, 3-33; soil emissions, 26±23; oceans, <3.
Manufactured	Fair	Great	70-88% of global emissions. Fossil fuel combustion estimated to produce 50-80 $TgNO_x$/yr; biomass combustion, 13-130 $TgNO_x$/yr; jet aircraft, 0.5-1.0 $TgNO_x$/yr.
Sinks			
Wet and Dry Deposition	n.a.	Great	Current sink estimates are 80-280 $TgNO_x$/yr.

Sources: Wuebbles and Edmonds 1988, 1991; Edmonds and Barns 1990.

emissions slightly exceeded 20 million tonnes. The emissions shown for the later years are believed to be reasonably accurate, however. Figure 3.35 ranks the various states by fossil source NO_x emissions. Time series charts of individual state fossil fuel emissions are contained in Appendix H (tabular data are presented in Appendix I).

3.7 CHLOROFLUOROCARBON EMISSIONS

The term chlorofluorocarbons (CFCs) refers to a family of compounds derived from methane or ethane. A CFC is formed by replacing hydrogen atoms with the halogens chlorine (Cl) or fluorine (F). When the halogen bromine (Br) atom is also used a replacement, the compounds are referred to as halons. A fully halogenated compound occurs when all the hydrogen atoms have been replaced by one or more of the halogens. CFCs and halons are fully halogenated. The term halocarbons may be used to refer to the fully halogenated compounds, as well as partially halogenated substances.

3.7.1 Background

In the recent past, emissions of CFC-11 have been growing at a rate of about 5% per year, while CFC-12 emissions have been increasing at a rate of about 3% per year However, more recent indications are that U.S. demand for these CFCs is declining substantially. Annual emissions of CFC-11 are also greater than CFC-12, as a percentage of annual production. This difference in emission rates and volumes is a reflection of the difference in uses for these two CFCs. Halocarbons are extremely stable, chemically inert, non-toxic, non-flammable compounds and possess excellent thermodynamic properties for applications such as working fluids in space conditioning equipment or blowing agents in insulation. These characteristics also make them ideal for use as solvents and sterilizing agents

Table 3.11. U.S. NO_x Emissions from Combustion of Fossil Fuel by Economic Sector (thousands of metric tonnes)

Year	Residential	Commercial	Industrial	Transportation	Utility	Total
1960	353	340	2680	4623	1954	9652
1961	355	333	2309	4690	2023	9713
1962	367	341	2351	4944	2149	10,154
1963	361	322	2433	5208	2341	10,668
1964	357	311	2566	5391	2508	11,135
1965	364	330	2660	5519	2671	11,546
1966	372	347	2724	5837	2938	12,220
1967	376	358	2637	6064	3045	12,482
1968	384	356	2647	6696	3362	13,449
1969	396	361	2644	7057	3599	14,059
1970	396	362	2643	7354	3818	14,575
1971	401	356	2427	7733	3921	14,480
1972	406	349	2472	8355	4205	15,789
1973	390	351	2548	8955	4475	16,722
1974	372	332	2421	8774	4344	16,246
1975	370	307	2218	8781	4324	16,003
1976	386	334	2288	9259	4675	16,945
1977	375	333	2239	9702	4963	17,615
1978	375	332	2147	10,161	4983	18,006
1979	350	327	2244	10,212	5268	18,406
1980	320	317	212	9750	5481	17,882
1981	302	282	1957	9821	5542	17,906
1982	303	282	1671	9615	5284	17,156
1983	288	270	1564	9807	5405	17,337
1984	300	279	1759	10,257	5667	18,265
1985	297	257	1718	10,422	5820	18,517
1986	290	262	1657	10,770	5720	18,701
1987	291	269	1682	11,065	5972	19,281

Source: DOE/EIA State Energy Data Base 1960-87.

among other uses (halons are used as fire suppressants, for example). However, when released to the atmosphere, this same characteristic non-reactivity allows CFCs and halons to reach the stratosphere intact. While intact, these compounds absorb and reradiate infrared radiation reflected from the Earth's surface, warming the atmosphere. When eventually destroyed in the stratosphere through photodissociation by ultraviolet radiation, free chlorine (CFCs) and bromine (halons) are released. The freed chlorine and bromine react with and destroy ozone (O_3). Although natural processes exist which result in both the creation and destruction of ozone, there is a growing scientific consensus that this additional source of ozone destruction is leading to a net loss in stratospheric ozone, as evidenced by the springtime depletion over Antarctica ("Ozone Hole") and some reported

depletion of the middle and high latitudes that cannot be wholly explained by known natural processes (WMO 1989, 1991).

Through a treaty known as the Montreal Protocol on Substances that Deplete the Ozone Layer, 1987, major producing and consuming countries have agreed to curtail production and use of CFCs and halons. Meeting in London in June 1990, the parties to the Montreal Protocol further amended that agreement to provide for a generally more rapid phase-out of these substances. The current plan calls for a 50% reduction (relative to 1986) in the consumption of the principal CFCs and halons by 1995, with complete elimination by the year 2000. Other CFCs are to be reduced by 20% (relative to 1989) by 1993 and eliminated by 2000. Also, the CFCs have an intervening reduction by 85% in the year 1997. Methylchloroform is to be reduced by 30% by 1995, 70% by 2000, and eliminated by 2005. Carbon tetrachloride, which is not emitted in significant quantities in this country, has similar restrictions: 85% reduction by 1995 and elimination by 2000. The effectiveness of the Montreal Protocol and London Agreement will depend on the degree of international participation.

A scale has been developed to measure the relative ozone depletion potential (ODP) of CFCs, halons, and other halocarbons on a molecule per molecule basis. A similar scale for halocarbon global warming potential (HGWP) has also been devised. With both scales, values for CFC-11 are arbitrarily set equal to one (for comparison, the HGWP of CO_2 would be 0.00015). These values are determined through atmospheric modeling of the transport, reactivity, and absorption characteristics of these compounds.

Table 3.12 shows the ODP, HGWP, and other relevant data for CFCs and halons now regulated by the Montreal Protocol (also see Figures 3.36 and 3.37). The Protocol places limits on the overall production and consumption of CFCs (known as Group 1 substances) and halons (Group 2). Limits on individual compounds within these groups may vary as long as the overall ozone depletion potential of the group does not exceed limits agreed on in the Protocol.

As can be seen from Table 3.12, CFCs and halons are both powerful ozone depleters and important GHGs. CFCs and related compounds are thought to contribute about 25% of the total radiative forcing effect of CO_2 and other trace gases. Just four of these compounds contribute 90% of the combined CFC effect (CFCs and related compounds). The following figures are very rough approximations of the individual contribution of each of these compounds: CFC-12, 40%; CFC-11, 20%; CFC-113, 20%; HCFC-22, 10%; other CFC-related compounds account for the remaining 10% (Hansen et al. 1989).

Some of the alternatives being considered as replacements for CFCs are known as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). These are partially halogenated compounds that contain hydrogen. The addition of hydrogen enhances reactivity with hydroxyl (OH) in the troposphere, thereby reducing atmospheric lifetime. However, some potential for greenhouse warming as well as ozone depletion still exists for several of these compounds.

3.7.2 Production, Use, and Emissions

Total worldwide production of CFCs and halons is not well known. However, current parties to the Montreal Protocol are required to report production and consumption of the controlled substances to the United Nations Environmental Programme (UNEP). While data for individual countries are held in confidence, some summary data have been made available. More detailed data are also available for consumption and use of CFCs and halons for the United States.

Production of CFCs and halons does not immediately equate to emissions. Of the total cumulative production of CFC-11 and -12, about 90%

Table 3.12. Ozone Depletion and Global Warming Potential[a]

Compound		Atmospheric Life (Years)	Atmospheric Concentration (pptv)	ODP	HGWP
CFC-11	CCl_3F	75	275	1.0	1.0
CFC-12	CCl_2F_2	110	470	0.9	3.0
CFC-113	CCl_2FCClF_2	90	70	0.9	1.4
CFC-114	$CCClF_2CClF_2$	185	7	0.7	4.0
CFC-115	$CClF_2CF_23$	380	5	0.4	7.5
Halon-1211		13	1	3.0[b]	--
Halon-1301		100	1	10.0[c]	--

(a) Values are approximate. These data are often presented as a range of values. Values also vary depending upon underlying assumptions and type (e.g., 1- or 2-dimensional) of atmospheric model used.
(b) As defined by the Montreal Protocol.
(c) The Montreal Protocol defines the ODP of the regulated CFCs as CFC-11 (1.0), CFC-12 (1.0), CFC-113 (0.8), CFC-114 (1.0) and CFC-115 (0.6).
Source: WMO 1989.

has been emitted to the atmosphere. The remaining 10% is "banked" in products such as air conditioners and refrigerators (as working fluids), spray cans (as aerosol propellants), and structural and flexible foam products (as blowing agents). Banked quantities of CFC-11 and CFC-12 are now equal to 2 years to 3 years of production.

The rate of emission from banked CFCs depends on the quantity held in relatively slow-release uses such as home refrigerators, as compared with short-term release products such as spray cans. To some extent, emissions of CFCs and halons that are banked in products can be avoided through improved handling practices, recycling, and destruction techniques. Rising prices of restricted CFCs and halons will result in efforts to reduce emissions and increase recycling. However, regulation will probably be required in circumstances where market forces are not sufficient to prevent emissions.

The application for which a CFC or halons is used is important because it determines the eventual emission rate (see Table 3.13). Applications such as aerosols and flexible foams constitute immediate release to the environment. However,

Table 3.13. Rate of Release by End-Use

	Years to Total Release
Aerosol	1
Flexible Foam	1
Rigid Polyurethane Foam	20
Rigid Non-urethane Foam	1
Fast Release Refrigeration[a]	4
Other Refrigeration	17
Solvents	1[b]
Fire Extinguishers (halons)	30-35

(a) Mobile air conditioners and centrifugal chillers.
(b) Only 85% is actually released. 15% is recycled.
Source: DOE/EIA 1989b.

(rigid) polyurethane foams, domestic refrigeration (refrigerators and air conditioners), and halon fire extinguishers represent much slower release times. Currently, about two-thirds of the total CFC and halon usage in the United States is in short-term (less than 5 years) applications The remaining one-third is in relatively long-term releases of up to 35 years.

3.7.3 Production, Consumption, and Emissions

Most CFC-producing companies in the industrialized world report CFC-11 and -12 production to the Chemical Manufacturing Association (CMA 1988). Table 3.14 shows world production, banking, and estimated emissions of CFC-11 and -12 in 1986, as reported by these companies, and world production data provided by UNEP (1989a). (Figure 3.38 shows world production of CFC-11 and -12, with the U.S. share of the total.) According to this table, CFC-12 is most important in terms of both overall production and emissions.

Recently, emissions of CFC-11 have been growing at a rate of about 5% per year, while CFC-12 emissions have been increasing at a rate of about 3% per year. Annual emissions of CFC-11 are also greater than those of CFC-12, as a percentage of annual production. This difference in emission rates and volumes is a reflection of the different uses for these two CFCs.

Table 3.15 shows CMA reported world sales of CFC-11 and CFC-12 by use. As can be seen from this table, the primary use of CFC-11 is as a foam blowing agent (55.2%) followed by aerosol uses (30.4%). Both open-cell foam blowing and aerosol uses result in short-term release of CFCs. The primary use of CFC-12, on the other hand, is for refrigeration (50%), which has a longer-term release scenario.

Table 3.16 shows world consumption data of CFCs by use as reported by UNEP and includes use data for CFC-113, -114, and -115. The figures for percentage usage of CFC-11 and CFC-12 from the CMA and UNEP sources compare well (assuming that most rigid foams are closed-cell and most flexible foams open-cell). Table 3.16 shows that the primary use of CFC-113 is as a solvent, while CFC-114 and -115 are used as refrigerants.

The U.S. International Trade Commission (1987) collects and reports data on U.S. production and sales of brominated, chlorinated, and fluorinated hydrocarbons. While some of these compounds are grouped, data are available separately for production and sales of specific compounds (CFC-11, CFC-12, HCFC-22, carbon tetrachloride, and methyl chloroform), at least in more recent years. Estimates of U.S. consumption of CFCs by compound and use have been made by both the EPA and the DOE's Energy Information Administration (EIA) (Hammit et al. 1986; DOE/EIA 1989b).

Table 3.17 shows U.S. consumption of CFCs by type, while Table 3.18 shows consumption by application. Given world production data as shown in Table 3.14, the United States consumes about one-third of CFCs worldwide. However, while a predominant use of CFCs outside the United States is as an aerosol propellant, this is a minor application in the United States. The United States banned most aerosol uses of CFCs in 1978.

3.7.4 Halons

Table 3.19 shows data for worldwide production and use of halons. As can be seen from Table 3.19, only a small percentage (8.8%) of the annual production of halons is used to suppress fires. Most of the annual halon production is "banked" in new equipment. An amount nearly equal to that used for fire emergencies is used for testing and for training with halon equipment.

Data for U.S. halon production and use have been published by EPA (Cummings-Saxton et al. 1987). Table 3.20 shows estimates of consumption, losses, and new equipment uses of Halons-1301 and -1211. According to Table 3.20, the United States consumes about 35% of world production of Halon-1301 and about 20% of world production of

Table 3.14. Production, Banking, and Estimated Emissions of CFC-11 and CFC-12, 1986 (thousands of metric tonnes)

	CFC-11		CFC-12		CFC-113	CFC-114	CFC-115
	Annual	Cumm.	Annual	Cumm.	Annual	Annual	Annual
CMA							
Production	350.1	6682.5	398.4	8949.3	--	--	--
Bank[a]	60.3	911.6	31.9	783.7	--	--	--
Emissions[b]	295.1	5871.1	376.5	8389.4	--	--	--
World Prod.	411.0		487.0		182.0	15.0	15.0

(a) Net additions to bank, i.e., Production - Emissions.
(b) Direct emissions from current year's production and emissions from previous year's bank of CFCs.
Sources: CMA 1988; UNEP 1989a.

Table 3.15. Sales of CFC-11 and CFC-12 by Use, 1986, as Reported by Companies Reporting to the CMA (thousands of metric tonnes)

	CFC-11		CFC-12	
Use	Volume	%	Volume	%
Refrigeration	25.9	7.4	198.3	50.0
Blowing (closed-cell)	129.6	37.0	38.1	9.6
Blowing (open-cell)	63.6	18.2	22.0	5.5
Aerosol Propellant	106.6	30.4	117.4	29.5
Others	24.4	7.0	22.5	5.7
Total	350.1	100.0	398.4	100.0

Source: CMA 1988.

Halon-1211. The United States does not now produce or use Halon-2402.

Annual U.S. emissions of Halon-1301 are equivalent to about 28% of production. Emissions of Halon-1211 are only about 15% of production. This difference in emissions occurs because a higher percentage of Halon-1301 is released during testing and unwanted discharges, while Halon-1211 is released during training. This difference in handling may stem from the fact that the majority of Halon-1301 is used to protect electronic equipment facilities (e.g., computer rooms), while a good portion of Halon-1211 is used aboard ships and aircraft.

3.7.5 U.S. Share of CFC Consumption

The U.S. share of consumption of CFCs is shown in Figure 3.39 and is broken down by end use in Figure 3.40.

3.8 COMPARISON OF GREENHOUSE GAS WARMING EFFECTS

3.8.1 Concept of Global Warming Potential

The previous sections have dealt with greenhouse gas emissions only in terms of gross emissions; however, for the purposes of policy formulation, it would be useful to be able to compare the warming effect of the various gases that differ in their direct and indirect contributions to radiative forcing and time profiles of decay, as well as direct influence on atmospheric composition. For example, on a per-molecule basis, CH_4 is about thirty time more effective than CO_2 as an infrared absorber; however, its lifetime is a small fraction of that of CO_2. But then, at the end of its lifetime, virtually all atmospheric CH_4 is oxidized to CO_2, so

Table 3.16. World Consumption of CFCs by Use, 1986 (thousands of metric tonnes)

	CFC-11		CFC-12				
	Volume	%	Volume	%	CFC-113	CFC-114	CFC-115
Refrigeration	33.8	8.2	228.6	46.9	--	3.6	15.0
Blowing (Rigid)	153.4	37.2	50.5	10.4	3.5	--	--
Blowing (Flexible)	60.0	14.6	--	--	--	--	--
Aerosol Propellant	122.7	30.0	162.3	33.3	--	--	--
Solvent	--	--	--	--	182.0	--	--
Others	25.1	6.1	31.9	6.6	--	--	--
Unallocated (over)	16.0	3.9	13.7	2.8	(3.5)	11.4	--
Total	411.0	100.0	487.0	100.0	182.0	15.0	15.0

Source: UNEP 1989a.

Table 3.17. U.S. Consumption of CFCs by Type, 1986 (thousands of metric tonnes)

	Consumption	Percent Of Total CFCs	U.S. Consumption as % of World Production
CFC-11	89.6	27.5	21.8
CFC-12	142.9	43.9	29.3
CFC-113	78.5	24.1	43.1
CFC-114	4.5	1.4	30.0
CFC-115	10.4	3.2	69.3
Total	325.9	100.0	29.3

Source: DOE/EIA 1989b. Used by permission.

Table 3.18. U.S. Consumption of CFCs by Application, 1986 (thousands of metric tonnes)

	Use	Percentage
Refrigeration	72.4	22.2
Mobile Air Conditioning	54.4	16.7
Foam	90.0	27.6
Solvents	64.7	19.8
Aerosols	11.1	3.4
Other	33.2	10.2
Total	325.9	100.0

Source: DOE/EIA 1989b.

that each central atom of carbon continues to contribute to warming in a new form. Hence, if a comprehensive approach is to be applied, a common metric is required to enable direct comparison between different policy instruments that affect both the magnitude and timing of greenhouse gas emissions.

One such metric, developed by the IPCC, is referred to as the Global Warming Potential (GWP). Initial thinking about the concept began in 1989 and is reflected in a series of draft papers that were reviewed by Wuebbles (1989). Formal papers began to appear in 1990 and include Lashof and Ahuja (1990), Derwent et al. (1990), Derwent (1990), Nordhaus (1990), and IPCC (1990). All of these early papers adopted a change in radiative forcing as their common unit of impact. Models of the atmosphere and radiation are used to simulate the effect on radiative forcing of the instantaneous release of a kilogram of CO_2, in that year and subsequent years, over a period of time into the future,

Table 3.19. Total World Production and Usage of Halons, 1986 (metric tonnes)

	Halon			
	1301	1211	2402	Total
Banked	7,000	11,200	850	19,050
Test/Training	1,100	840	20	1,960
Unwanted Discharge	300	140	10	450
Service	900	420	20	1,340
Fires	700	1,400	100	2,200
Total	10,000	14,000	1,000	25,000
% of Total Halons	40%	56%	4%	100%

Notes: The UNEP *Economic Panel Report* lists Halon-1301 production as 11,000 metric tonnes and Halon-1211 production as 18,000 metric tonnes in 1986.
Source: UNEP 1989b.

Table 3.20. U.S. Halon Usage and Emissions, 1985[a] (metric tonnes)

	Halon-1301	Halon-1211
Production & Imports	3,636	2,818
Exports	136	68
Domestic Consumption	**3,500**	**2,750**
Equipment Manufacturer Losses	90	40
Losses at Distributors		
Fill-related	93	--
Discharge testing	311	31
Fire events	234	114
Unwanted discharges	19931	
Service and leakage	93	--
Training	5	225
Total Losses	**1,025**	**441**
Total Emissions[b]	**1,023**	**430**
Agents Entering New Equipment[c]	**2,475**	**2,309**

(a) Based on results of a coordinated survey in late 1986 by the principal trade organizations representing agent manufacturers, equipment manufacturers, and distributors/servicers.
(b) Emissions are equal to losses except for fire events, where 10% of the released agent is assumed to be chemically converted during the fire event into non-ozone-depleting materials.
(c) Domestic consumption less total losses.
Source: Cummings-Saxton et al. 1987.

relative to a standard reference scenario. The change in radiative forcing is added over a specific period of time; e.g., 20 years, 100 years, 500 years, or infinity. The experiment is then run for other gases and the cumulative effect of each gas on radiative forcing is then compared to the cumulative effect of CO_2 on radiative forcing.

While all of the formulations cited above are similar in construct, each varies somewhat in the details of its implementation. Differences include the way gases are treated with regard to their residence time in the atmosphere after emission, their solar and infrared radiative absorption properties, and the indirect climatic effects resulting from chemical interactions with other greenhouse gases. In addition, studies treat the time profile of the change in radiative forcing differently. Some studies simply add changes on an equal basis over different numbers of years. Others apply discount rates to each year's change in radiative forcing before summing. From the perspective of its natural science, the construct developed by Derwent et al. (1990) for IPCC (1990) is the most complete to date (values of IPCC GWP are shown in Table 3.21), but note that the IPCC is currently reassessing these coefficients in light of new information on atmospheric lifetimes of some gases. All of these studies define the GWP for a greenhouse gas relative to CO_2, the greenhouse gas of current primary concern to climate change.

While natural scientists continue to refine the construct of GWP coefficients for different gaseous emissions, social scientists have also explored the concept. Reilly (1990) notes that the whole point in constructing a GWP index in the first place is to obtain a relative measure of damage. Implicit in the standard formulation of a GWP is the assumption that the effect of a one-degree change in radiative forcing at any two points in time is the same. This need not be the case. Marginal damages are likely to vary over time. Reilly (p.2) also points out

Table 3.21. *Values of Global Warming Potential as Used by the Intergovernmental Panel on Climate Change (IPCC)*

Trace Gas	Global Warming Potential Integration Time Horizon (yrs) 20	100	500
Direct Effects			
Carbon dioxide	1	1	1
Methane (incl. indirect effects)	63	21	9
Nitrous oxide	270	290	190
CFC-11	4500	3500	1500
CFC-12	7100	7300	4500
HCFC-22	4100	1500	510
CFC-113	4500	4200	2100
CFC-114	6000	6900	5500
CFC-115	5500	6900	7400
HCFC-123	310	85	29
HCFC-124	1500	430	150
HFC-125	4700	2500	860
HFC-134a	3200	1200	420
HCFC-141b	1500	440	150
HCFC-142b	3700	1600	540
HFC-143a	4500	2900	1000
HFC-152a	510	140	47
CCl_4	1900	1300	460
CH_3CCl_3	350	100	34
CF_3Br	5800	5800	3200
Indirect Effects			
CH_4 effect on tropospheric O_3	24	8	3
CH_4 as CO_2	3	3	3
CH_4 as stratospheric H_2O	10	4	1
CO effect on tropospheric O_3	5	1	0
CO as CO_2	2	2	2
NO_x effect on tropospheric O_3	150	40	14
Non-methane hydrocarbons as tropospheric O_3	28	8	3
Non-methane hydrocarbons as CO_2	3	3	3

Source: IPCC 1990.

that "gases have non-climate-related economic effects that differ amongst gases and these should be counted as credits (e.g., direct CO_2 fertilization of crops) or debits (e.g., CFCs as contributors to ozone depletion)." While the introduction of a calculation of full damage and benefit from a pulse emission of a gas adds considerable complexity to the problem, Reilly shows that the successful introduction of such a concept could significantly change GWP measures. Reilly developed coefficients using alternative damage functions for the effects of a change in radiative forcing on a steady-state economy and alternative allowances for a CO_2 fertilization effect on agriculture. He found that the application of these varying assumptions, in conjunction with a simple model of the atmosphere, yielded a range of values for coefficients at least as large as the range of values associated with range of integration times investigated by the IPCC. It is important to note that these figures are intended to be illustrative only. The results of this experiment are reported in the Table 3.22.

A direct implication of Reilly's work is that GWP measures are not directly comparable from year to year; that is, the base atmosphere will change over time as a result of the accumulation of greenhouse gases from previous emissions. This will not only change the chemical and radiative interactions of the gases, but the damage associated with each degree change in radiative forcing will also be affected by the scale of previously inflicted damage.

It is also important to note that GWP measures are marginal; that is, they measure the consequences of a one-time, 1-kilogram release of an individual gas into a standard atmosphere. The consequence of teragram- and petagram-scale releases of gases into the atmosphere are not taken into account; neither are the consequences of simultaneous releases of gases. As these gases interact both chemically and rotatively, scale effects are potentially non-trivial.

Finally, it should be noted that GWP values are based on best current understanding of sources and dispositions of greenhouse gases, but as discussed earlier, the best current understanding is far from certain. As a consequence, GWP coefficients could change as the scientific understanding of sources, sinks, and natural processes progresses. Furthermore, the "lifetime" of the numeraire, CO_2, is based on a model of ocean carbon uptake only and does not include terrestrial processes other than as a net

Table 3.22. Comparisons of Trace Gas Indices

	Economic-Based			Physical Effects Only		
	Climate+ CO_2 fert (quads)	Climate Effects (quads)	Climate Effects (linear)	Radiative Forcing	IPCC-GWP 20 yr	IPCC-GWP 500 yr
CO_2	1	1	1	1	1	1
CO	3.7	2.9	0.9	2.3	7	2
CH_4	92	74	21	58	63	9
N_2O	260	208	201	206	270	190
HCFC-22	8950	7174	1427	5440	4100	510
CFC-11	6343	5085	1389	3970	4500	1500
CFC-12	9119	7309	2140	5750	7100	4500
CFC-113	5917	4743	1319	3710	4500	2100

Notes: CO_2 fert=CO_2 fertilization effect on plant productivity and water-use efficiency taken into account in addition to climate effects; quad.=economic damage function associated with a change in radiative forcing is assumed to be quadratic in form; linear=economic damage function associated with a change in radiative forcing is assumed to be linear in form.
Source: Reilly 1990. Used by permission.

source of carbon release to the atmosphere. Values for gases that have large indirect effects, such as CO, volatile organic compounds (VOCs), and NO_x, are particularly suspect.

3.8.2 Comparison of U.S. Greenhouse Gas Emissions on a GWP Basis

The stated objective of this chapter was to provide a frame of reference for discussions of policy implications of greenhouse gas control and mitigation. As a summary of the foregoing discussions of the individual gases, it is illuminating to apply the GWP coefficients as weight factors to the various U.S. and world total manufactured emissions as a measure of relative impact. We have adopted the IPCC 100-year coefficients for our analysis.

Figure 3.41 shows the U.S. GWP-weighted contribution to be about one-fifth of the world total. As might be expected from a cursory review of the GWP coefficients, on an emitted weight basis, CO_2, with about 92% of total weight, contributes just over half of the total warming potential, whereas the five CFCs, with less than 1/200th of a percent of the weight, account for about one-sixth of the warming potential.

Finally, to show the effect of the choice of integration interval on the GWP calculation, Figures 3.42 and 3.43 show similar presentations for 20- and 500-year intervals, respectively. In the shorter run, the shorter-lived gases have correspondingly greater effect, while over the longer period, CO_2, with the longest life, dominates.

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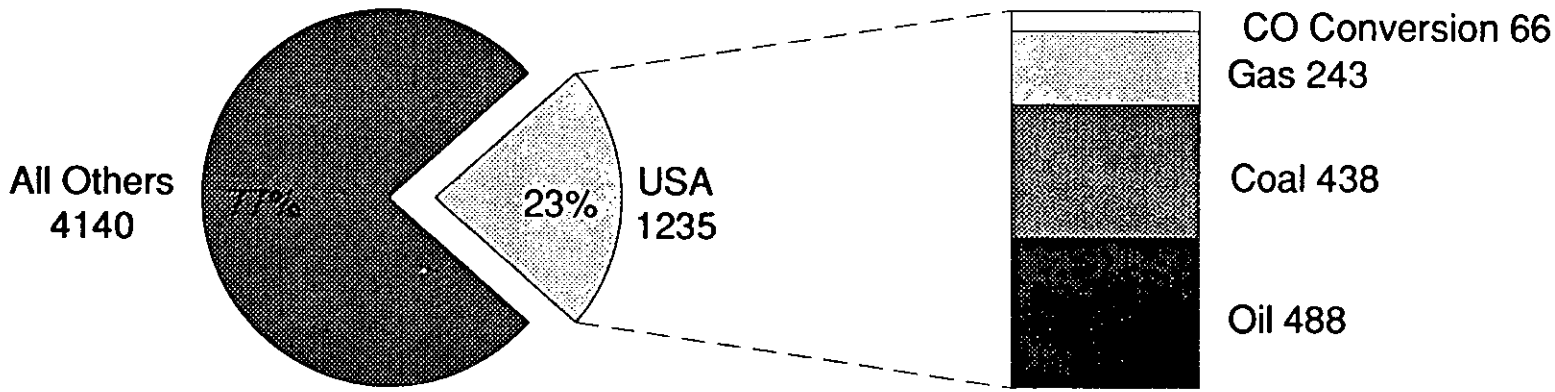

Figure 3.1. U.S. Share of Fossil Fuel CO_2 Emissions (TgC/yr)

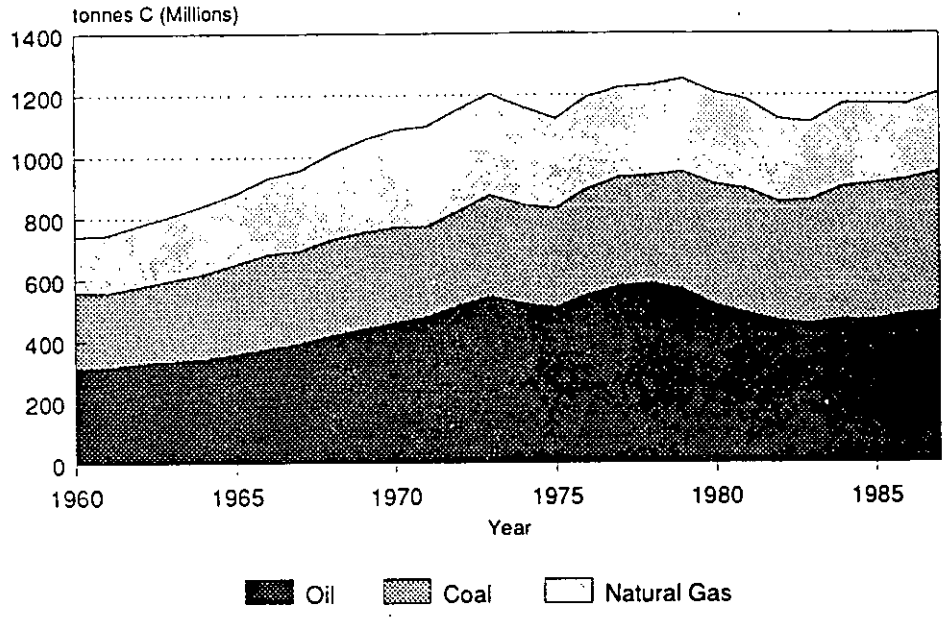

Figure 3.2. U.S. Carbon Dioxide Emissions from Fossil Fuel Combustion - Source: DOE/EIA SEDS 1960-89

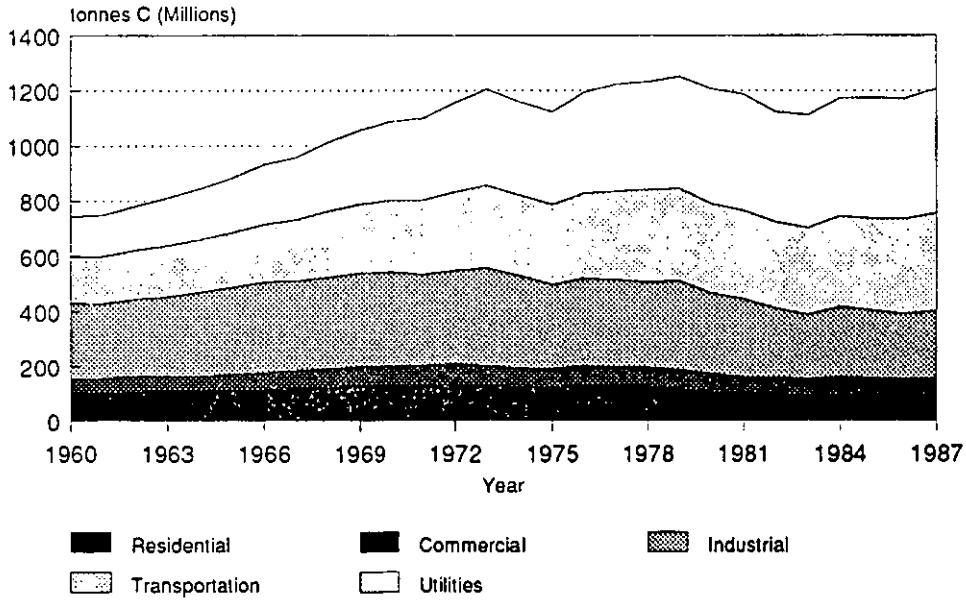

Figure 3.3. U.S. Carbon Dioxide Emissions by Economic Sector - Source: DOE/EIA SEDS 1960-89

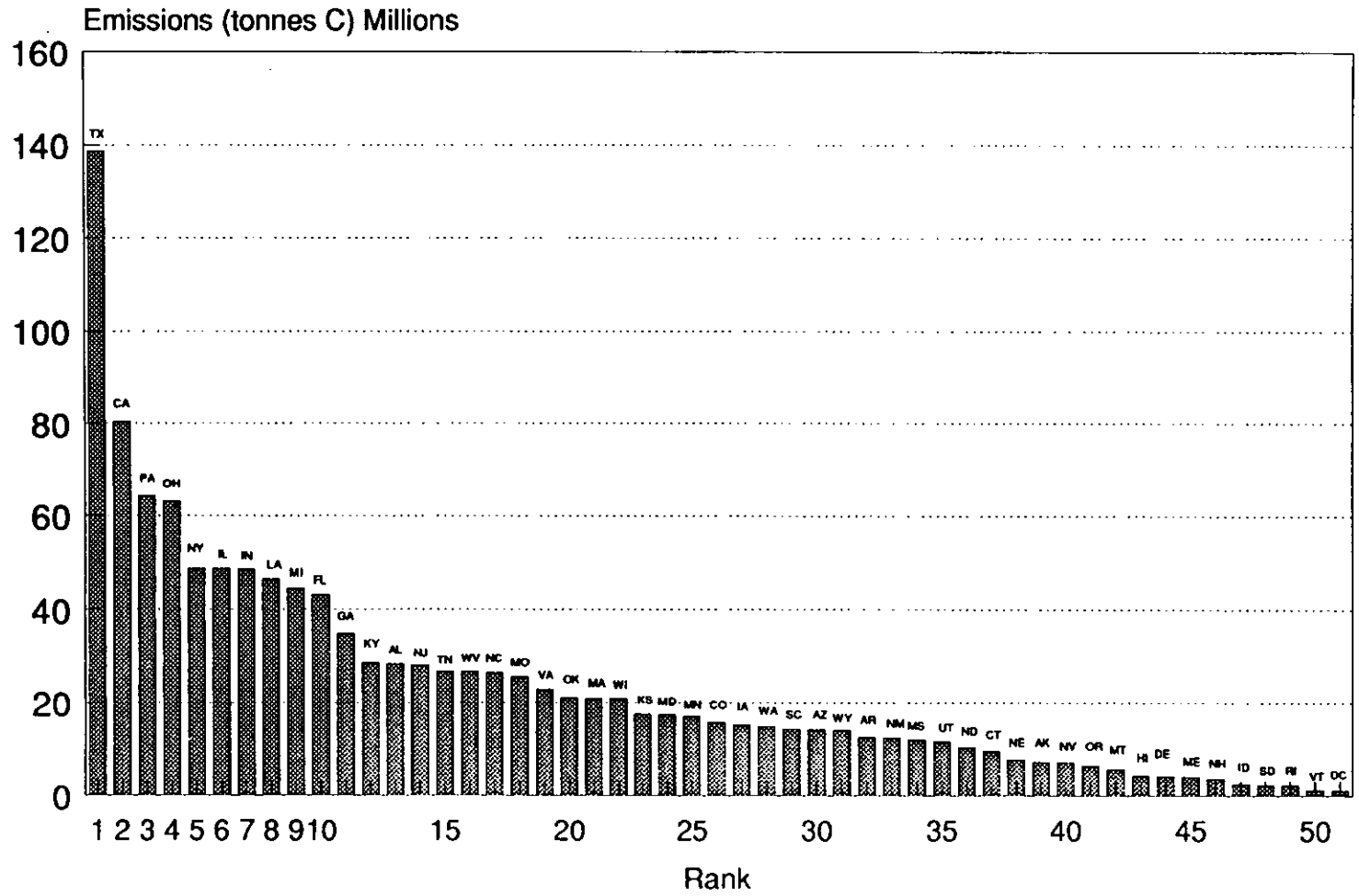

Figure 3.4. U.S. Combustion Emissions of Carbon Dioxide by State--1987 - Source: DOE/EIA State Energy Data Base

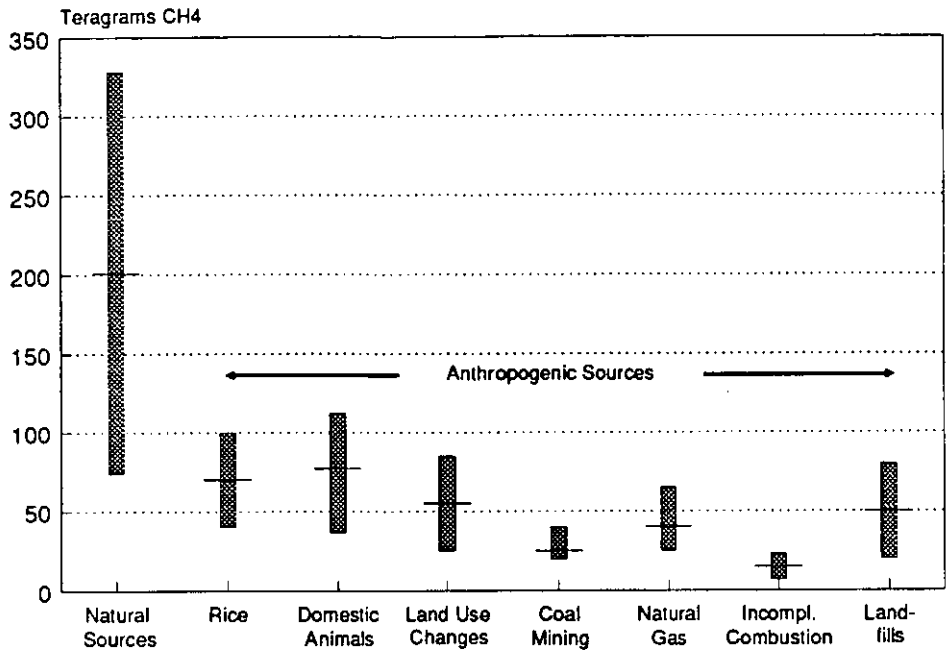

Figure 3.5. Global Sources of Atmospheric Methane Emissions

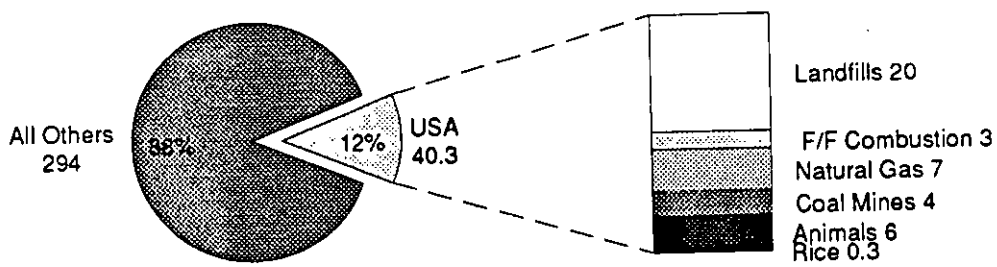

Figure 3.6. U.S. Share of Anthropogenic Methane Emissions ($TgCH_4$/yr)

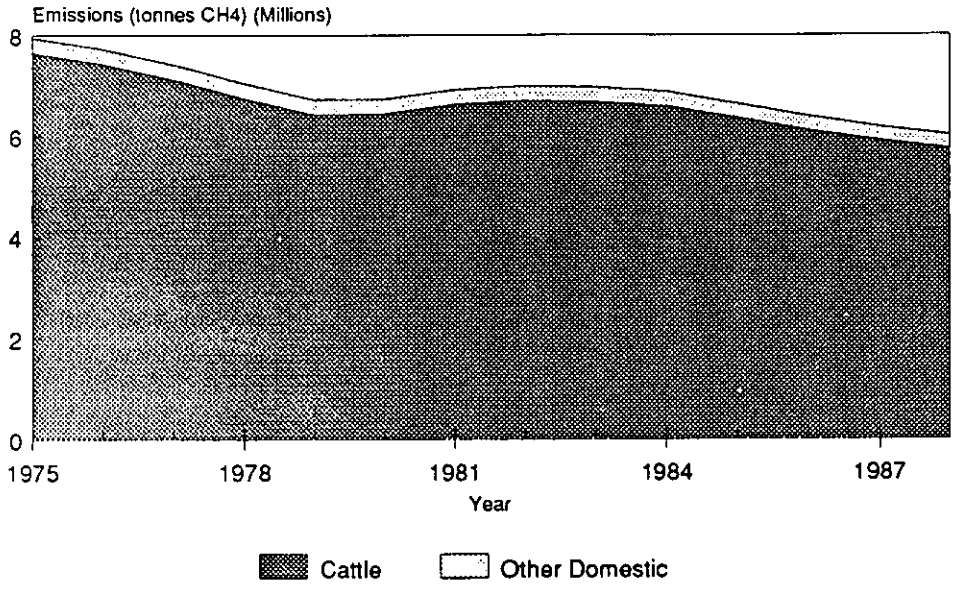

Figure 3.7. U.S. Methane Emissions from Domestic Animals - Source: USDA Agricultural Statistics 1977-88

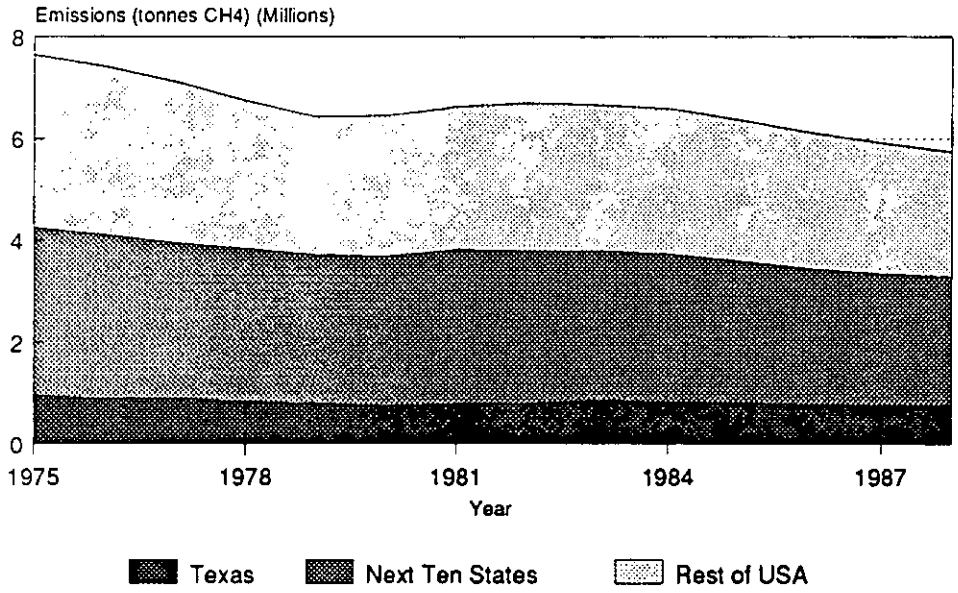

Figure 3.8. U.S. Methane Emissions from Cattle - Source: USDA Agriculture Statistics 1977-88

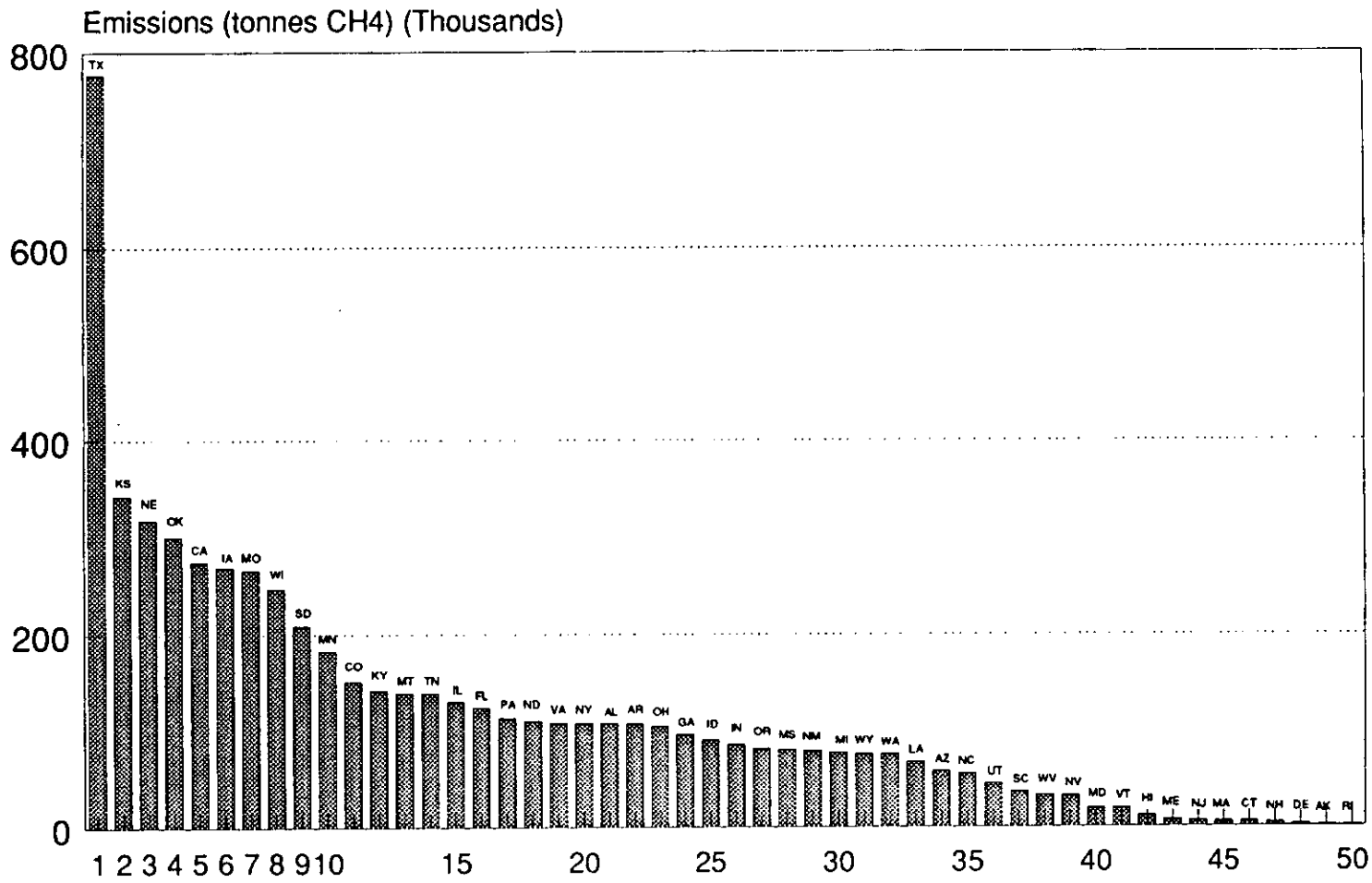

Figure 3.9. Methane Emissions from Cattle: Ranking by State--1987 - Source: USDA Agricultural Statistics 1977-88

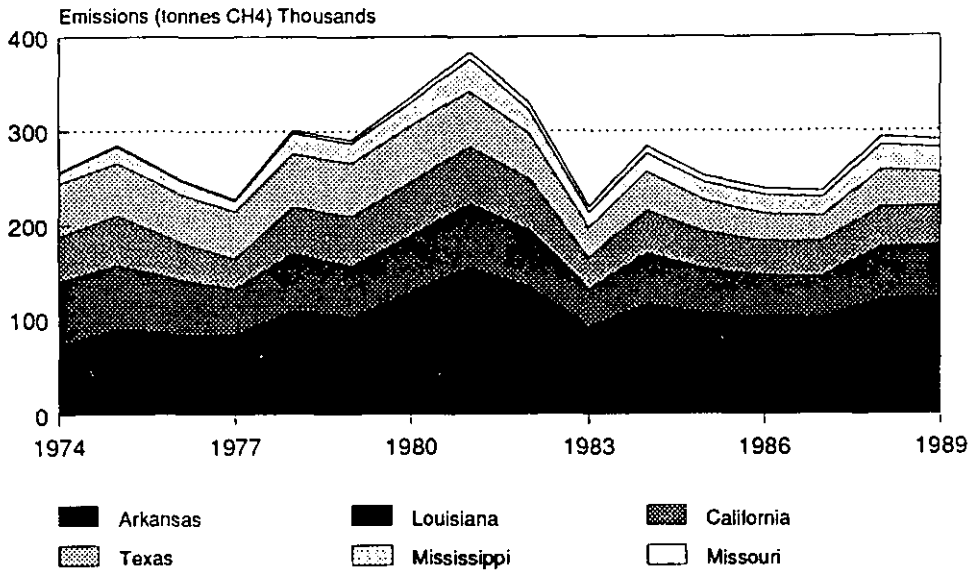

Figure 3.10. U.S. Methane Emissions from Rice Production - Source: USDA Agricultural Statistics 1977-88

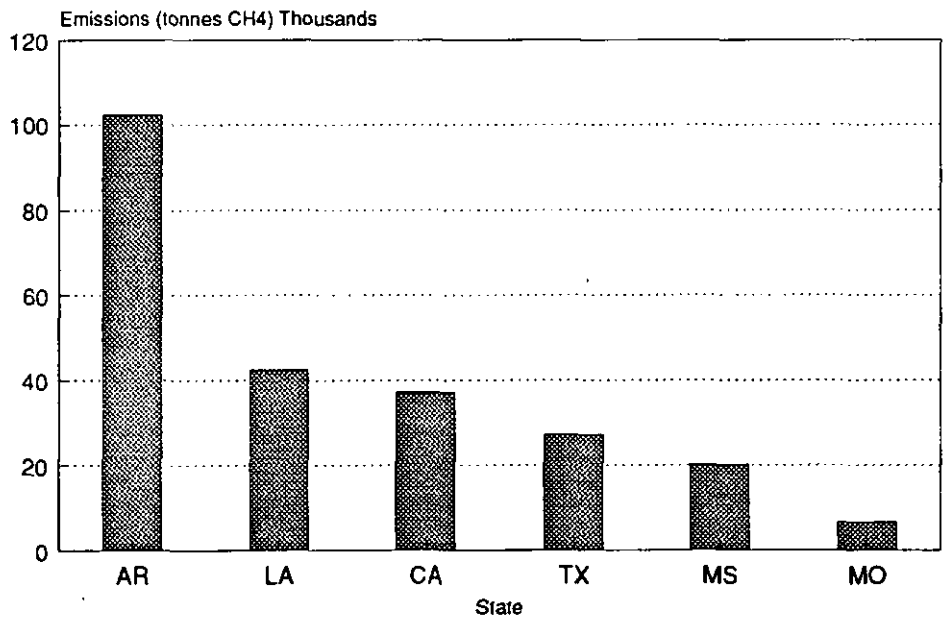

Figure 3.11. Methane Emissions from Rice Production: Ranking by State--1987 - Source: USDA Agricultural Statistics 1977-88

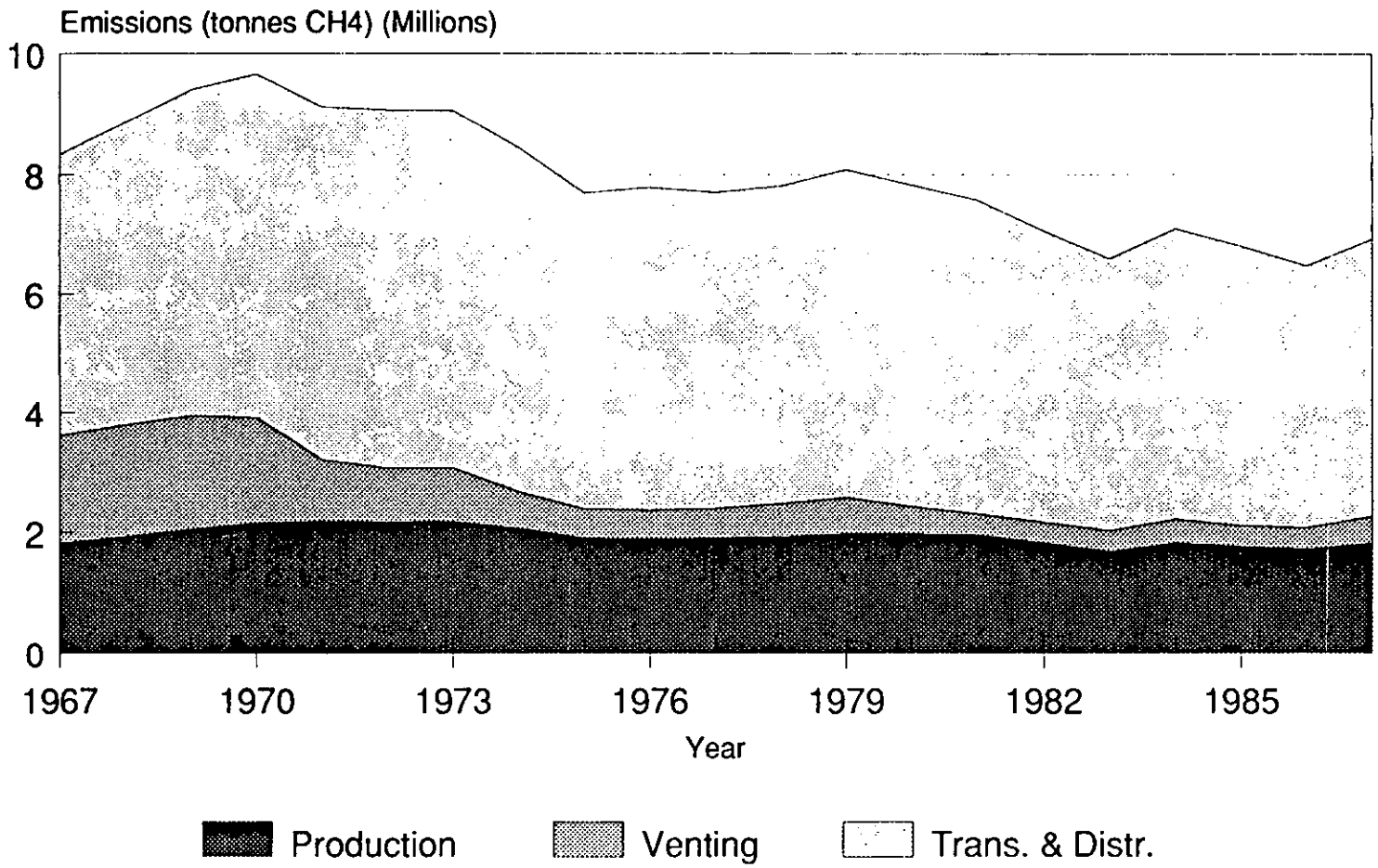

Figure 3.12. U.S. Methane Emissions from Natural Gas - Source: DOE/EIA Natural Gas Annual 1986-7

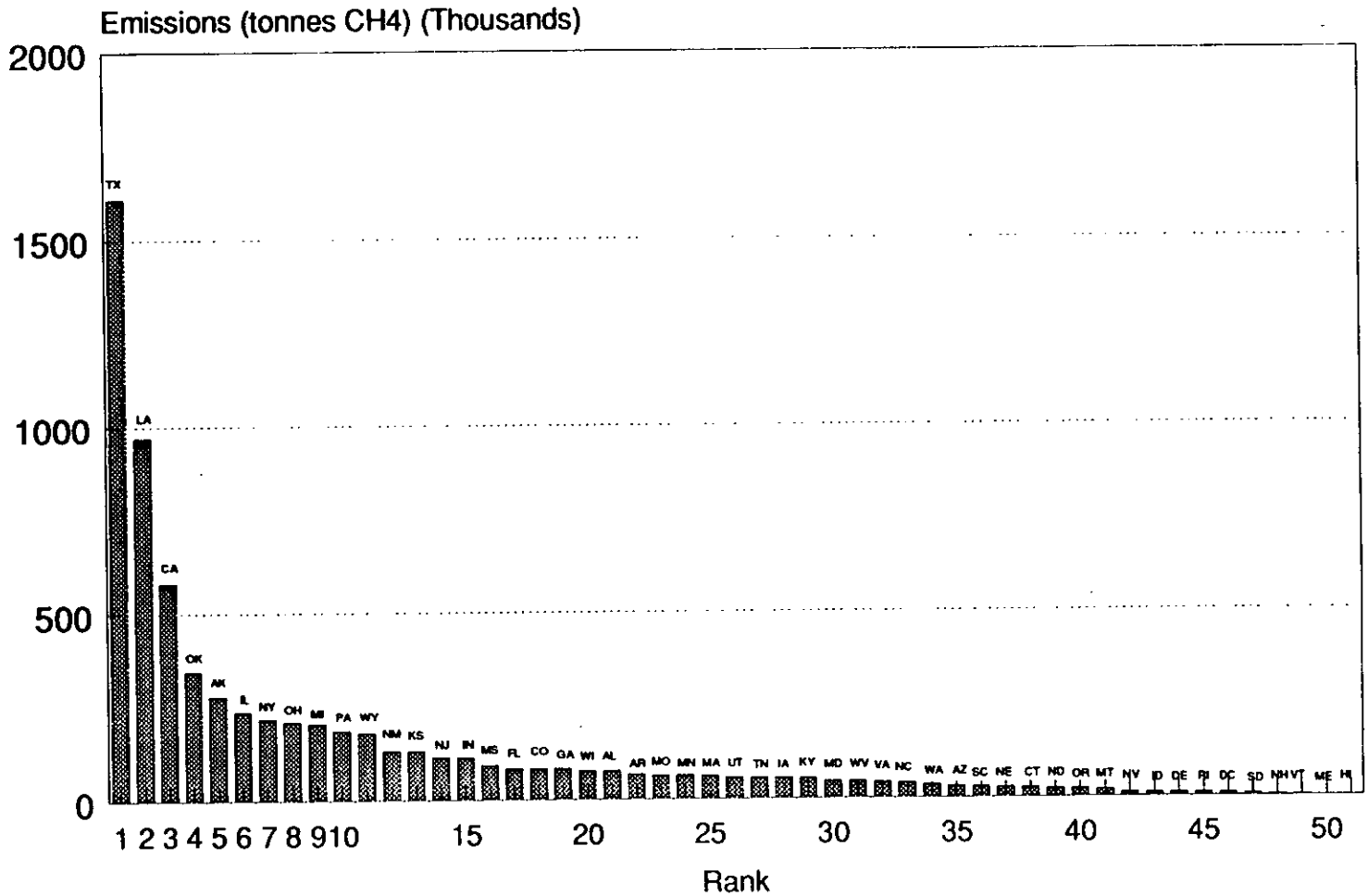

Figure 3.13. U.S. Methane Emissions from Natural Gas by State--1987 - Source: DOE/EIA Natural Gas Annual 1986-7

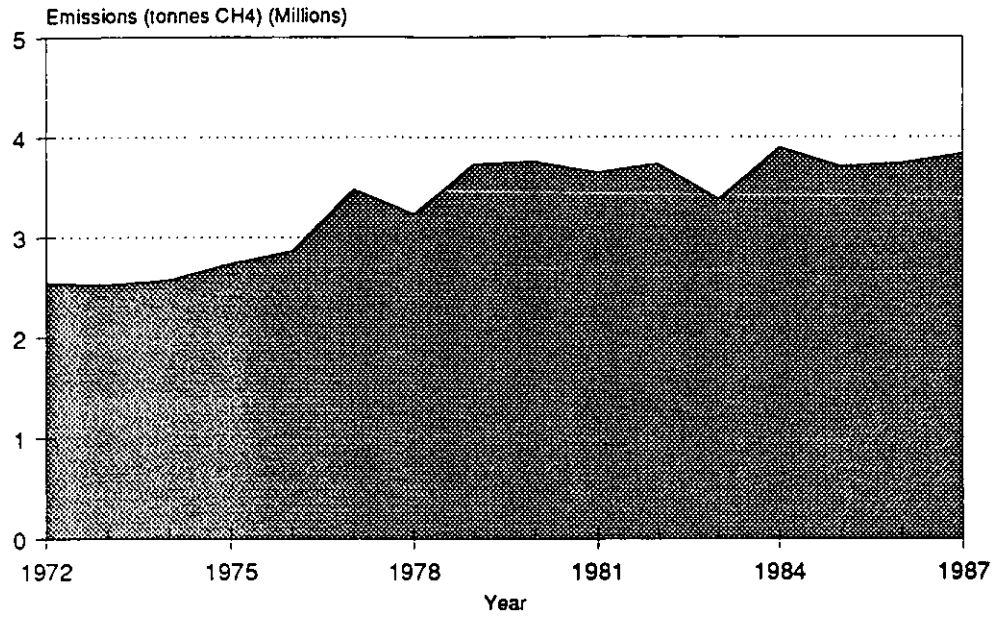

Figure 3.14. U.S. Methane Emissions from Coal Mining - Source: DOE/EIA Coal Production 1977-87

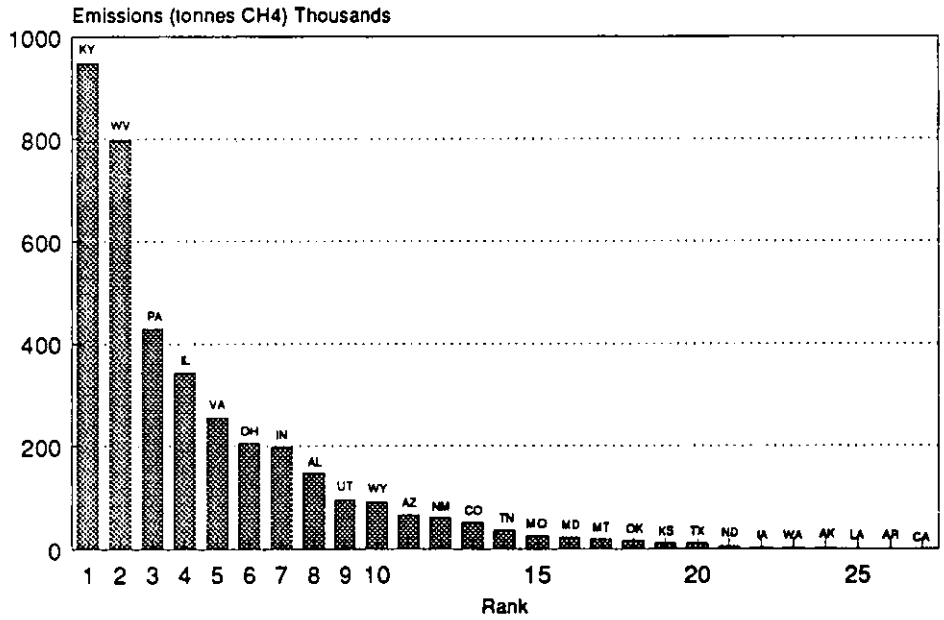

Figure 3.15. U.S. Methane Emissions from Coal Mining by State--1987 - Source: DOE/EIA Coal Production 1977-87

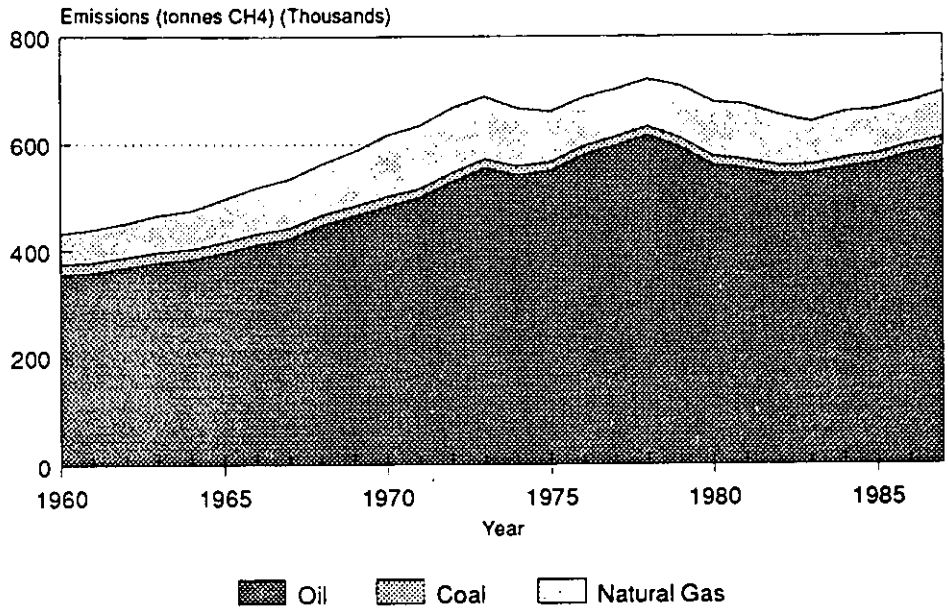

Figure 3.16. U.S. Methane Emissions from Combustion of Fossil Fuels - Source: DOE/EIA SEDS 1960-89

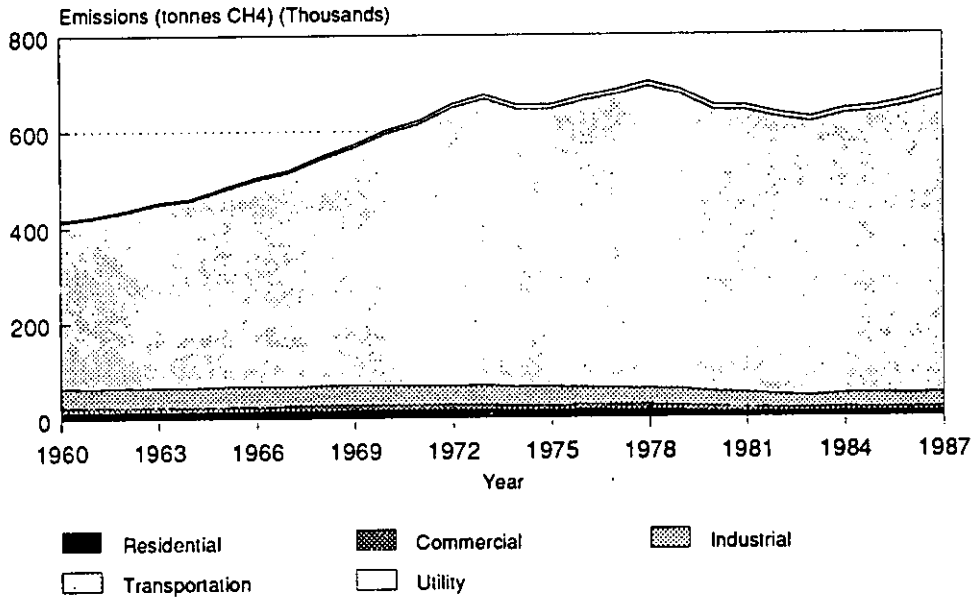

Figure 3.17. U.S. Methane Emissions from Combustion of Fossil Fuels--By Sector - Source: DOE/EIA SEDS 1960-89

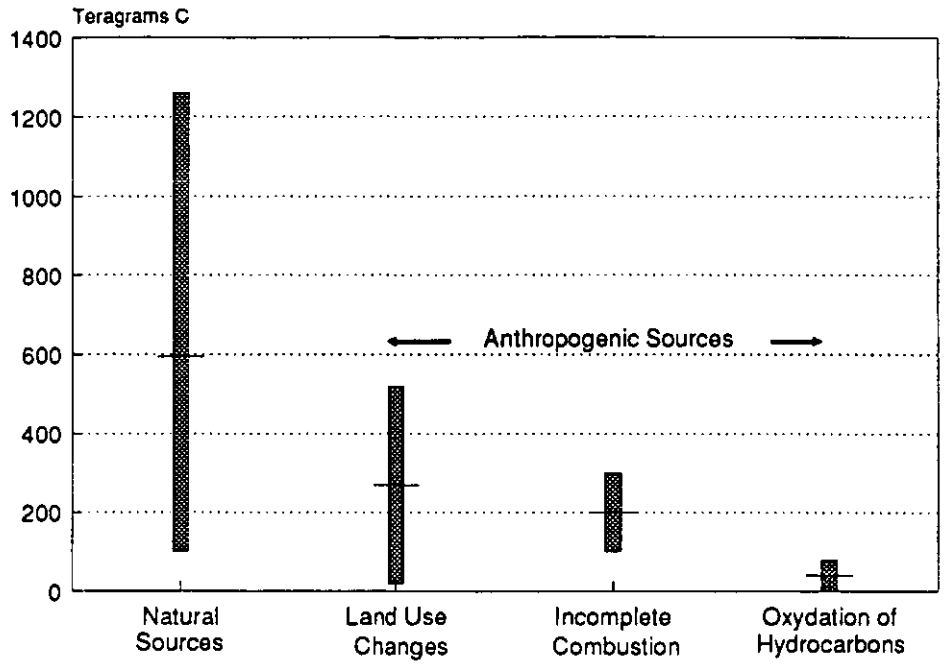

Figure 3.18. Global Sources of Atmospheric Carbon Monoxide Emissions

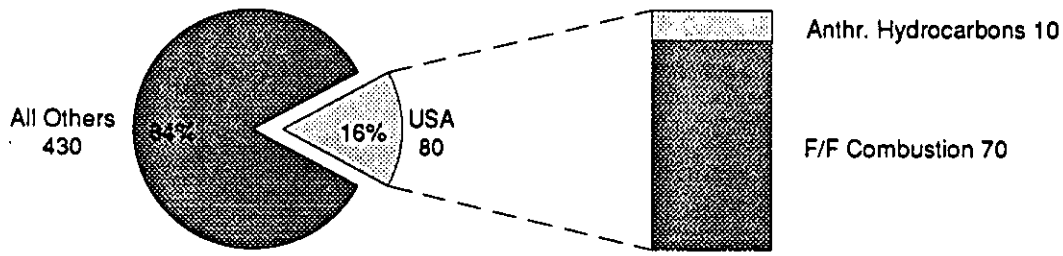

Figure 3.19. U.S. Share of Anthropogenic Carbon Monoxide Emissions (TgC/yr)

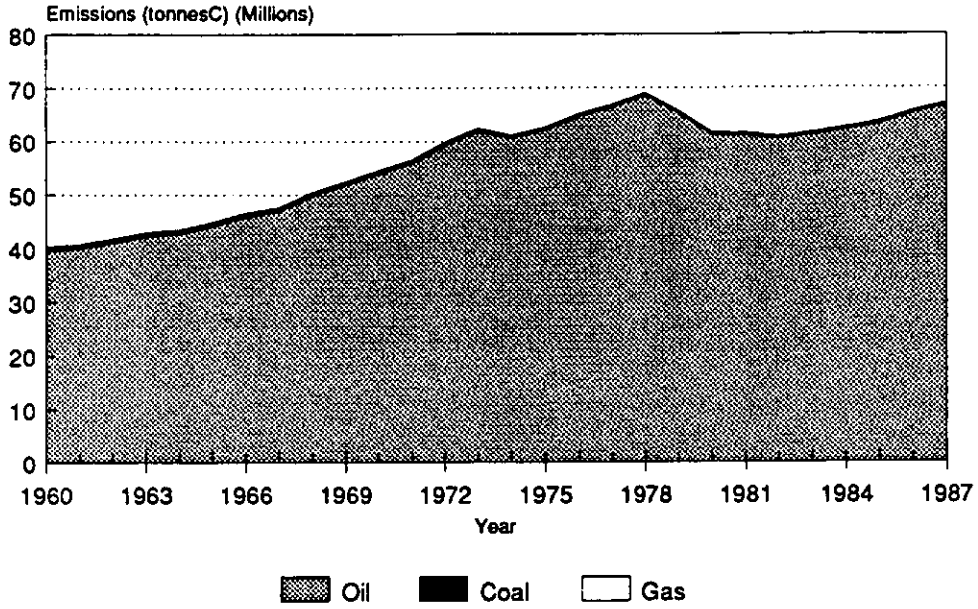

Figure 3.20. U.S. Carbon Monoxide Emissions from Combustion - Source: DOE/EIA SEDS 1960-89

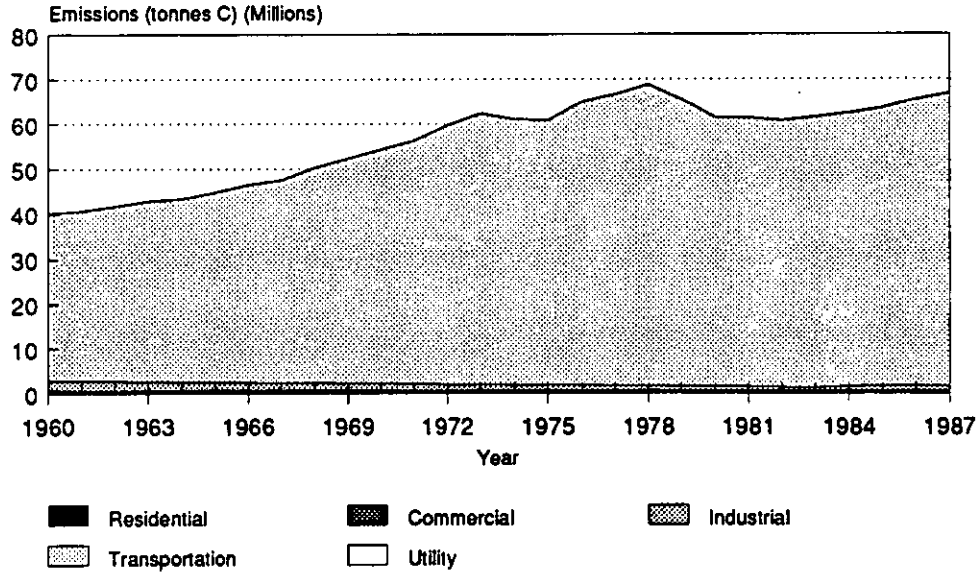

Figure 3.21. U.S. Carbon Monoxide Emissions by Sector - Source: DOE/EIA State Energy Data Base 1960-87

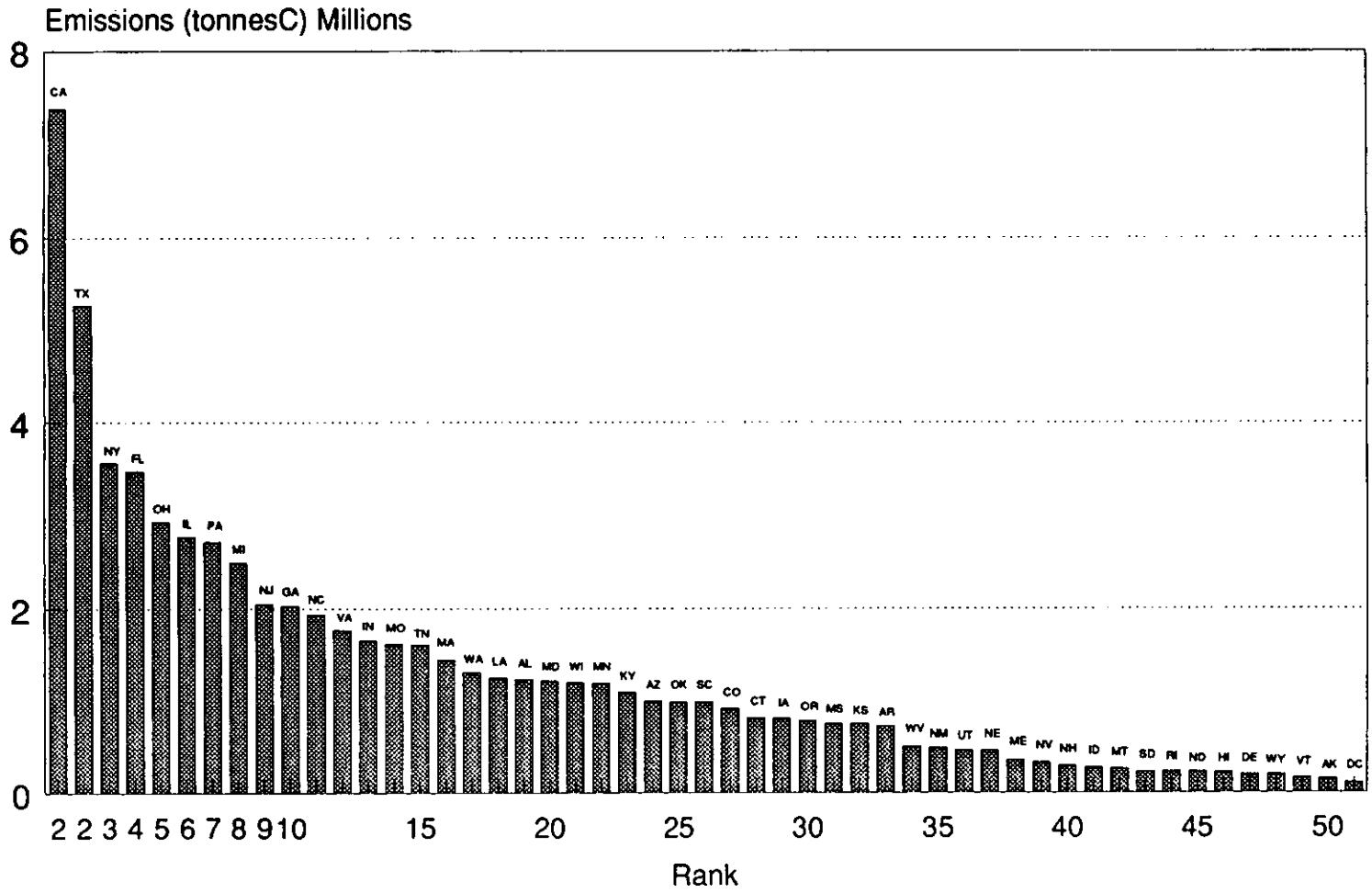

Figure 3.22. U.S. Carbon Monoxide Combustion Emissions by State--1987 - Source: DOE/EIA State Energy Data Base

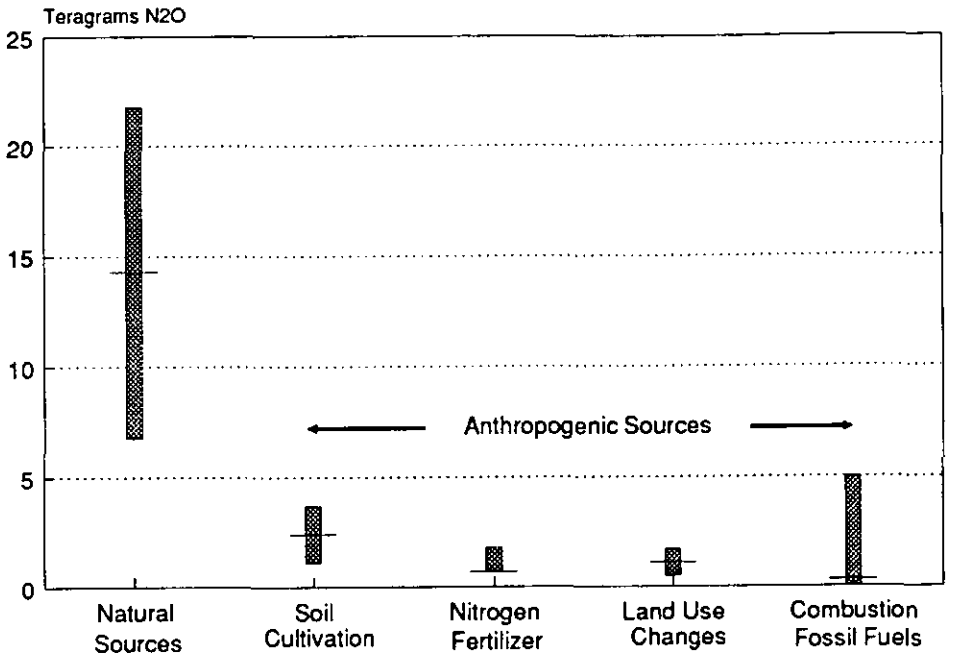

Figure 3.23. Global Sources of Nitrous Oxide Emissions

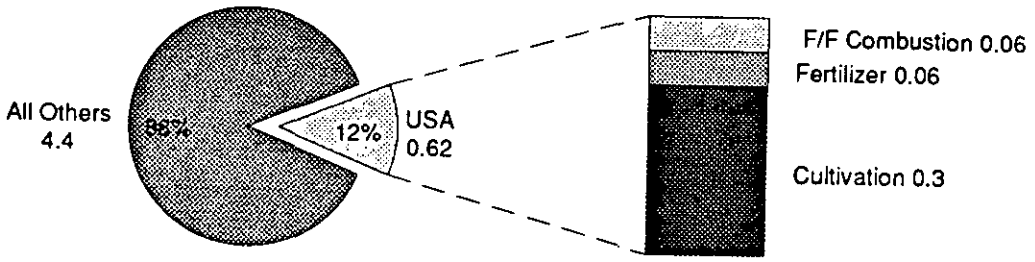

Figure 3.24. U.S. Share of Anthropogenic N_2O Emissions (TgN_2O/yr)

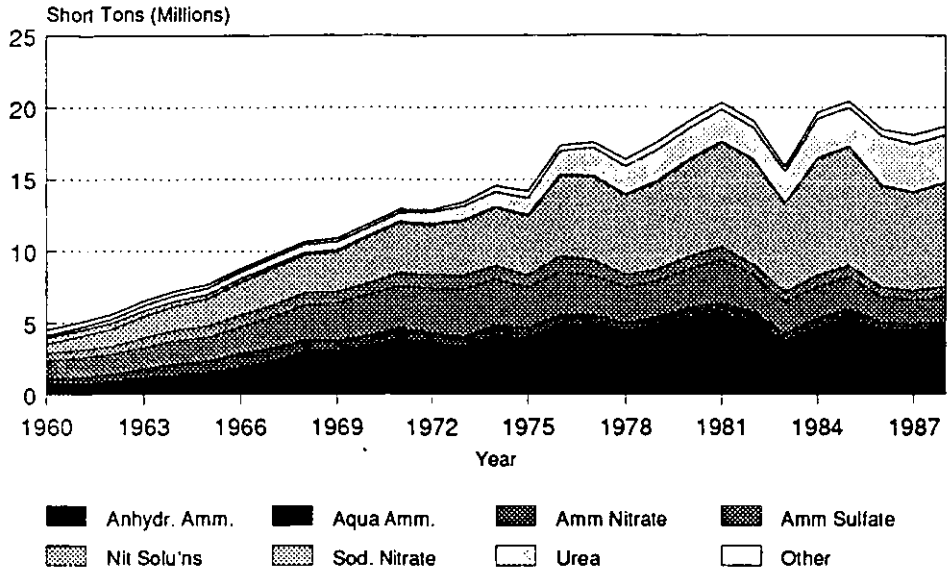

Figure 3.25. U.S. Consumption of Nitrogen Fertilizer - Source: USDA Fertilizer Use and Price Statistics, 1960-89

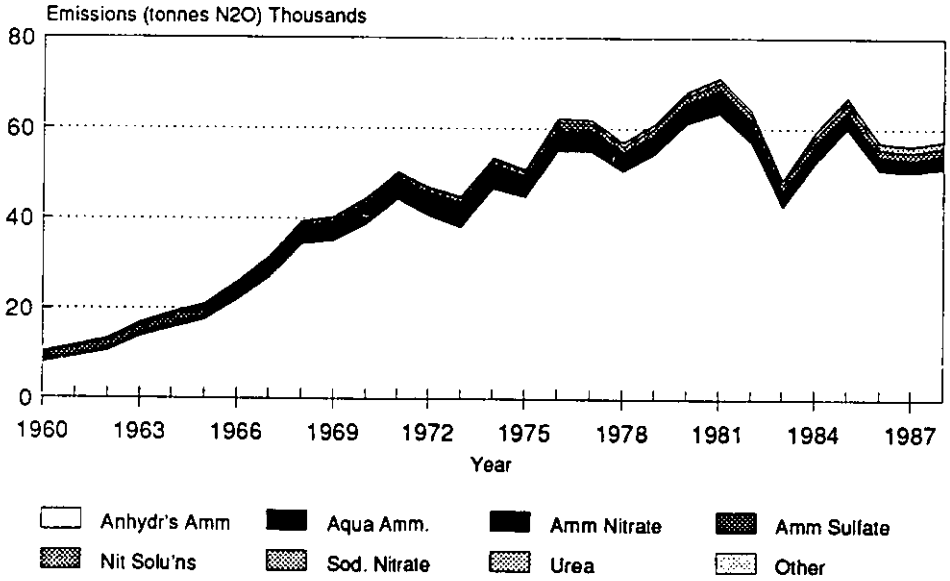

Figure 3.26. U.S. Nitrous Oxide Emissions from Nitrogen Fertilizers - Source: TVA, Commercial Fertilizer Consumption, 1989

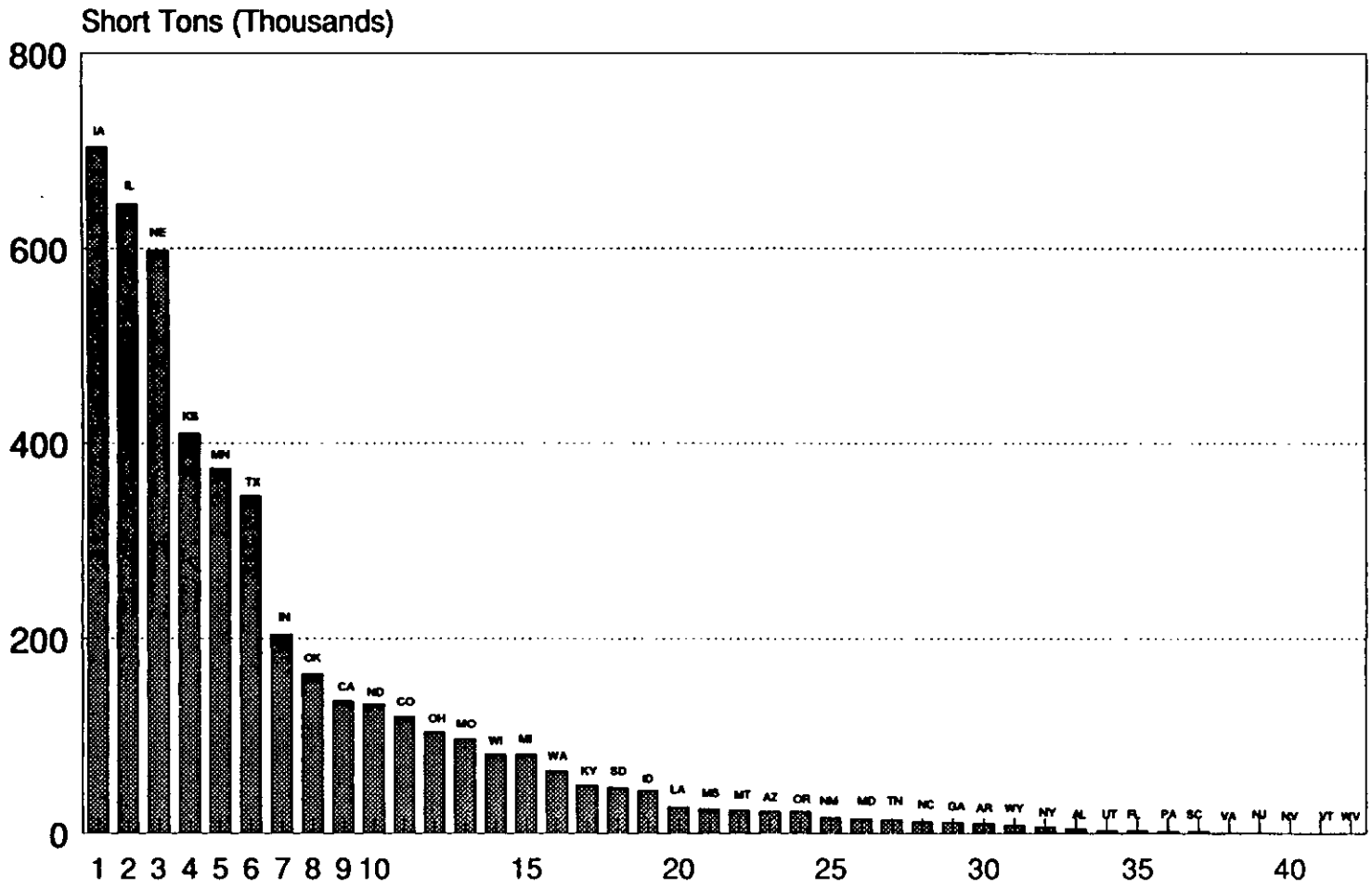

Figure 3.27. Use of Anhydrous Ammonia Fertilizer: Ranking by State--1989 - Source: TVA, Commercial Fertilizer Consumption, 1989

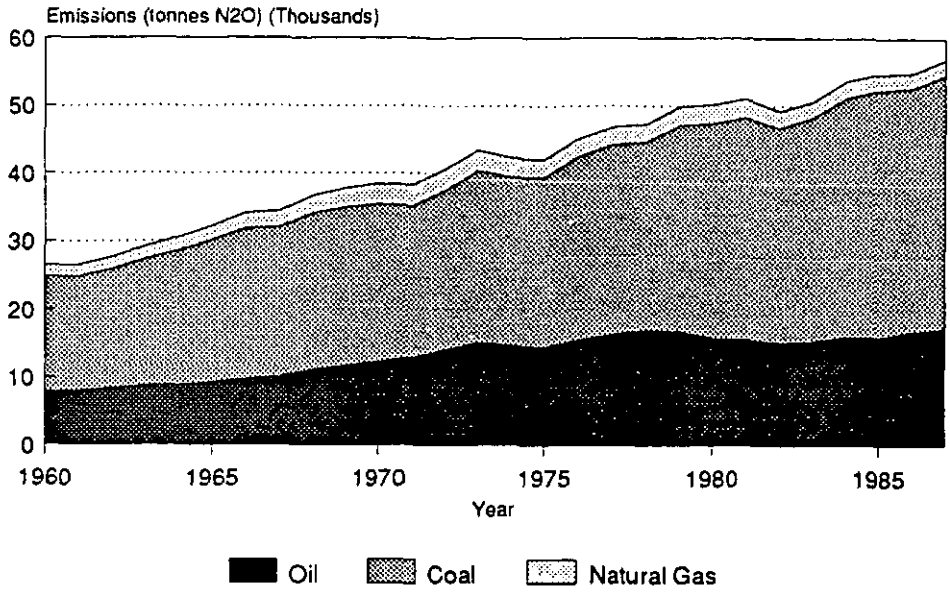

Figure 3.28. U.S. Nitrous Oxide Emissions from Combustion of Fossil Fuel - Source: DOE/EIA State Energy Data Base, 1960-87

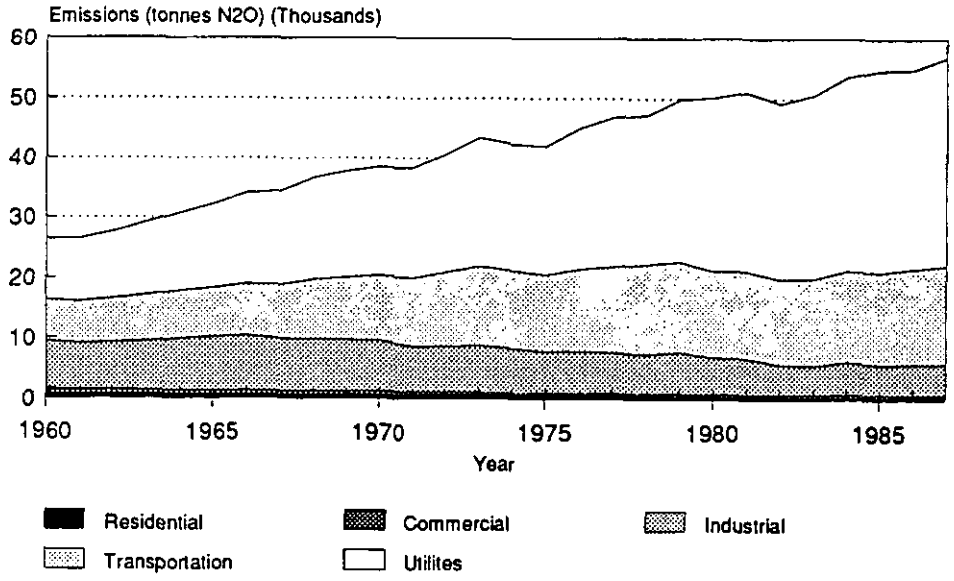

Figure 3.29. U.S. Nitrous Oxide Emissions from Combustion by Sector - Source: DOE/EIA State Energy Data Base, 1960-87

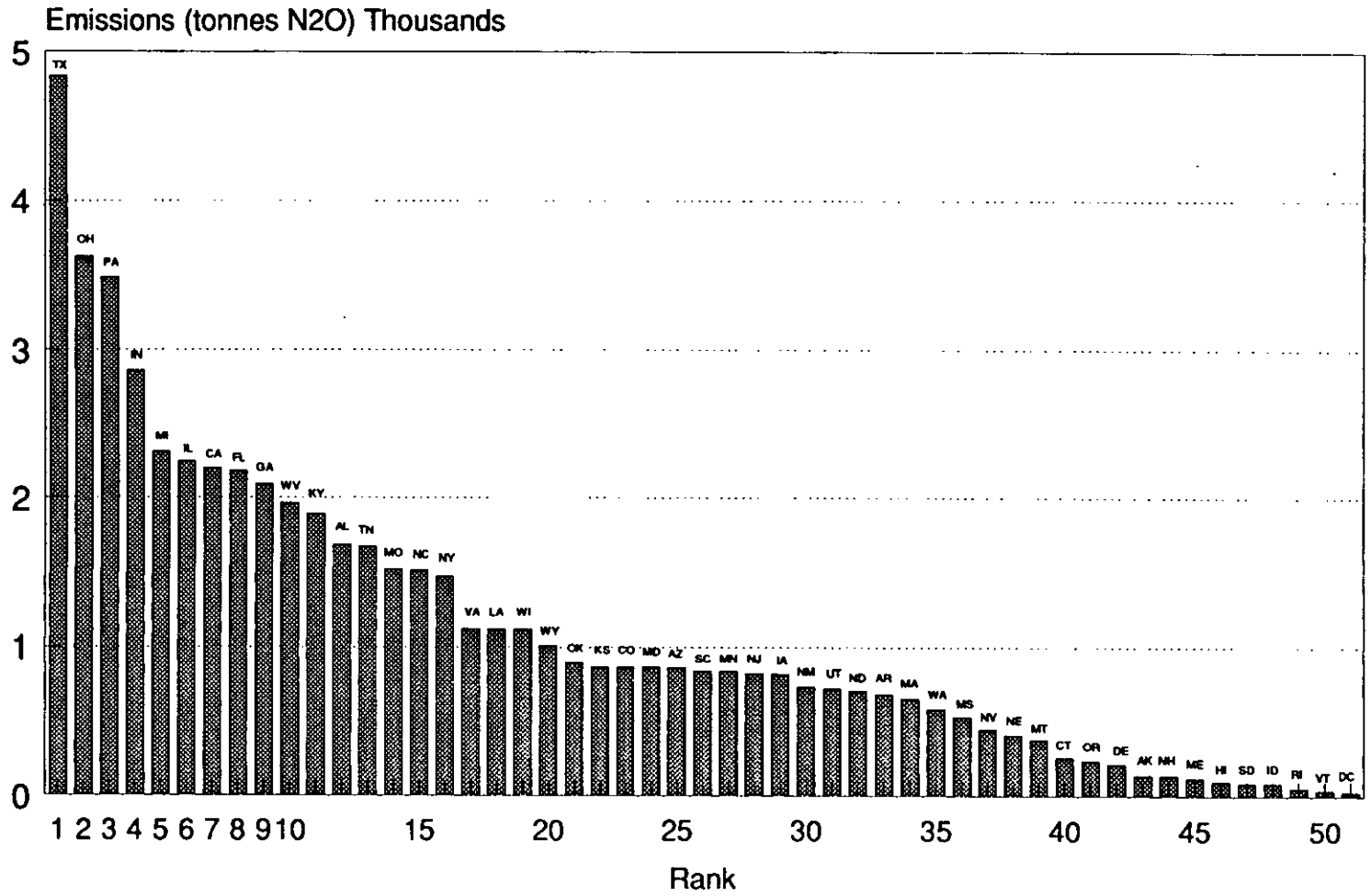

Figure 3.30. U.S. Nitrous Oxide Emissions from Combustion by State--1987 - Source: DOE/EIA State Energy Data Base

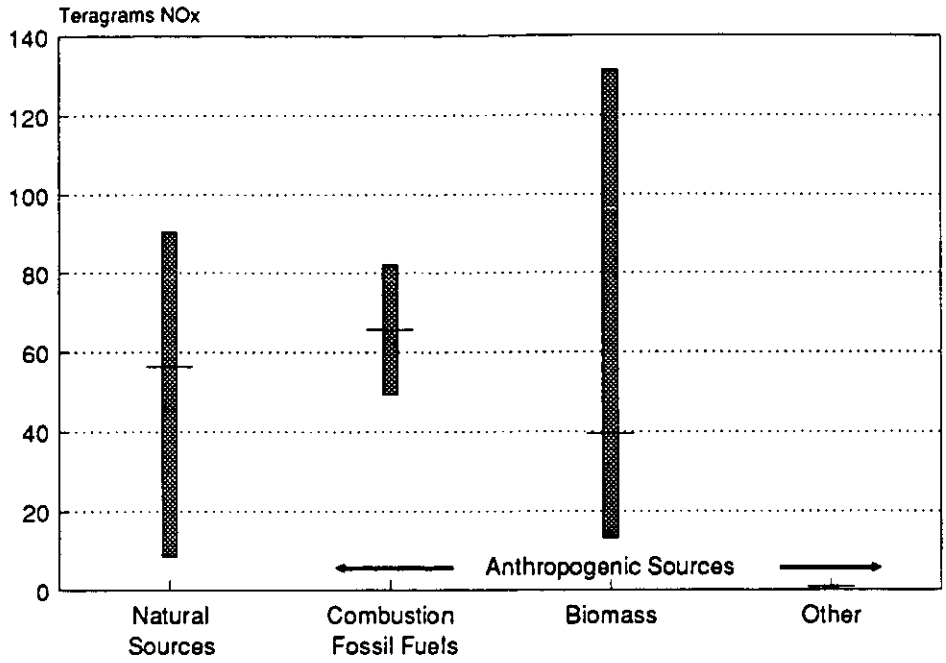

Figure 3.31. Global Sources of Nitrogen Oxide Emissions

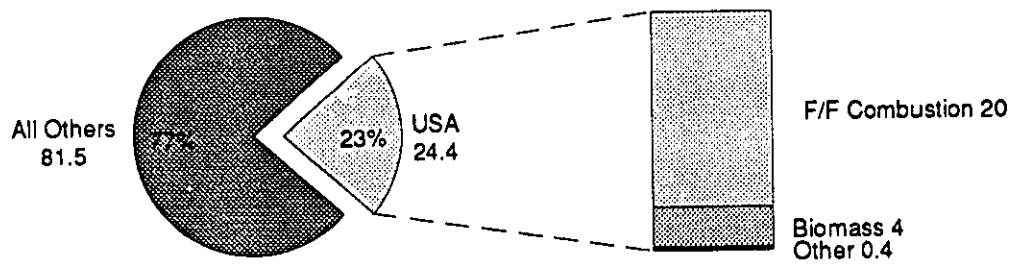

Figure 3.32. U.S. Share of Anthropogenic NO_x Emissions ($TgNO_x$/yr)

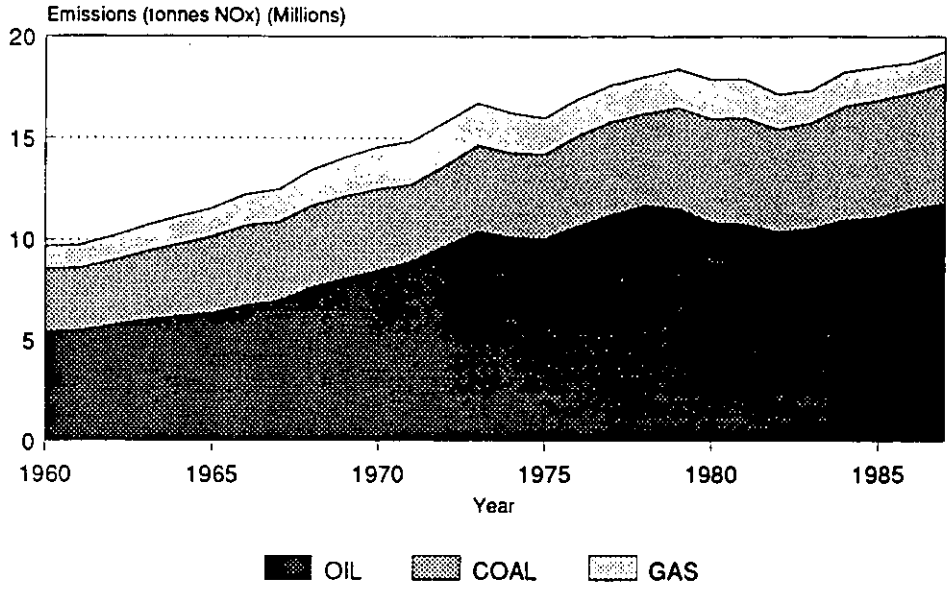

Figure 3.33. U.S. NO_x Emissions from Combustion of Fossil Fuels - Source: DOE/EIA State Energy Data Base 1960-87

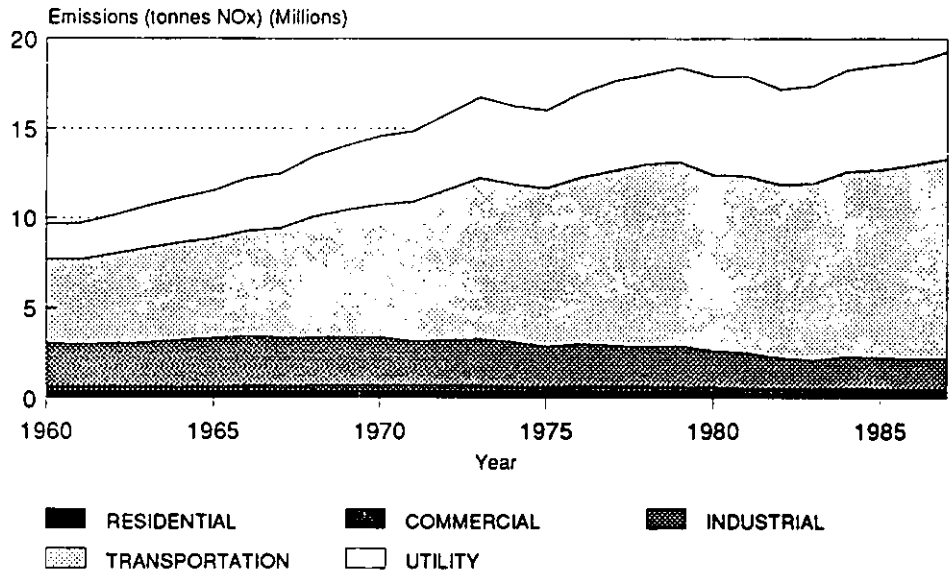

Figure 3.34. U.S. NO_x Emissions by Sector - Source: DOE/EIA State Energy Data Base 1960-87

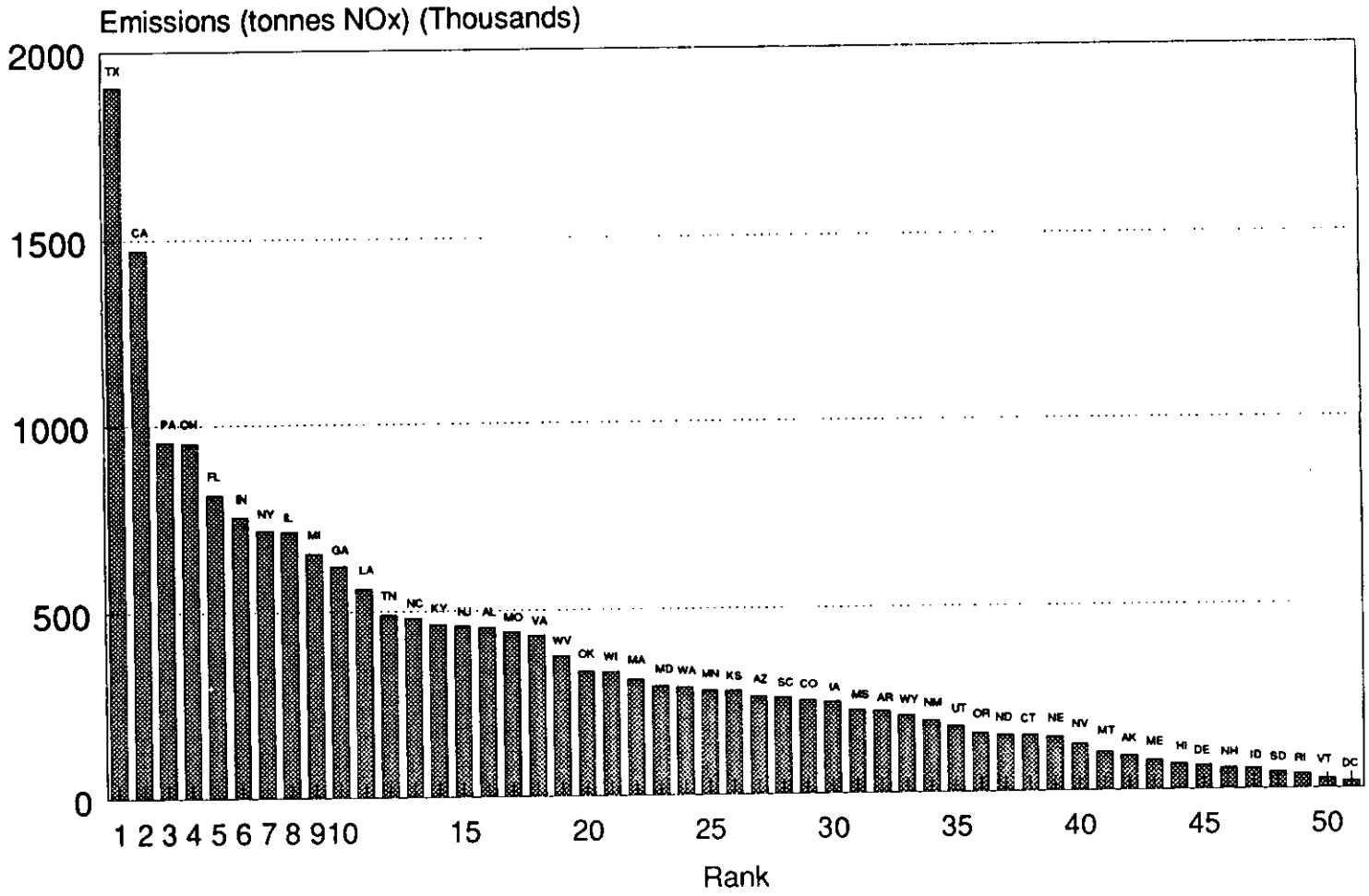

Figure 3.35. U.S. Nitrogen Oxide Emissions from Combustion by State--1987 - Source: DOE/EIA State Energy Data Base

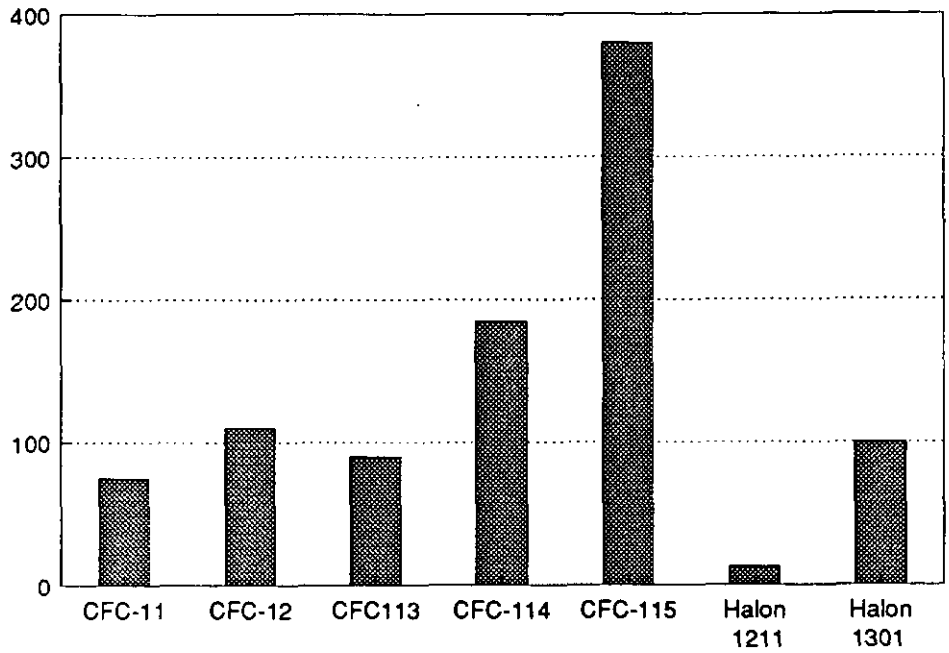

Figure 3.36. Comparison of CFCs--Atmospheric Lifetime (years)

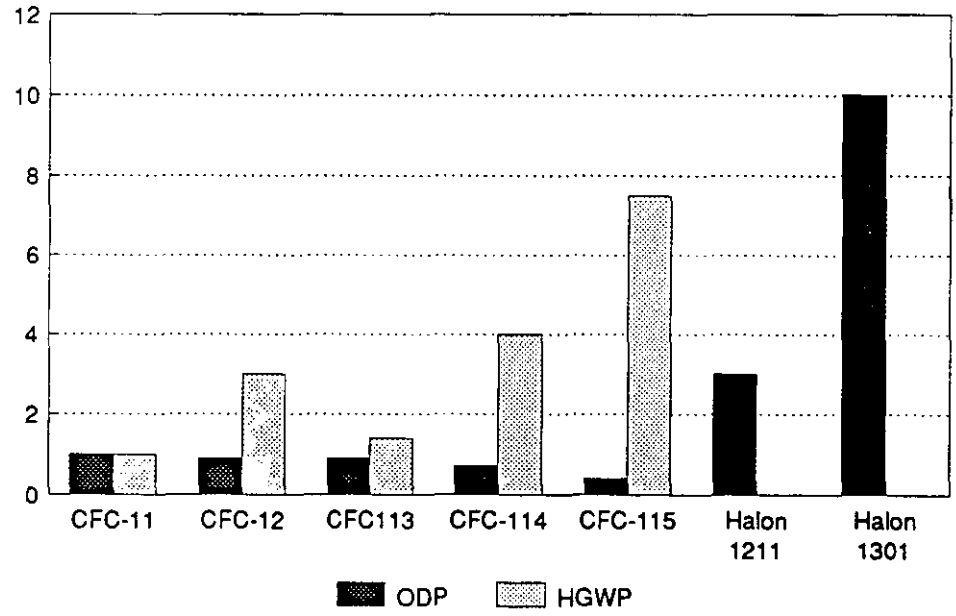

Figure 3.37. Comparison of CFCs--Ozone Depletion and Global Warming

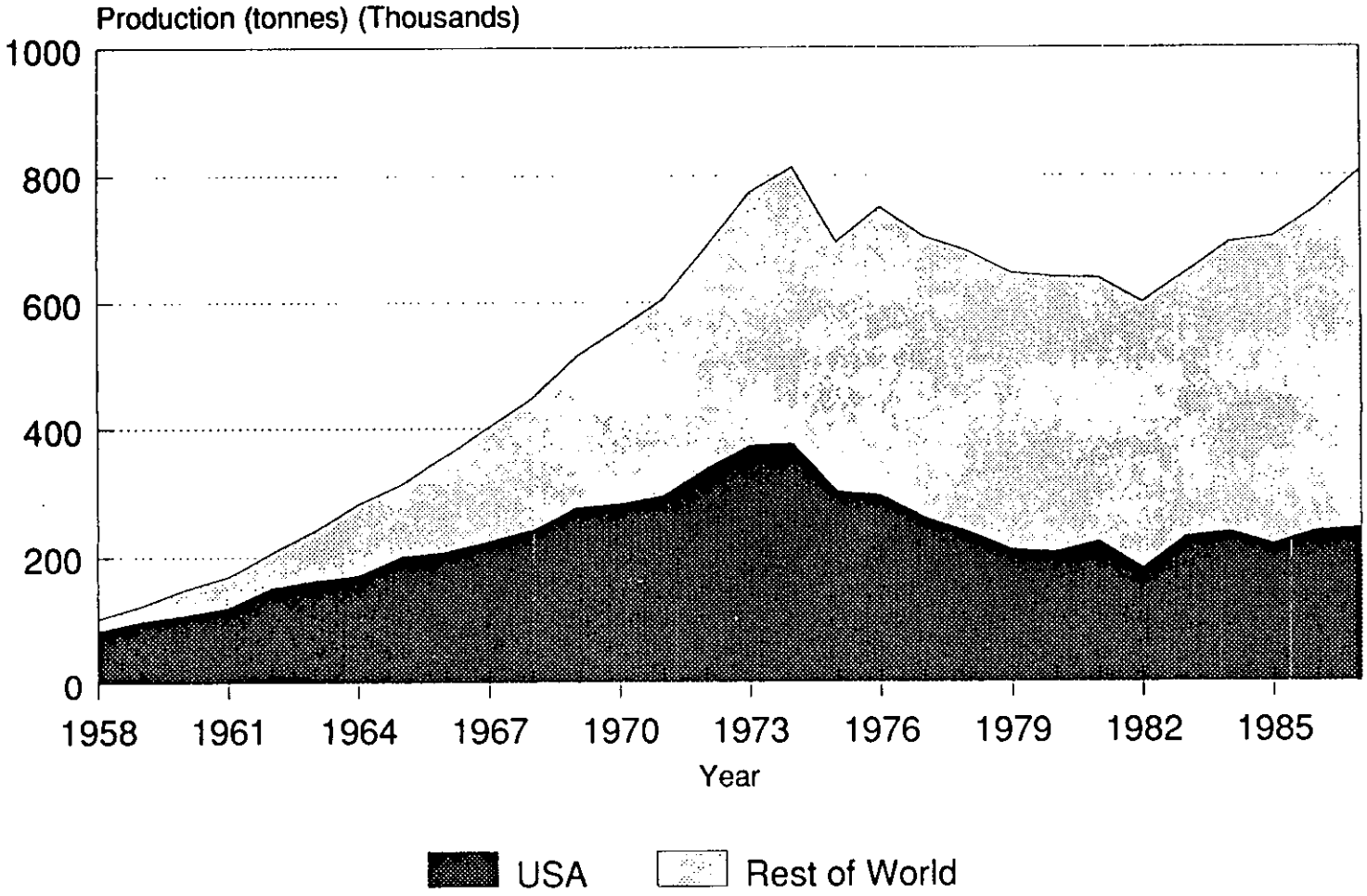

Figure 3.38. World Production of CFC-11 and CFC-12 - Source : CMA (1988) and DOE/EIA (1989)

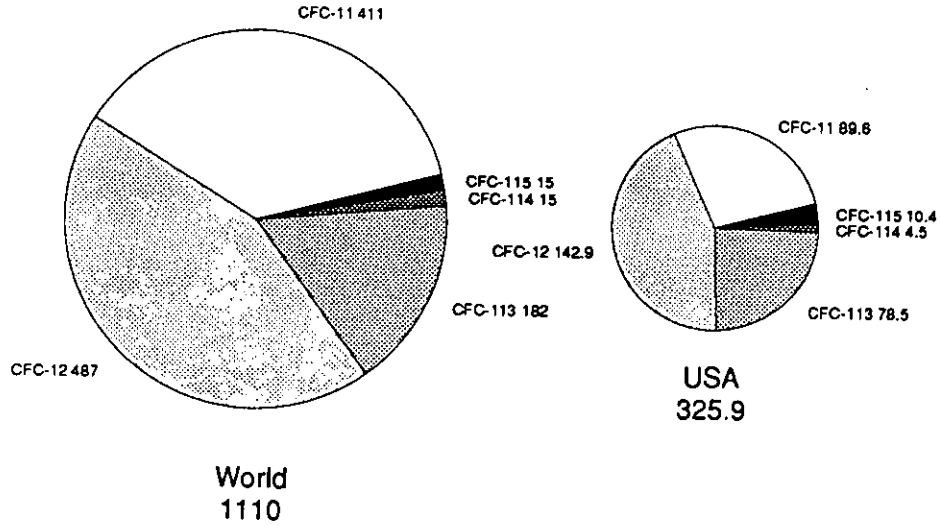

Figure 3.39. World Consumption of CFCs (thousands of tonnes) - Sources: UNEP (1989) and DOE/EIA (1989)

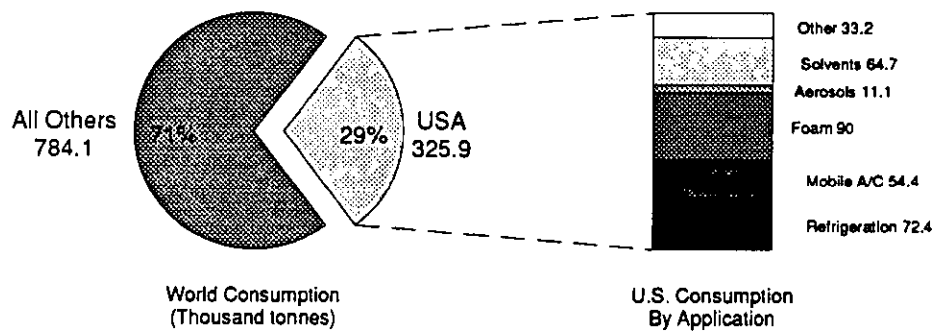

Figure 3.40. U.S. Share of World CFC Consumption--1986 (thousands of tonnes) - Source: DOE/EIA (1989)

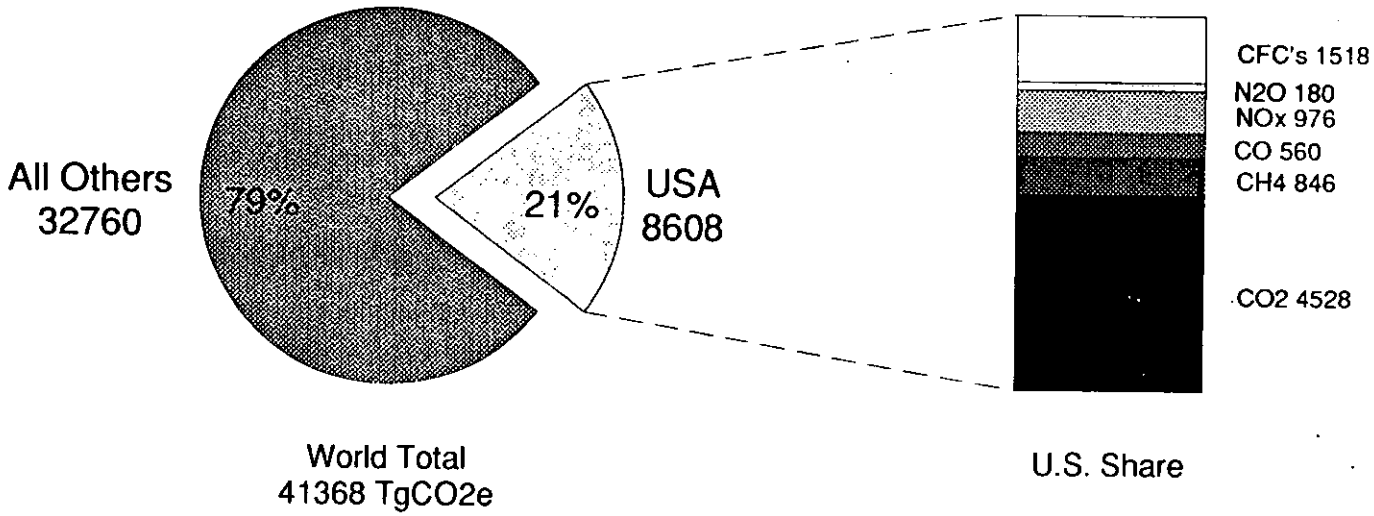

Figure 3.41. U.S. Share of World 100-Year Global Warming Potential--1987

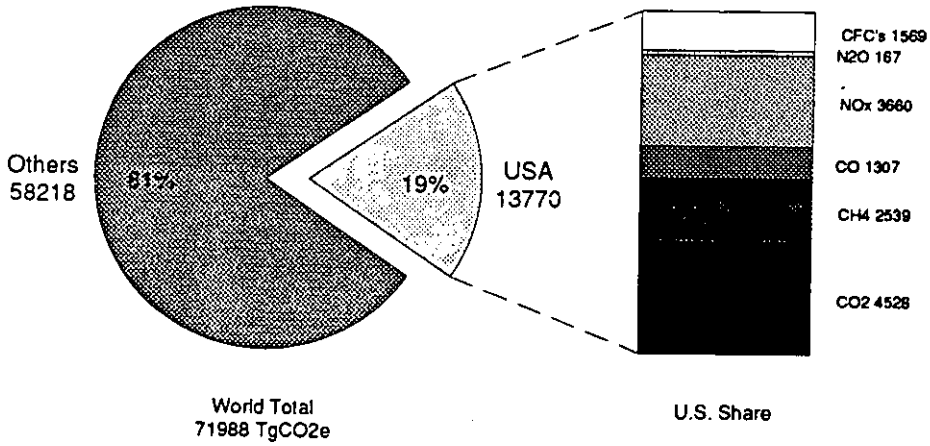

Figure 3.42. U.S. Share of World 20-Year Global Warming Potential--1987

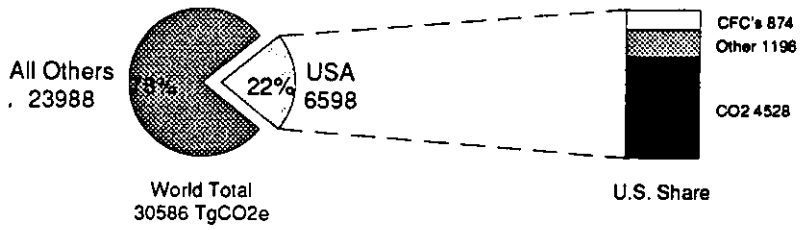

Figure 3.43. U.S. Share of World 500-Year Global Warming Potential--1987

4.0 AN APPROACH TO ANALYZING THE TECHNICAL POTENTIAL AND COST OF REDUCING U.S. ENERGY-RELATED GREENHOUSE GAS EMISSIONS

4.1 INTRODUCTION

The congressional request that launched this study calls for a comprehensive investigation of policy options for the stabilization and reduction of carbon emissions. Policies specified include "energy pricing, energy efficiency requirements, alternative fuels, and alternative end-use and supply technologies." These policies are to be tested against target emission reductions of 20% in the next 5 years to 10 years and 50% over the next 15 years to 20 years.

The scope of the congressional request suggests a broad, integrated approach, while the diverse nature of the energy sector suggests a thorough, technology-specific analysis. The analytical approach used in this study attempts to meet both these requirements. The purpose of this chapter is to explain the structure of the analysis and the various analytical tools used in generating the findings and conclusions.

This chapter begins by identifying the various fiscal and regulatory policies tested and describing the Current Policies Case to which they are compared. Next, the analytical tools and methodologies used in the study are described. The remainder of the chapter describes three specific models--Fossil2, the Edmonds-Reilly Model, and the DRI Macroeconomic Model--that were used in the analysis.

4.2 STRUCTURE OF THE ANALYSIS

The analysis presented in this report uses the Administration's 1991/1992 National Energy Strategy (NES) as a point of departure for exploring different policy options available to address the global climate change issue. The policies considered fall into three distinct groups:

Group 1 Current Policies

Group 2 NES Actions - policies outlined in the NES (some of which influence greenhouse gas emissions) that were not then part of U.S. energy policy

Group 3 Global Climate Policy Options that go beyond the NES Actions in reducing energy-related greenhouse gas emissions.

4.2.1 Current Policies

The reference case used for this study is the same Current Policy case used for the NES analysis. Assumptions regarding economic growth, technology availability, the structure of the energy system and current policies are identical. A complete discussion of the reference and the underlying technical assumptions is available in Appendix A of DOE 1991b.[a]

The reference includes several major energy policies assumed to remain in place independent of initiatives taken to mitigate greenhouse gas emissions. These include:

- the Montreal Protocol and the London Agreement
- conservation initiatives, including efficiency standards enacted prior to the NES
- development plans for renewable energy resources in place prior to the NES
- the President's America the Beautiful tree planting initiative.

(a) More detail may be found in the *Assumptions for the Annual Energy Outlook* (DOE/EIA 1990).

The Montreal Protocol and the more recent London Agreement are designed to eliminate the most important ozone-depleting gases. Under the Montreal Protocol (to which the United States is a party), CFC production would be gradually reduced to one-half of 1986 levels by 1998, and halon production would be frozen at 1986 levels. Under the June 1990 London Agreement, production and new uses of CFCs and halons will end by the year 2000. Provisions to end production of other chlorine-containing solvents were added, as were nonbinding provisions to gradually phase out production of HCFCs. The reduction of these gases, which are among the most radiatively active known, will act to mitigate the global warming potential, in addition to protecting stratospheric ozone.

Energy conservation initiatives currently in place include efficiency standards for appliances and lighting in federal facilities. These efforts are enhanced by federal building guidelines, standards, and, to a lesser extent, energy analysis and diagnostic centers. Thus, conservation already plays an important role in the NES Current Policies. Homes are projected to use 10% less energy in 2010 than they did in 1990; offices will save 17%, and factories will save 30% over the same period (DOE 1991a). In general, conservation results in reduced greenhouse gas emissions, especially when electricity produced by coal-fired generators is displaced.

Renewable energy policies assumed in the reference include initiatives to encourage cost-competitive ethanol transportation fuels. In addition, programs currently in place strive to reduce costs and increase penetration of electricity generated from municipal solid waste, photovoltaic and hydroelectric sources. Overall, in the Current Policies, renewable energy is assumed to grow by more than 50% between 1990 and 2010. This growth mitigates greenhouse gas emissions, primarily by displacing energy sources that produce higher levels of CO_2.

The President's tree planting initiative, proposed in the FY 1991 budget, calls for planting one billion trees each year. By adding biomass, the trees sequester atmospheric carbon until they burn or decay. The policies involving carbon sequestration or offsets represent additions to this billion-tree base.

4.2.2 NES Actions

The NES Actions case incorporates policies proposed by the 1991/2 National Energy Strategy and is identical to the NES "with Strategy" described in the NES document (DOE 1991a, 1991b). The NES Actions incorporate all the reference assumptions along with several additional initiatives. The most important of these initiatives, from the perspective of decreasing greenhouse gas emissions, include the following:

- Integrated Resource Planning
- Nuclear Regulatory Reform
- Natural Gas Reform
- Energy from Municipal Solid Waste
- Alternate-Fueled Vehicles
- Enhanced Energy Technology R&D
- North American oil and gas production and transportation improvements
- SO_2 and NO_x Controls in the Clean Air Act Amendments
- Landfill Controls.

Together, these options make up the NES Actions case tested for this study. The analytical specification outlined below attempts to reflect both the letter and spirit of the NES proposals as closely as possible.

Integrated Resource Planning (IRP) could change the institutional and pricing structure within which utility-provided energy is produced and consumed. IRP, also known as least-cost utility planning, refers to a variety of instruments by which

utilities can offset future demand for electricity by investing in measures to reduce end-use electricity consumption. With IRP, electric utilities could pursue business development beyond traditional generation, transmission, and distribution activities. Utilities could provide energy services through demand-side management, conservation program operation, design assistance, etc., while maintaining their ability to generate revenues. With a broader set of choices available, utilities are encouraged to pursue least-cost planning, even when implementation of the plan involves selling less energy. Two IRP measures included in this illustrative case are:

- regulatory changes that allow the cost of certain conservation measures to be recovered by consumers
- a federal information and technical assistance program.

The Nuclear Regulatory Reform package includes both developing new reactor technologies and reforming regulation of construction, operation, and decommissioning of nuclear installations. Additional measures considered include extending the productive lifetimes of nuclear reactors by 20 years and a comprehensive solution to nuclear waste long-term storage and isolation. Life extension and the development of new technologies act to reduce reactor costs, while regulatory reform reduces the construction lead time.

Natural Gas Regulatory Reform in the NES incorporates initiatives to support research and development of natural gas production and consumption technologies, along with the reform of federal statutes and regulations that are seen as hindering the use of natural gas. These reforms include measures to encourage more efficient pricing of natural gas and gas pipeline services and eliminate unnecessary restrictions on natural gas imports and exports.

The Energy from Municipal Solid Waste (or Waste-to-Energy, WTE) option encourages the conversion of municipal solid waste to useful energy. Under the NES, WTE plants are expected to provide approximately 2 quads of primary fuel as input to electricity production by the year 2010. The DOE will conduct studies to better understand the technical, regulatory, and environmental concerns associated with WTE systems.

The Alternate-Fueled Vehicles option includes financial incentives for developing and using alternate-fueled vehicles, as well as research into advanced transportation fuels from renewable sources such as biomass. In the NES Actions Case, methanol-powered vehicles account for almost half of the fleet of light duty-vehicles by 2030, while electric vehicles make up over 10% of the total fleet.

Enhanced Energy Technology R&D assumes that DOE initiatives accelerate basic research, technology development, and technology transfer. These initiatives result in lower costs, earlier availability, or a larger recoverable resource in each of the targeted areas. Technologies benefitting from this policy include advanced gas and oil recovery systems, biofuels and advanced renewables, conservation measures for buildings and industry, electricity transmission, distribution, and storage, and advanced transportation systems.

The Clean Air Act Amendment provisions that decrease acid precipitation also act to limit greenhouse gas emissions, although the effect on greenhouse gases is relatively small. Utility companies pay the cost of compliance, then pass the rate increases along to their customers. The customers react by increasing investments in conservation measures, so they ultimately use less energy. While this effect is incorporated in the analysis, provisions that seek to limit volatile organic carbon (VOC) emissions are excluded, due to uncertainty concerning their effects. Scientists expect that the GWP

index for VOCs and tropospheric ozone may change substantially over the next decade, but are unable to predict even the direction of change.

Landfill Controls refer to EPA plans to propose a rule to regulate emissions of non-methane VOCs from municipal landfills. Reducing these emissions will also reduce methane emissions from these landfills. Projected methane reductions from existing and new landfills for the period 1990 to 2010 were based on Cristofaro and Scheraga (1990). Methane reductions for the period 2010 to 2030 were estimated using the average rate of reduction over the previous 10 years.

The Montreal Protocol and the London Agreement do not influence the NES Actions Case relative to the Current Policies Case, since these agreements are included under the Current Policies assumptions. As NO_x and SO_2 are not included as greenhouse gases, the only difference in GWP-weighted energy-related emissions between the two cases is caused by the indirect influence of higher electricity prices, as noted above.

Individual policies for reducing CO_2 emissions have different effects in the near-term, (e.g., by the year 2000), compared to the long-term (e.g., by the year 2030). The analysis shows the relative contributions to the total CO_2 emission reduction (compared to the Current Policies) of individual policy actions as follows:

Year 2000	
Energy Efficiency & Integrated Resource Planning (IRP)	25%
Alternate Fueled Vehicles and Transportation R&D	23%
Natural Gas Reform	23%
Municipal Solid Waste	15%
Other Policy Actions	14%
Year 2030	
Energy Efficiency & Integrated Resource Planning (IRP)	15%
Alternate Fueled Vehicles and Transportation R&D	25%
Nuclear Reform	36%
Industrial Energy Efficiency	11%
Other Policy Actions	13%

With the NES Actions in place, incremental effect of the Clean Air Act Amendments of 1990 (CAAA) on carbon emissions is rather small. Differences between the NES Actions and NES without CAAA are about 2% in 2030.[a]

4.2.3 Global Climate Policy Options

This study examines several different policy options beyond those adopted in the NES that are available to further mitigate the rate of global climate change. The NES policies were designed so that the combined benefits from all national energy-related objectives more than compensated for the expected costs. Climate-related strategies beyond NES would only be undertaken if the expected benefits from reducing emissions related to climate change alone were determined to outweigh the costs. The purpose of this study is to outline the costs. No attempt is made to assess benefits beyond greenhouse gas emissions reductions. The research tools necessary to conduct a benefits assessment are in a more primitive state of development than those used to assess costs. And while such cost-benefit analysis would be useful, it falls outside the scope of this study.

Individual policy instruments examined in this volume were drawn from the analysis of a wide array of possible policy instruments documented in DOE (1989). Five broad strategy groupings are identified in DOE (1989): Fiscal Incentives;

(a) Differences between the NES Actions with the Clean Air Act Amendments of 1990 (CAAA) and without the CAAA appear below. These differences are due to increased conservation investments, fuel switching and behavioral changes caused by higher electricity prices.

Year	Increase (millions of mtC/yr)	(% change relative to NES)
1990	0	0%
1995	9	1%
2000	18	1%
2005	23	1%
2010	23	1%
2015	23	1%
2020	25	1%
2025	31	2%
2030	37	2%

Regulation; Information; Research, Development and Demonstration; and Combined Strategies. These instruments provide specific policy tools capable of inducing all sectors of the economy to alter behavior. Information and Research, Development and Demonstration policy instruments are included within the set of NES Actions. This study focuses on Fiscal Incentives, Regulation, and Combined Strategies that go beyond the NES Actions. Within the latter three categories, a limited set of policy instruments were chosen that were representative of these classes of actions and, which, on theoretical and empirical grounds, appeared to hold promise of effectiveness in reducing greenhouse gas emissions. The specific policies addressed here are discussed below and are illustrated conceptually as Figure 4.1.

Fiscal Policies

The fiscal policies tested consist of a tax on carbon emissions and a tax on GWP-weighted energy-related greenhouse gas emissions. These are considered separately below.

Policies that impose carbon taxes assess a charge on each metric tonne of carbon (mtC) emitted into the atmosphere. Relatively carbon-rich fuels, such as coal and oil, face higher tax rates (on an energy content basis) than does natural gas. Nuclear and biomass-derived fuels are assessed no tax, since they are assumed to have no net carbon dioxide emissions. Combustion of traditional biomass fuels, such as crop residues and dung, releases CO_2 to the atmosphere, but such fuels are in a balanced cycle of absorption and respiration, which has a short timeframe. The use of other biomass fuels such as firewood may provide either a net annual source or sink for carbon, depending upon whether the underlying biomass stock is growing or being exhausted. For the purpose of accounting, all biomass fuels are treated as if they are in an annually balanced carbon cycle. From the perspective of the energy consumer, under a carbon tax, delivered prices for coal increase substantially more than those for oil or gas. Delivered prices for electricity increase as well, but the magnitude of the price rise is a function of the electricity generation technologies in place at a given point in time. Since transformation, generation, and transmission losses are unusually substantial, retail electricity costs are highly sensitive to carbon tax rates.

The primary effect of carbon taxes is to change the economics of the fuel choice decisions made by electric utilities and final consumers of energy. All things being equal, when new equipment decisions are made in a competitive market, low-carbon fuels hold an advantage over high-carbon fuels and subsequently gain market share. Greater efficiency in the use of carbon-based fuels is also encouraged. Secondary effects include increased demand for conservation technologies and changing consumption patterns.

This study tests several different levels of carbon taxes and assesses their impact. Later chapters present these results and provide a discussion of their value and limitations.

Policies that impose taxes on global warming potential (GWP) are similar to general carbon taxes in that they increase the delivered fuel prices. Direct combustion of coal (primarily by the industrial sector and cogenerators) and its use as a primary fuel for electricity production are most affected. The effects are similar to those wrought by carbon taxes, except that the GWP tax has a relatively higher impact on coal and natural gas, as compared to a carbon tax, since the production of coal and distribution of natural gas releases methane into the atmosphere.

Regulatory Policies

Regulatory policies tested for this study involve setting efficiency standards for buildings, powerplants and automobiles. All new purchases after mid-1991 are assumed to meet minimum performance requirements.

New commercial buildings and dwellings, regardless of the type of fuel consumed, face stringent energy-related building codes. Insulation measures

to conserve space heating energy, as well as more efficient lighting, appliances and hot water equipment are mandated. In this study, specific levels of conservation investment are chosen to be efficient with regard to the cost per unit reduction in carbon emissions; that is, standards are set to make the cost per tonne of carbon emissions reduction equal across buildings sector energy end uses (see detailed explanation in 7.5.1).

Automobile manufacturers face higher fuel economy standards and must produce more efficient cars and a greater number of alternatively-fueled vehicles. Energy savings and substitution of natural gas- and biomass-fueled vehicles reduce carbon emissions. This policy is implemented by changing the underlying assumptions behind the behavior of the transportation sector.

Two types of electric utility regulations are considered in this study. Powerplant efficiency standards mandate state-of-the-art combustion technology for new fossil fuel-fired generating stations. Utilities must either install the most efficient plant or pay a penalty based upon the projected lifetime CO_2 emissions of the plant. The Reforestation Case incorporates the assumption that utilities must plant enough new trees to offset the carbon emitted over the life of any new generation plant. In this analysis, the cost of these trees varies and increases as the best land is planted.

Combined Fiscal and Regulatory Options

Several options that are considered combine the features of taxation and regulation to mitigate climate change potential. The first involves an alternative form of the carbon and GWP tax policies known as a "deposit-refund" scheme. With this policy, firms that emit carbon may either purchase carbon offsets (e.g., those generated by reforestation programs) or pay the tax. The second combines utility-initiated reforestation with building standards. Here, the most effective supply-side option is combined with one of the highest impact demand-side policies.

Finally, plans to set carbon and GWP-weighted energy-related emission caps are tested. Under these scenarios, individuals may acquire the right to generate emissions. Firms would be allowed to buy and sell carbon offsets (created by planting trees) and emissions rights. In these scenarios, firms could engage in reforestation projects or buy the emissions offsets from the owner of such projects as an alternative to intensifying integrated resource planning, switching fuels or purchasing emission rights.

4.3 MODELS AND THEIR USE IN THIS STUDY FOR PREDICTING CO_2 EMISSIONS

From an analytical perspective, the problem of predicting energy-related CO_2 emissions might be broken down into three related components.

The first involves determining what society wants energy to do (heat water, drive machinery, etc.) and how much of each service is required. In general, when more energy services are desired, both the amount of energy required to provide them and the related emissions grow. The demand for energy services may be increased by an expanding economy or a growing population, for instance, and decreased by slower economic growth or a shift away from energy-intensive industries.

The second component entails identifying which source of primary energy will be used to provide each of these services. Each energy source has its own emissions profile. For example, coal produces almost twice the carbon emissions of natural gas and about 25% more carbon than oil while releasing the same amount of energy. At the other extreme, the direct use of solar and nuclear technologies produces no net carbon emissions at all.

The third component consists of determining the efficiency with which the primary energy sources are used. Efficiency improvements allow smaller quantities of primary fuel to be consumed to provide a given level of service. These improvements result from two separate mechanisms. The

most straightforward of these involves investing in conservation capital. More efficient capital stock allows more frugal consumption of energy. Less obvious, but equally important, is selection of the fuel used to provide services. For instance, consumption of electricity for resistance space heating involves direct combustion of primary fuel and losses due to conversion, generation, and transmission. Direct combustion of fuel at the point of space heat delivery can eliminate much of the inefficiency.

When the demand for energy services, fuel choice, and efficiency are considered together, it is possible to examine the behavior of the energy system given different policy initiatives. One might expect that policies that encourage a highly efficient mix of industry and stimulate conservation investments will result in lower emissions than policies favoring continuation of the status quo. Conversely, higher emissions may be expected from policies that dramatically lower coal prices or promote rapid penetration of electric appliances, unless such appliances are more efficient than those they replace.

Policies that redefine elements of the energy system often have both visible, primary impacts and less obvious secondary effects. For instance, an increase in energy conservation may result in less energy being consumed but, since lower consumption acts to depress prices and increase demand, the long-term savings could be less than originally estimated. Feedback systems, both within and outside of the energy sector, are critical to the process of predicting carbon emissions and the impact of policies designed to control them. Some of these systems and the methods used to model them are discussed later in this chapter. A brief description of the general modeling techniques available appears below.

4.3.1 Modeling Approaches

There are at least two distinct approaches to describing and modeling the energy system. The "top-down" approach begins with a general description of the system and the relationships among its components. The second, the "bottom-up" approach, begins by describing specific technologies and examines the effects of different policies on relatively small parts of the system. Each approach has advantages that may be exploited to conduct meaningful analysis, but each has inherent limitations. The approach adopted for this study seeks to combine the techniques to gain the best characteristics of each.

The bottom-up approach examines the link between technology and emissions, using detailed studies of both existing and emerging technologies (see, for example, Goldemberg et al. 1987). Existing technologies are characterized in terms of efficiency, purchase cost, and cost of operation. They are replaced over time with emerging technologies that are similarly characterized and that will provide more efficient energy consumption. This move toward efficient technology facilitates a reduction in carbon emissions.

The top-down approach deals in broad, economy-wide aggregates, without specifying the technological detail, the specific policy instruments, or calculation of the full costs associated with various emissions reduction policies (see, for example, Lashoff and Tirpak 1991). Policies considered are usually general ones, such as increased energy efficiency, fuel switching, or reforestation.

The strength of the top-down method is its broad, system-wide perspective and its comprehensive scope. The weakness of such analysis is that broad policies of this type are actually implemented with specific policy instruments like regulations, taxes, subsidies, information and education campaigns, and technology R&D spending. These measures differ in their effectiveness, since factors such as costs, public acceptability of the instrument, distribution of impacts, and technological availability are quite variable.

While both the bottom-up and top-down methodologies provide valuable insights into the nature of responses to potential climate change, a next

step to supplement existing analysis is the consistent evaluation of these implementing measures and the integration of technological detail with macroeconomic behavior. To examine the interplay between policy instruments, microeconomic technology, macroeconomic effectiveness in emissions reduction, and cost, a new set of tools was developed.

The approach taken for this study employs the top-down approach, but it does incorporate some features of the bottom-up method. The combination is achieved by using an integrated model of the energy sector that incorporates substantial technological detail. The models, key data elements, and related analytical tools are described here.

Fossil2, the integrating model for this study (and for much of the NES analysis), is a dynamic simulation model of U.S. energy supply and demand designed to project long-term (30- or 40-year) behavior. The model was originally constructed in 1978 for the DOE to analyze policies and provide projections for the National Energy Policy Plans. Because Fossil2 was not designed to answer all the questions in this study, it was supplemented with the DRI Macroeconomic Model, the Edmonds-Reilly Model, and sector-specific models provided by the Energy Information Administration (EIA). These are described in the following sections.

4.4 THE FOSSIL2 MODEL OF THE U.S. ENERGY SYSTEM

Fossil2 can be characterized as a partial equilibrium energy market model.[a] Energy markets clear over time through feedback among prices, demand and production capacity. The model uses the System Dynamics methodology and is written in the PC-DYNAMO computer language. Fossil2 was chosen for this analysis because it includes:

1. technology-based structures that represent the economics and technology characteristics of specific energy supply and demand options
2. the effects of resource depletion on the costs and finding rates of fossil fuels
3. lags or delays in the adjustment of energy supply and demand to prices (due to construction lead times or capital turnover)
4. the effects of feedback loops (or interactive effects on the behavior of energy supply, demand and price)
5. market penetration of new technologies or fuels in the energy marketplace.

The model is used as an integrated analytical framework to incorporate the set of technology and policy assumptions generated by the DOE and its National Laboratories for the 1991/1992 NES. These assumptions combine to establish the Current Policies Case projection of U.S. energy supply, demand, and prices from 1950 to the year 2030. The model allows these assumptions and policies to be varied so that alternative scenarios can be studied and their effectiveness in meeting certain objectives quantified and analyzed.

Conceptually, the model may be divided into energy supply, energy demand, and energy conversion sectors. A diagram of its major components appears in Figure 4.2.

4.4.1 Energy Supply

The energy supply sectors of Fossil2 represent the decisions that lead to the commitment to new energy production capacity, the operation of existing production capacity, and the setting of energy prices for oil, gas, coal and electricity. Energy producers choose to invest in production technologies that maximize the industry's rate of return (or minimize the total cost of production), subject to environmental constraints (for example, SO_2 restrictions or water availability). The sectors track

(a) Further explanations of Fossil2 may be found Appendixes A and D of the *National Energy Strategy: Technical Annex 2: Integrated Analysis Supporting the National Energy Strategy: Methodology, Assumptions and Results* (DOE 1991b).

production capacity and assets and calculate energy prices in accordance with the rules that are generally followed in each industry. Energy markets and demand and production capacity for each fuel type (oil, gas, coal, electricity) determine the price of the fuel at any given time. They change through time as a function of economic growth, oil prices, and past investments in conservation or production technologies. Fuel prices "feed back" to the energy consumers to affect investment decisions for both demand (conservation) technologies and new supply technologies. In the case of electricity markets, prices are regulated at fixed return on investment as allowed by state regulatory commissions. This price feedback structure simulates the dynamic behavior of energy markets as they adjust to varying conditions of supply and demand through time.

Oil and Gas Production

The oil and gas sector of the Fossil2 model projects oil and gas industry investment, production, and imports for petroleum, natural gas, and synthetic fuels. The sector also estimates natural gas prices (world oil prices are exogenously specified). Fossil2 currently considers oil and gas resources only in the continental U.S., Alaska, and in the Gulf of Mexico. Oil and gas industry decisionmaking and behavior are simulated by modeling explicitly, on an aggregate basis, the major structural elements of the domestic oil and gas industry. By doing so, the sector captures the long-term dynamics of fossil fuel discovery, production, and depletion. This dynamic treatment allows it to model the transition from reliance on conventional oil and gas resources to unconventional resource and production technologies.

The modeling of the oil and gas industry is sufficiently flexible to allow testing of several types of policy options and alternative scenarios. For example, the model can be adjusted to assess the impact of improved exploration, drilling, and recovery techniques such as thermal enhanced oil recovery (EOR) and synthetic fuels from coal and tar sands. The model also permits varying oil and gas industry income tax and tax credit policies. The resource base estimates can be modified to reflect either alternative oil and gas resource availability scenarios or expanded access to provinces that are restricted or not considered part of the base resource pool.

Coal Production

The coal production sector simulates the operation of existing coal mining capacity, the creation of new mining capacity, and the setting of long-term delivered prices of coal. The coal mining industry is represented as one aggregate entity with two production methods--surface mining and underground mining. This entity produces coal, collects revenues, pays expenses, sets prices, and makes decisions about how to expand production to meet future growth in demand. The model determines how much investment in new production capacity is necessary to keep capacity utilization within acceptable limits. Industry investment in new production capacity can be constrained if, for some reason, internal funds plus available financing are not able to cover the cost of required capacity. Coal prices are generally cost-based and include components of the average cost of production, return on equity, and a delivery charge, although profits (return on equity) may escalate if production capacity has difficulty keeping up with demand.

Renewable Energy Production

Renewable energy resources are represented as supply-side resources when they are operated or consumed by independent power producers, but as demand-side resources when used in the residential, commercial, and industrial sectors. Utilities employ solar, wind, and biomass sources. Some specific technologies use only renewables (e.g., wind turbines or photovoltaics), while others combine conventional resources [e.g., solar intercooled steam-injected gas turbines (ISTIGs)] to enhance reliability and dispatchability. Residential and commercial consumers have access to biomass, solar, and wind energy to provide electricity and heat. Industrial consumers have access to solar energy to provide process heat.

Because of their unique characteristics, which make an economical functional relationship with other technologies difficult, much of the demand and capacity for renewable energy resources is specified exogenously to Fossil2 and based on more thorough preliminary studies performed for the NES analysis. For example, electricity generation capacity and capacity utilization from renewable energy sources such as wind, hydroelectric, and municipal solid waste have been determined externally. The broader implications of policies concerning these energy sources can then be assessed in relation to the electricity generating sector as a whole. The use of dispersed renewables, such as wood for stoves and alcohol fuels for vehicles, is also exogenous in the current version of Fossil2. An important exception is passive solar heating in buildings, which is treated distinctly as a conservation measure that can be used by consumers in response to increasing energy costs.

4.4.2 Energy Demand

The Fossil2 energy demand sectors are based on the concept that energy consumers act to minimize their energy service costs, which include both the capital costs of energy-using equipment and the cost of fuel. Consumers choose the combination of fuels and end-use technologies that can provide services (such as comfort, light, and industrial steam) with minimum life-cycle costs relative to the discount rate that consumers apply to these purchases. They make a trade-off between normal energy-using equipment and investments in more expensive, energy-efficient equipment (such as efficient furnaces, light bulbs, or boilers), which allow lower fuel expenditures. Consumers can also choose among different technology and fuel combinations, such as gas furnaces or electric heat pumps. The demand sector is divided into four major energy-using sectors: residential, commercial, industry, and transportation. Each of the sectors is further divided into major end-use categories that represent different types of energy service demands.

Residential and Commercial Energy Demand

The residential and commercial sectors are treated separately, but are very similar in structure. The same four end-use service categories are defined in each: space heating, cooling, thermal, and appliances/lighting. The thermal category is a combination of water heating, cooking, and drying. These thermal services provide some type of heat and can be met with a variety of fuels. The appliances/lighting category, on the other hand, represents end-use devices that are electricity-based for which no fuel substitution is possible. Due to the aggregate nature of the model, individual building types are not represented separately, but are combined and expressed as one aggregate energy service demand. Energy service demand for each end-use category is calculated from base year service demand and the macroeconomic inputs in each year (projected building stocks and commercial floor space). Conservation investment decisions are made using a least-cost algorithm based on fuel prices, financial assumptions, the costs and efficiencies of available conservation technologies, and the applicable consumer discount rates. Once conservation investment levels are determined, the costs of providing energy services with each appropriate fuel type are calculated and used to determine fuel market shares. A capital turnover or "vintaging" structure keeps track of the efficiency and fuel-use characteristics of all existing stocks as stock is added, retrofitted, and retired. Finally, use of existing equipment can be modified through short-term behavioral responses such as using less/more energy when the relative price is higher/lower than usual.

Conservation technologies are represented in supply curves that are specific to each end use and fuel type. The curves are constructed from data representing technologies currently available or expected to be available, given current data. The conservation supply curves relate the costs and energy savings associated with customers' options for energy efficiency investments in different end-use

markets. The supply curves in the model reflect the economic construct of diminishing returns in the availability of energy conservation as more of the potential to reduce energy consumption within the current infrastructure is expended.

The model calculates whether a capital investment in energy efficiency is "worth" the savings in fuel costs it provides, given consumers' different investment criteria. Consumers are assumed to invest in conservation up to the point where the fuel savings associated with an efficiency choice are just equal to the additional investment expense. The value of the fuel savings over the lifetime of the measure depends on the "hurdle" or discount rate used. Historical evidence indicates that consumers make energy investments as if they have a relatively short payback period (2 years to 5 years), equivalent to a relatively high discount rate.

The effects of various types of regulatory and fiscal policy instruments on energy use in residential and commercial buildings can be tested using Fossil2. Efficiency standards in the end-use categories described above can be implemented in the model by specifying "floors" on the conservation supply curves. These floors are minimum levels of energy efficiency that must be met at various points in time. Under these standards, consumers are forced to bear the higher costs of the more efficient capital equipment, which are specified by the conservation supply curves. Another policy option that can be modeled is accelerated research and development of energy-using equipment in buildings. Under this option, the conservation supply curves are shifted so that, at each level, energy efficiency is available at a reduced cost. This action encourages consumers to purchase conservation equipment, but does not drastically increase fuel prices. Finally, the effects of fiscal policies such as taxes and tax credits can also be modeled for the buildings sector. Taxes and tax credits respectively raise or lower the capital and fuel costs of using energy, which in turn affect energy investment and fuel use in the model.

Industrial Energy Demand

The structure of the industrial sector is similar in many ways to the residential and commercial buildings sectors. The industrial sector uses the same major components of energy service demands, conservation, market shares, capital turnover, and behavioral responses described for the buildings sector. Four major end-use energy service categories are represented for industry: steam, process heat, machine drive/electrolytic processes, and feedstocks. Steam technology options include cogeneration technologies as well as conventional boilers. Process heat includes direct and indirect heating used in a variety of industrial processes. Machine drive/electrolytic processes is an all-electric category representing motors, pumps, and electrolysis in the chemicals and aluminum industries. Feedstocks are fuels used for non-energy purposes, such as oil for plastics. These service demands are projected as functions of changes in industrial production. Although individual industries are not explicitly represented in the model, the growth in each service demand is based on a projected future mix of industries.

The changing relationship between overall industrial production, output growth, and energy service demands is represented in product/process change "multipliers"--nonlinear functions that change through time. These multipliers attempt to capture the effects of the change in industrial mix among industrial groups, the change of products within these groups, and the major changes in processes used to make these products. The industrial mix changes affect the growth in services because some industries are more energy-intensive than others and may change the type of services required (e.g., increasing machine drive while decreasing steam needs). Changes in products, from primary to finished goods, for example, can have a similar effect.

The policies that can be tested in the industrial sector are similar to those described above for

residential and commercial buildings. Standards and accelerated research and development are set using the conservation supply curves for the industrial energy-consuming equipment. The economic response to financial incentives and taxes in the industrial sector is also considered and can be assessed.

Transportation Energy Demand

Because the transportation system is not modeled in as much detail as the other demand sectors, Fossil2 relies on projections from more detailed external sources to serve as inputs to its transportation sector. These external sources include expert judgment and model results. Models used to inform the Fossil2 Current Policies and NES Actions Cases include the Greene Oak Ridge Transportation Model and the Argonne TEEMS Model. Fossil2 uses information about demand by the type of travel (light-duty vehicles, trucks, air travel, and miscellaneous freight) and by fuel. Only to the extent that fuel prices deviate from the baseline fuel prices do consumers exhibit changes in their demand in Fossil2.

Due to the lack of detail in the structure of the transportation model of Fossil2, the response of this sector to policy options must generally be considered externally. However, the model does allow for modifying market shares of vehicle fuel-types and efficiencies (mpg), so the impact of changes within the transportation sector on the aggregate energy economy can be measured.

4.4.3 Energy Conversion

Energy conversion is treated separately here not only because of its significance in any energy policy, but also because it overlaps the categories of energy suppliers and energy demand. The electricity sector of Fossil2 is the major energy conversion component of the model. In this sector, primary fuels such as coal, oil, gas, and renewables are converted into electricity, which is then distributed to consumers. The modeling of the electricity generation sector represents the decisions that lead to the commitment of new generation capacity, the operation of existing capacity, and the setting of electricity rates. The sector first determines new capacity needs based on forecast load growth. Utility and non-utility generators then compete for a share of this market for new capacity based on a least-cost algorithm. The "winning technologies" are put into construction and are eventually added to existing capacity, where they are dispatched in a least-cost manner to satisfy electricity loads from the demand sector of the model. Finally, all costs associated with system construction and operation are combined under traditional ratemaking rules to determine electricity prices. These prices are then fed back into the demand sectors, helping to determine current and future load growth.

Energy conversion in Fossil2 also occurs in the synfuels industry. Synfuel production (oil from coal, for instance) becomes competitive only at very high fuel prices and is typically a small part of the total energy supply picture.

4.4.4 Emissions Calculations

Fossil2 is used to calculate carbon emissions from the direct combustion of fossil fuel. These calculations combine the primary demand for each fuel with carbon coefficients, which specify the carbon content per Btu for each fuel. Emissions are reported from Fossil2 as metric tonnes of carbon (mtC).

Emissions related to the energy sector that are not associated with fuel combustion include methane emissions from coal mining and leaks associated with natural gas extraction, transmission, and distribution. These are calculated externally to Fossil2 as a function of total primary consumption of these fuels.

Other important emissions include methane from landfills, nitrogen oxides from fossil fuel use, and halogenated hydrocarbons. These, along with reductions in atmospheric carbon associated with the President's America the Beautiful tree planting initiative, are also calculated separately.

All of this information is assembled in an external spreadsheet model. This model analyzes the collective impact on climate change by combining the total emissions of each gas with a GWP factor and assumptions about the relative concentrations of carbon monoxide and carbon dioxide in the emissions stream. The GWP factor measures the radiative forcing associated with each gas relative to CO_2 by factoring in its radiative efficiency and its atmospheric half-life. The GWP reported from the spreadsheet model is expressed in terms of CO_2 equivalent (CO_2e) units.

4.4.5 Model Limitations

No model of a system as complex as the energy economy is without shortcomings, however, and it is important to bear in mind the limitations of the Fossil2 model in describing the behavior of the U.S. energy system.

First, Fossil2 is a national model representing the energy system of the United States alone. The model does estimate imports and exports of energy resources, but it cannot consider the effects of national policies on the behavior of energy systems in the rest of the world. As a result, Fossil2 must rely on outside analyses to baseline its internal predictions of energy trade and world energy prices.

Because it is a model of the energy system and not a general equilibrium model of the full economy, the interactive effects of energy policies with the rest of the economy are not completely realized in Fossil2. As a result, Fossil2 may understate the reaction of the economy to changes in the energy system that result from energy policies or energy price changes.

Although Fossil2's technological detail is one if its strengths as a model, there are situations in which the link to actual technologies can be a limitation as well. As an example, consider the conservation supply curves in the energy end-use sectors of the model. The conservation potential and associated costs in these curves reflect specific energy-consuming technologies that are either currently available are expected to be available (as part of the NES analysis). Because Fossil2 is linked to these technologies, there exists an implicit maximum of energy efficiency potential in the model. In other words, there is no disembodied rate of technological improvement assumed in the model that would allow energy efficiency to increase to levels beyond the capability of the current best available technologies. Therefore, the model may understate the role of future technological advances that may occur in response to higher energy prices; this means the model may overestimate the energy consumption in the end-use sectors under high energy price scenarios.

4.5 THE EDMONDS-REILLY MODEL

The Edmonds-Reilly Model, Version 3.55 (ERM) is used to estimate the long-term impact on global economic and environmental systems of carbon taxes imposed in the United States. Chapter 10 contains a discussion of these findings. The ERM is calibrated to reflect the NES Actions Case, including domestic energy demand and economic growth in the United States. Sectors representing other regions contain ERM reference case assumptions. The remainder of this section discusses the structure and content of the ERM.

The ERM is a well-documented (Edmonds and Reilly 1985; Edmonds et al. 1986), frequently used, long-term model of global energy and greenhouse gas emissions. The model can be thought of as consisting of four parts: supply, demand, energy balance, and greenhouse gas emissions. The first two modules determine the supply of and demand for each of six major primary energy categories in each of nine global regions. The energy balance module ensures model equilibrium in each global fuel market. (Primary electricity is assumed to be untraded; thus, supply and demand balance in each region.) The greenhouse gas emissions module is a set of three post-processors that calculate the energy-related emissions of CO_2, CH_4, and N_2O. The

model is currently configured to develop scenarios for five benchmark years: 2000, 2025, 2050, 2075, and 2100.

Energy demand for each of the six major fuel types is developed for each of the nine regions. Five major exogenous inputs determine energy demand: population; labor productivity; exogenous energy end-use intensity; energy prices; and energy taxes, subsidies, and tariffs.

The model calculates base GNP directly as a product of labor force and labor productivity. An estimate of base GNP for each region is used as both a proxy for the overall level of economic activity and an index of income. The base GNP is, in turn, modified within the model to be consistent with energy-economy interactions. The GNP feedback elasticity is regional, allowing the model to distinguish energy supply-dominant regions such as the Middle East, where energy prices and GNP are positively related, from the rest of the world, where that relationship is inverse.

The exogenous end-use energy intensity improvement parameter is a time-dependent index of energy productivity. It measures the annual rate of growth of energy productivity that would continue independent of such other factors as energy prices and real income changes. In the past, technological progress and other non-price factors have had an important influence on energy use in the manufacturing sector of advanced economies. By including an exogenous end-use energy-intensity improvement parameter, scenarios can be developed that incorporate either continued improvements or technological stagnation assumptions.

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

The energy-demand module performs two functions: it establishes the demand of energy and its services, and it maintains a set of energy flow accounts for each region. Oil and gas are transformed into secondary liquids and gases used either directly in end-use sectors or indirectly as electricity. Hydro, nuclear, electric solar, and fusion energy are accounted for directly as electricity. Non-electric solar energy is included with conservation technologies as a reduction in the demand for marketed fuels.

The four secondary fuels are consumed to produce energy services. In Organization for Economic Cooperation and Development (OECD) regions, energy is consumed by three end-use sectors: residential/commercial, industrial, and transportation. In the remaining regions, final energy is consumed by a single aggregate sector.

The demand for energy services in each region's end-use sector(s) is determined by the cost of providing these services and by the levels of income and population. The mix of secondary fuels used to provide these services is determined by the relative costs of providing these services using each alternative fuel. The demand for fuels to provide electric power is then determined by the relative costs of production, as is the share of oil and gas transformed from coal and biomass.

Energy supply is disaggregated into two categories, renewable and non-renewable. Energy supply from all fossil fuels is related directly to the resource base by grade, the cost of production (both technical and environmental), and the historical production capacity. The introduction of a graded resource base for fossil fuel (and nuclear) supply allows the model to explicitly test the importance of fossil fuel resource constraints, as well as to represent fuels such as shale oil, only small amounts of

which are likely to be available at low cost, but for which large amounts are potentially available at high cost. Nuclear resources are treated as other fuels in that availability is constrained by a resource base when light-water reactors are the dominant producers of power. Breeder reactors, by producing more fuel than they consume, are modeled as an essentially unlimited source of fuel that is available at higher cost.

A rate of technological change is also introduced on the supply side. This rate varies by fuel and is expected to be both higher and less certain for emerging technologies.

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

Recently-produced biomass is treated as if its carbon absorption occurred in the year of release. This approximation can either under- or overestimate actual net annual fluxes, depending on whether the underlying stock of biomass is either expanding or contracting. A more thorough discussion of this assumption and its consequences may be found in Edmonds and Barns (1990).

The ERM is used to project the impact on other countries economics of policies adopted in the United States. It uses energy demand and emissions data produced with Fossil2 and generates information on international trade, energy consumption, and emissions. Chapter 10 provides a more detailed discussion of the international implications of U.S. emissions policy.

4.6 THE DRI MACROECONOMIC MODEL

The Data Resources, Inc. (DRI) Quarterly Macroeconomic Model simulates the operation of the U.S. economic system. For this study, the DRI Model is used to estimate the impact of greenhouse gas mitigation policies on investment, GNP growth, and other aspects of the economy. Fossil2 and the DRI Model are related in that Fossil2 uses GNP growth as an input to generate energy demand, while DRI uses energy demand as an input to generate estimates of economic growth. Together, they provide a focused assessment of changes in the energy sector and a more general estimate of the impact on the rest of the economy.

The DRI Model is an econometric representation of eight interactive sectors of the economy and over one hundred exogenous variables. The interactive sectors deal with: domestic spending (by consumers, businesses, and government), domestic income (wages, profits, interest, and rent), taxes, international transactions, the financial sector, inflation, capital availability, and consumer expectations. These sectors and their interactions are displayed in Figure 4.3. More detailed information about the theory, properties, and coverage of this model is available in DRI (1990).

Conceptually, the DRI Model stems from the long-run growth models of the Tobin, Solow, and Phelps variety, and the short-run dynamics of a post-Keynesian perspective. Monetarist theory and supply-side economics play an important role in the representation of the financial and supply sectors.

The DRI Macroeconomic Model accepts user-specified input to characterize energy use in several of its sectors. These inputs are used to estimate price, supply, and industrial production sector activity. Potential GNP is calculated with a Cobb-Douglas production function that uses labor, capital, energy, and technological progress as inputs. When the DRI Model is used in this study, the energy component is represented by estimates of total demand at full employment obtained

through Fossil2 simulations. Technological progress is defined as a time-dependent variable.

The DRI Model proves particularly useful when examining policies that exert a dramatic effect on energy prices, especially when the price changes are driven by increased taxes. The macroeconomic perspective allows the industrial sector to adjust its investment patterns and the way in which it uses the various means of production. Further, impacts on the financial sector, domestic income and spending, and the international community (elements absent from Fossil2) are characterized and factored into calculations of GNP growth and changes in the rest of the economy.

4.7 ANALYSIS OF MARGINAL, TOTAL, AND AVERAGE COST AND GNP LOSS

The concept of cost is more complex than it initially appears. The first and most important step in the calculation of cost is defining precisely what we mean by the term. From society's perspective, the key question in determining cost is what must be given up to obtain a given emission reduction. One important measure of cost is the value of new, final goods and services that were foregone by society in order to obtain a given emissions reduction. For the purposes of this exercise, we will adopt this as our measure of cost.

Working from this definition, it becomes obvious that the cost of measures to reduce greenhouse gas emissions is linked in an important way to the relationship between energy and the economy. A crude depiction of these interactions is shown in Figure 4.4. An important initial observation is that energy is not a major final product, but is instead used primarily in the production of other new final goods and services. That is, energy is consumed mainly for the value of the energy services that it provides and not for its own sake.

Primary factors of production, principally capital (machines, buildings, vehicles, and technology) and labor, as well as primary mineral resources such as oil and coal, are used by industries to produce new final goods and services. Industry can be grossly aggregated into the energy and non-energy, or materials, sectors. The energy sector uses capital, labor, materials, and some energy to produce final energy products and energy for the materials sector. The materials sector, in turn, uses capital, labor, energy, and some of its own materials to produce net materials, non-energy products (which are used by the energy sector), and new, final, non-energy goods and services. The idea of energy as an intermediate good whose technology affects GNP is not new. Researchers such as Hudson and Jorgenson (1974), Hogan and Manne (1977), and Reister and Edmonds (1977) developed these ideas more than a decade ago.

We can also use Figure 4.4 to illustrate several frequently used measures of the cost of carbon emissions reduction and to suggest a methodology by which estimates of losses in the value of new final goods and services might be computed. We identify four different costs:

- Cost 1: Unit Cost
- Cost 2: Technology Cost
- Cost 3: Energy System Cost
- Cost 4: GNP Cost.

The system boundary expands as one moves down the cost list, and the confidence one has in the calculated cost results declines.

Cost 1, Unit Cost, is the simplest to measure. It measures the cost as faced directly by the purchaser. The direct effect of energy costs per $100 fuel carbon tax applied in the United States circa 1987, in 1989 constant dollars, is given in Table 4.1 (from Fossil2 model with Current Policy Base Case assumptions).

Cost 2, Technology Cost, uses a somewhat broader system boundary to measure cost than does Cost 1. Technology cost is the cost of emissions

Table 4.1. Fuel Price Changes per $100 Carbon Tax

Fuel	Base Cost	Added Cost	% Added Cost
Crude oil ($/bbl)	$16.01	$12.19	73
Gasoline ($/gal)	$0.98	$0.26	27
Heating oil, distillate ($/gal)	$0.89	$0.29	33
Wellhead natural gas ($/tcf)	$1.81	$1.49	82
Residential natural gas ($/tcf)	$5.87	$1.50	25
Minemouth coal ($/short T)	$23.02	$55.33	240
Utility coal ($/short T)	$33.51	$55.33	165
Electricity (c/kwh)	6.5c	1.76c	27

reduction at the level of energy services (for example, the cost of reducing carbon emissions by one metric tonne of carbon while producing one passenger kilometer via passenger automobile). The analysis of the technology cost of emissions reduction requires assumptions regarding fixed costs of energy inputs and product prices. Two alternative technologies that produce the same service are compared. The resulting differential yields the technology cost. Technology costs can be either positive or negative. As mentioned earlier, this is sometimes referred to as the bottom-up approach. In many cases, technologies can be identified that produce a service at costs lower than technologies presently in use. See, for example, Goldemberg et al. (1987). This has lead to the proposition that the cost of some emissions reductions might be negative.

The assertion of negative costs raises several tough questions. For example, if the technology is so good, why has the market not adopted it? There are numerous reasons why technologies do not penetrate. It takes time for capital stocks to turn over, and there are limits on the rate of expansion of relevant systems. Information is imperfect, and it takes time to establish the cost-effectiveness of the technology and for this information to become broadly available. In addition, consumer preferences and tastes are a major determinant in technology penetration. While the technology cost may be valid for the first unit produced, the introduction of the technology on a large scale would affect the assumed constant prices of energy inputs and the price of the finished product. All of the preceding represent frictions in the system that would slow the introduction of a new technology, but not halt it. Negative cost technology may also not reflect important non-monetary real costs. Technologies may not be perfect substitutes for one another. For example, fluorescent light may be qualitatively different than incandescent light. But the market system may also be flawed. For example, access to capital may be hampered for small investors. Energy may not be priced at marginal cost. And the profit potential of energy-saving technologies may simply be below the size threshold of decisionmakers. We address this issue more fully in Chapter 7.

Cost 3, Energy System Cost, computes costs in terms of the entire energy system, including energy production, transformation, transport, and use. All energy system costs are variable. The prices (unit costs) of all energy commodities are determined within the system analysis. Energy System Cost differs from Cost 4, GNP Cost, by virtue of the fact that, while energy system costs are all variable, non-energy system costs such as wage rates and interest rates are assumed to be fixed. It differs from Cost 2, Technology Cost, in that total energy service demand is not fixed. Substitution can occur between various energy services and between energy services and other goods and services. For example, in the computation of the cost of reducing carbon emissions by one metric tonne of carbon per year, not only can various passenger automobiles be substituted for each other in the provision of personal transport services, but public transportation and ride-sharing can also be substituted for private transportation services. In addition, changes in the total demand for personal transport services can occur.

One can calculate the cost of emissions reduction for the energy system in several ways. Two alternative paradigms are the optimization and behavioral approaches.

As the name implies, the optimization approach identifies the best possible energy system and its

evolution over time within constraints. Optimization models can be used to directly compute the minimum cost of a reduction in fossil fuel carbon (or other undesired) emissions. The method requires the construction of two scenarios for comparison. The first is the reference scenario. The reference scenario provides a constrained optimum energy system trajectory when carbon emissions are not a concern. However, the reference scenario does include constraints on the energy system such as resource availability or constraints on the rate of penetration of new technologies. The second scenario differs from the first in that an additional constraint is placed on fossil fuel carbon emissions. The cost of the emission reduction can be computed as the difference between the two scenarios.

The behavioral approach, on the other hand, uses a model that attempts to reflect the way that the energy system works in fact. The behavioral model seeks to mimic energy system behavior rather than to optimize it. The Fossil2, the DRI Quarterly, and the Edmonds-Reilly Models are behavioral models. These models do not provide direct information on the cost to the energy system of invoking alternative policy instruments. Such information must be extracted by inference. In Chapters 6 and 7, specific methods for inferring energy system costs are developed for specific policy instruments under consideration.

While these two approaches would appear, on the surface, to be extremely different in their implications for energy system scenarios, they are quite close in implementation. There are two reasons for this. First, economic theory suggests that a competitive system and an optimized system should behave similarly. Second, the constraints imposed on optimization models reflect both technology and behavior. Constraints on the rate of penetration of new technologies are an example of a constraint that reflects behavior. In practice, these models produce results that are comparable.

Cost 4, GNP Cost, is the full general equilibrium cost of an emissions reduction. This general equilibrium cost is the total cost to society of an emissions reduction. It includes all direct and indirect costs of reducing fossil fuel carbon emissions, including effects on energy and non-energy system markets. The difference between Cost 4 and Cost 3 is that feedback effects of substitutions between labor and capital, and energy services and other goods and services, reflected through prices, are included.

Because, under regular circumstances, the marginal product of energy declines as more energy is utilized, other things being equal, and the marginal cost rises as more energy is produced, other things being equal, the loss in GNP will not exceed the value of the carbon emissions reduction. This says nothing more than that the economy will first undertake those things that reduce carbon emissions most cheaply. Society will continue to take measures to reduce carbon emissions up to the point where the GNP loss from the last tonne of carbon is equal to the tax rate. We note that this value is different from the tax revenue, which is simply the tax rate multiplied by the level of emissions.

This suggests that one way to compute the GNP loss is to calculate the relationship between the tax rate and the reduction in CO_2 emissions relative to the NES Actions Case for any given year and integrate.[a] This integral yields a total cost of zero in the NES Actions Case, as the tax rate is zero. (See Appendix J for an explanation of the cost calculation methodology used in this study.)

Inherent to the calculation of costs in the above procedure is the presumption that the NES Actions Case with its associated institutional framework is a cost minimum trajectory, and that despite the fact that there may be individual technologies that could be introduced at lower cost than those actually adopted in the reference scenario, the failure to adopt these technologies represents either the existence of some adjustment costs, localized deviation

(a) This relationship is the net marginal cost of carbon emissions reduction schedule, (MPEy - MPLy/MPLf)/α. Integrating over the values between CO_2^t and CO_2^* will yield the value of the lost GNP.

from average conditions, or an artifact of the preceding history of energy prices, policies, and expectations. As discussed above, the correction of a market failure can provide a mechanism for reducing emissions and increasing output simultaneously. The potential gains from such changes are limited. Once corrected, a market failure is no longer a source of emissions reduction potential.[a]

An interesting problem arises in models that are driven by the GNP. If there is a non-trivial loss in GNP, then this effect needs to be fed back to the energy system. In many models, this is done via an energy-GNP feedback elasticity. This is the case with the Edmonds-Reilly (1985) Model and the DOE's Fossil2 model, for example. Such models then produce a revised GNP. But the GNP feedback elasticity is not derived from a production function relationship, and there is nothing in these models that would keep the reduction in GNP consistent with the theoretically-correct cost generated by mapping taxes into carbon emission and integrating to obtain total cost.

In addition, energy system models are predicated on the assumption that the prices of non-energy system inputs, relative to energy prices, are determined outside the model. This is reasonable if the energy system has little impact on the rest of the economy, but may no longer be valid if the energy system begins to make non-trivial demands on other parts of the economy such as capital markets.

The way in which costs are reported can lead to confusion. There are three related concepts that are important: total, marginal, and average cost.

- Total cost is the entire cost, calculated at some period in time, associated with an emissions reduction policy.
- Average cost is the total cost of the policy per unit emission reduction; that is, total cost divided by the total reduction.
- The marginal cost is the cost of the last unit of emission reduction.

If total cost is to be minimized, each unit of emission reduction should be accomplished at minimum cost. That is, the least expensive options should always be executed before more expensive options. If this approach is taken, then the last unit of emission reduction is always the most expensive, for the simple reason that all of the less costly alternatives have already been undertaken. It is therefore also true that marginal costs must always exceed average costs. Finally, the total cost and the tax revenue are different. Tax revenue is the tax rate multiplied by the carbon emissions. It is the value of the unreduced emissions.[b] Total cost, on the other hand, is the value of foregone resources consumed in reducing emissions.

In the analysis of costs, we have sought to calculate estimates of reductions in the dollar value of new, final goods and services produced in a given year (GNP). We have used the tools of economic analysis to construct these estimates. Reductions, relative to the NES Actions Case, are reported in the year in which they occur. There are obvious differences in the burden of costs incurred in the present and in the future. The discount rate is a tool frequently used to enable a comparison between costs incurred at different points in time, but great uncertainty exists as to the proper rate of comparison. Problems in determining the correct rate occur for a variety of reasons, including the fact that the most important beneficiaries of possible changes in the rate of emissions of greenhouse gases will be future generations, while costs may be incurred to a greater extent by those presently alive (see, for example, NAS 1991). Rather than attempt to deal with uncertainties associated with comparing costs across time, we have chosen to report

(a) It should also be pointed out that not all changes to the institutional structure of an economy yield improvements. The history of U.S. energy policy is filled with examples of changes that were later found to be ill-advised.

(b) That is, it is the price-weighted emissions, which is, of course, different from the consumer and producer surplus derived from those emissions.

costs in the year in which they occur only. We provide perspective by comparing these costs to the then-current GNP.

Finally, it is important to recall that the analysis conducted here makes no attempt to assess the potential benefits of greenhouse gas emissions reductions.

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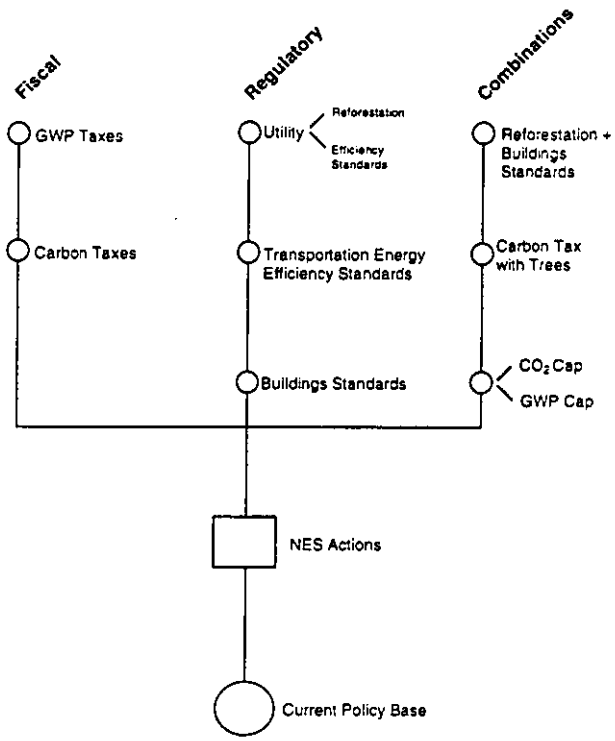

Figure 4.1. Conceptual Framework

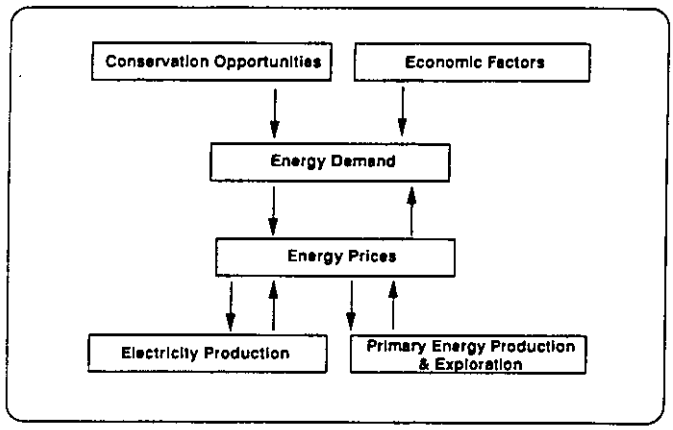

Figure 4.2. Fossil2 Structure

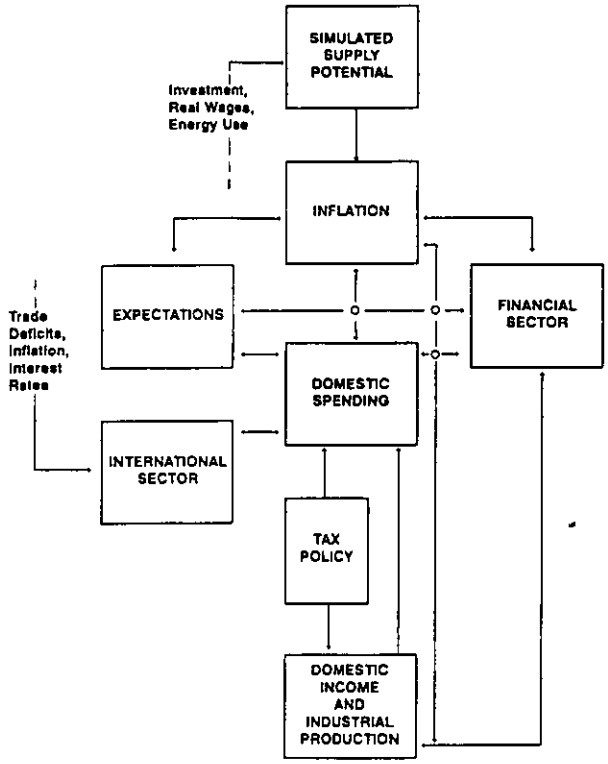

Figure 4.3. Overview of the DRI/McGraw-Hill Model

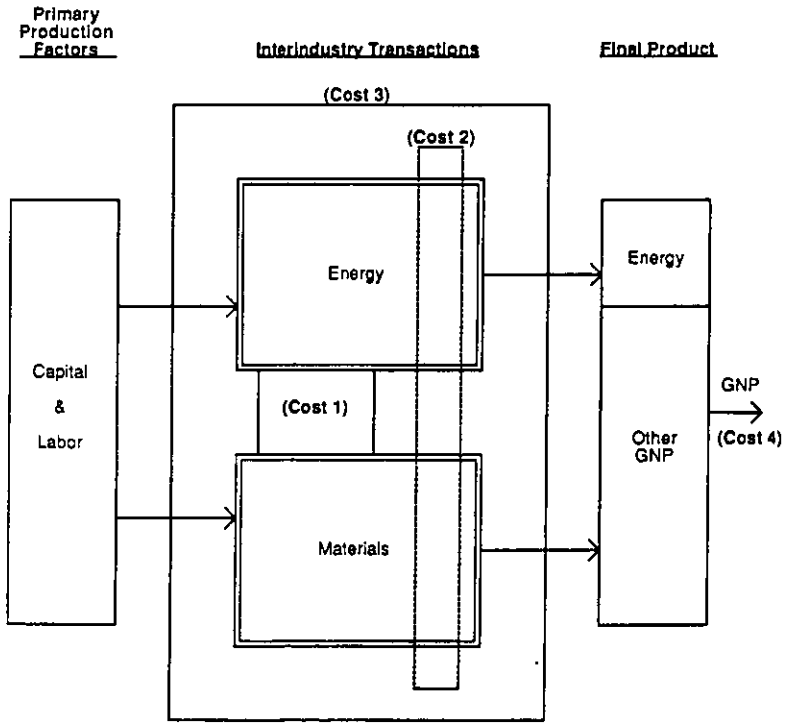

Figure 4.4. Energy-Economy Interactions

5.0 CURRENT POLICY BASE AND NES ACTIONS

5.1 INTRODUCTION

This report analyzes how policy options beyond those contained within the NES might further reduce potential future U.S. greenhouse gas emissions and at what cost. The analysis of the NES Actions and their impact on GHG emissions thus becomes an important point of departure.

It is not our intent in this study to make exact predictions about the future. Our objective is, rather, to provide useful analyses applicable to determining the potential potency of various policy instruments to affect U.S. emissions of greenhouse gases. We provide numerical results for the different policies analyzed to illustrate the projected effects of these policies in a concise and consistent format.

Because of the uncertainty involved in studying the future, even the definition of a reference baseline becomes a fundamental problem. In other words, substantial difficulty exists in merely determining the starting point against which the effectiveness of additional policies are to be measured.

Several alternative approaches to this problem are frequently used. One approach is to construct a number of possible future scenarios without any explicit policy to alter future greenhouse gas emissions. These cases could be taken to bracket the future of the U.S. energy system without greenhouse policy intervention. There are two problems with this approach. First, it is impossible to bracket all important energy variables with a small number of cases. Also, this approach needlessly muddles the analysis of policy instruments by multiplying the number of cases to be analyzed by the number of reference cases.

In the analysis that follows, we use the results of the NES Actions Case as our point of reference. The NES Actions Case results are not intended as a strict forecast. The future will undoubtedly be somewhat different. For this analysis to be useful, however, we do not need to forecast the future. What we need is a simple, clear, consistent statement of a plausible evolution of the U.S. energy and economic system against which to test the consequences of potential policy instruments. We have used the NES Actions result as our reference case to maintain consistency with other Administration and DOE analyses.

In acknowledgement of the uncertainty in defining a baseline or reference scenario, we have performed some limited sensitivity analyses on the costs and effectiveness of greenhouse policies with the NES Actions baseline modified. One of the NES Actions is nuclear regulatory reform, which is expected to result in new investments in nuclear electric capacity. As a sensitivity analysis, we have studied a modified NES Actions scenario in which the expected increase in nuclear capacity is not realized. This is just one of several potential sensitivity analyses that could be undertaken, but it serves to illustrate in general the effect of uncertainty on the results.

The preceding chapter discussed the modeling structure employed to perform the analysis of alternative policy instruments and bundles on the energy system and the emission of greenhouse gases. This chapter discusses the assumptions and results of the Current Policies (base reference) Case and the NES Actions Case. We begin by discussing in Section 5.2 the assumptions that underpin the Current Policies Case. These assumptions form the point of reference from which all other cases originate. Section 5.3 discusses the implications of these assumptions for energy prices, consumption, production, energy dependence, and greenhouse gas emissions. Sections 5.4 and 5.5 describe the NES Actions Case assumptions, implications, and results. Section 5.6 discusses the assumptions and results of the sensitivity analysis employed in both this and subsequent chapters.

5.2 CURRENT POLICIES CASE ASSUMPTIONS

Three general assumptions guided the development of the Current Policies Case. The first is that there are no major changes in current laws and energy policies as of December 1990. Second, there are no major changes in the structure of the U.S. economy and world energy markets. Third, new technologies currently under research or development are allowed to penetrate the market; technologies that are only speculative in nature are excluded. The spirit of this Current Policies Case is a "continuation of current trends" case.

5.2.1 World Oil Price and Macroeconomic Assumptions

World Oil Price Assumptions

The world oil price assumptions are adapted from the EIA Oil Market Simulation Model (DOE/EIA 1990a). The Current Policies Case price path is presented in Table 5.1. This trend is the middle EIA oil price path modified slightly due to the slightly higher GNP growth rates of 1990 to 1995 assumed in this study. The EIA midpath is derived by considering economic and energy-market trends, as well as alternative estimates of world energy resources.

Table 5.1. World Oil Prices (1989$/barrel)

Year	Reference
1990	16.85
1995	20.38
2000	28.11
2005	33.56
2010	37.74
2015	40.81
2020	43.25
2025	45.51
2030	47.09

Sources: DOE/EIA 1990a; DOE/EIA, Office of Energy Markets and End Use. (Current Policy base case track is EIA midcase modified by final strategy economic growth assumptions.)

Macroeconomic Assumptions

Macroeconomic assumptions concerning economic growth, labor productivity, and labor force growth are taken from the 1990 *Economic Report to the President* (Council of Economic Advisors 1990); other macroeconomic assumptions are from the EIA-based DRI Macroeconomic Model. The U.S. economy, as measured by real GNP, is assumed to grow at an average rate of 3.0% per year between 1990 and 2000, 2.7% per year from 2000 through 2010, and only 1.8% per year from 2010 to 2030 as the population growth rate slows.

Long-term economic growth is fundamentally determined by the rate of growth of the primary factors of production, labor and capital, and changes in factor productivity. The lower future GNP growth rate assumptions reflect lower assumed rates of growth of labor and capital relative to those of the last several decades. GNP growth is approximately one-half of one percentage point down from the 1970s and 1980s, and over a full percentage point lower than the growth rates achieved in the 1960s. A decline in labor force growth rate is a major contributor to the anticipated slowdown in the growth rate of the potential output of the economy. A rise in the capital stock formation rate, which enhances labor productivity, is expected to partially offset adverse demographic trends.

The GNP and other macroeconomic assumptions are listed in Table 5.2.

5.2.2 Energy Demand Assumptions

The Fossil2 Energy Model has four demand sectors: residential, commercial, industrial, and transportation. Each sector is organized by end-use categories. The residential and commercial sectors have similar structures and assumptions and are therefore discussed together.

Residential and Commercial Sectors

The residential and commercial sectors of the Fossil2 Model consume five fuel types of energy

Table 5.2. Macroeconomic Assumptions

Year	GNP (billion 1989$)	Population (million)	Occupied Housing Stock (million)	Commercial Floor Space (bil/ft^2)	Industrial Production Index (1985=100)	Disposable Income (Billion 1989$)
1990	5,331	251	93.9	62.9	107.6	3,818
1995	6,219	261	99.5	69.4	129.8	4,110
2000	7,178	269	105.5	79.6	153.0	4,633
2005	8,262	276	110.9	89.2	178.2	5,273
2010	9,372	283	116.1	98.1	204.2	5,890
2015	10,382	289	120.9	106.7	228.1	6,501
2020	11,365	294	125.1	115.3	252.0	7,114
2025	12,365	298	128.6	123.5	272.5	7,736
2030	13,383	301	131.7	131.6	292.2	8,378
Macroeconomic Assumptions Growth Rates (% per Year)						
1990-1995	3.1%	0.8%	1.2%	2.0%	2.6%	1.5%
1995-2000	2.9%	0.6%	1.2%	2.8%	3.3%	2.4%
2000-2005	2.9%	0.5%	1.0%	2.3%	3.1%	2.6%
2005-2010	2.6%	0.5%	0.9%	1.9%	2.8%	2.2%
2010-2015	2.1%	0.4%	0.8%	1.7%	2.2%	2.0%
2015-2020	1.8%	0.3%	0.7%	1.6%	2.0%	1.8%
2020-2025	1.7%	0.3%	0.6%	1.4%	1.6%	1.7%
2025-2030	1.6%	0.2%	0.5%	1.3%	1.4%	1.6%

Sources: Economic growth rates: CEA 1990. Other: DOE/EIA, Office of Energy Markets and End Use.

(liquids, natural gas, coal, electricity, and renewable) in four end-use categories (space heating, space cooling, thermal, and lighting/appliances). Major assumptions for these sectors can be organized into two groups: building stock characteristics and financial parameters.

Building Stock Assumptions. The buildings sectors assumes that, to be fully functional, each housing unit or thousand square feet of commercial building space requires a mixture of end-use service demands. The service demand concept assumes that people do not want to consume energy directly, but instead want the services that energy provides--heat, warmth, hot water, light, etc. These service demands are grouped into four end-use categories: space heating, cooling, thermal, and appliances/lighting. The thermal end-use category includes water heating and appliances that produce heat for activities such as hot water heating, clothes drying, and cooking. The lighting/appliances end-use category includes lighting and all non-thermal appliances (refrigerators, freezers, television sets, clothes washers, radios, etc).

The most important input to the buildings sectors is the forecast of future building stock, since growth in fuel use is largely a function of growth in service demand. The forecast of future residential and commercial building stock are given in Table 5.2. It is assumed that each housing unit or thousand square feet of commercial building space requires, on average, a certain amount of space heating, space cooling, thermal use, and appliance use. A capital stock turnover structure in the model keeps track of additions and retirements of buildings and appliances by fuel type. Important stock assumptions include appliance and air conditioning saturations (Table 5.3), and capital lifetimes (Table 5.4). Energy consumption data for each end-use category are calculated based

Table 5.3. Appliance and Air Conditioning Saturation Assumptions

	Residential Sector			Commercial Sector	
Year	Appliances/Homes (1985=1.00)	Homes with AC (fraction)	Thermal Appliances/Homes (1985=1.00)	Appliances/1000 ft^2 (1985=1.00)	Facilities with AC (fraction)
1990	1.10	0.62	1.12	1.01	0.66
2000	1.63	0.62	1.31	1.04	0.70
2010	1.79	0.62	1.41	1.08	0.74
2020	1.80	0.62	1.47	1.08	0.76
2030	1.81	0.62	1.56	1.08	0.76

Sources: DOE/EIA 1990b; DOE/EIA, Office of Energy Markets and End Use.

Table 5.4. Capital Lifetime Assumptions

Sector and End-Use Category	Capital Lifetime (years)
Residential Sector:	
Space heating	20
Space cooling	15
Thermal	10
Lighting and appliances	10
Commercial Sector:	
Space heating	20
Space cooling	15
Thermal	10
Lighting and appliances	10

Note: Buildings are assumed to have 50-year lives.

Sources: Residential, commercial, heating: DOE/EIA 1990b, DOE/EIA, Office of Energy Markets and End Use. Other commercial: AES 1986.

on stocks, energy prices, conservation investments and behavioral adjustments.

Financial/Behavioral Assumptions. The end-use demand categories each have several different technologies, using different fuels, that can satisfy demand for energy services. The relative amounts of each technology that are added each year are determined by a market-share algorithm based on the concept of energy service cost. The energy service cost of a technology measures the cost/mBtu of supplying energy services using that technology. It includes a capital cost component and a fuel cost component. The capital cost component includes the first cost of the technology, the additional cost of any conservation measures purchased, the capital recovery factor, and the base service demand. The fuel cost component includes the cost of the fuel, the savings derived from any conservation measures purchased, and the efficiency of the technology. It is assumed that the lowest cost option will be selected, so the market share equation computes the probability that each technology will be less expensive than all others. These market shares are used to determine what fuels and technologies the new building stock will use to satisfy the new service demands.

Consumer investment in conservation technologies is based on the fuel cost portion of the energy service cost. It is assumed that consumers will invest in conservation measures that are less expensive than the fuel cost on an equivalent annual cost basis. Such investment is sometimes referred to as price-induced conservation. Conservation measures can be added either when the building is first built or retrofitted

later, and the cost of the measures is correspondingly different. The effect of conservation is to satisfy energy service demand at a lower fuel use (in other words, to increase the total efficiency of the technologies).

Conservation investment for each end use is calculated on the basis of fuel prices, the consumer discount rate, existing stock efficiencies, and characteristics of new conservation technologies. Fuel prices are generated within the model. Current Policies Case fuel prices are displayed in Table 5.5 for selected years.

Consumer discount rates for each end use were given in Table 5.4. Conservation characteristics for each end use are represented by two curves in the model, the conservation marginal cost curve and the conservation total cost curve. The conservation marginal cost curves represent the total savings from technology measures that fall below a given marginal capital cost (in $/mBtu); the conservation total cost curves represent the total cost of these measures on a unit basis (per home or 1000 ft^2 of commercial space). As additional conservation investments are made in an end-use category, additional conservation measures are purchased. Because the cost of measures is specific to building types, measures are given for different buildings.

Short-term level-of-use adjustments are made using an assumed relationship between the total fuel bill and disposable income. Short-term level-of-use drops as the fuel bill rises relative to disposable income, and rises as the fuel bill drops relative to disposable income, through a behavioral factors demand multiplier curve. This curve adjusts level-of-use by as much as 20% up or down, although separate curves are input for each end-use category. The disposable income assumptions are given in Table 5.2.

Small amounts of dispersed (i.e., not grid-connected) renewable energy consumption are assumed in the residential and commercial sectors. Space heat wood fuel, wind and photovoltaic use are given Table 5.6. With the exception of residential wood, this market is assumed to remain small.

Industrial Sector

The industrial sector of the Fossil2 Model consumes five fuels (liquids, natural gas, coal, electricity, and renewable). Due to the aggregate nature of the Fossil2 Model, consumption is projected across five end-use categories (steam, process heat, feedstocks, machine drive/electrolytic processes, and cogeneration) rather than by SIC category. Major assumptions for this sector can be organized into three groups:

Table 5.5. Residential and Commercial Fuel Prices
(1989$/mBtu)

	Residential Sector			Commercial Sector		
Year	Distillate	Natural Gas	Electricity	Distillate	Natural Gas	Electricity
1990	6.42	5.69	22.01	4.89	4.88	20.33
2000	8.52	7.72	22.64	7.12	6.84	20.92
2010	10.30	9.35	24.50	9.03	8.41	22.63
2020	11.32	10.77	25.23	10.12	9.78	23.31
2030	12.03	11.73	25.80	10.89	10.72	23.83

Source: NES Current Policy Base Case.

Table 5.6. Buildings Renewable Consumption Assumptions

	Residential Sector			Commercial Sector		
Year	Wood (quads)	Wind (quads)	PV (quads)	Wood (quads)	Wind (quads)	PV (quads)
1990	0.9	0.00	0.00	0.03	0.00	0.00
2000	1.1	0.01	0.00	0.05	0.01	0.00
2010	1.4	0.02	0.00	0.08	0.02	0.00
2020	1.6	0.03	0.01	0.12	0.03	0.01
2030	1.7	0.04	0.05	0.16	0.04	0.05

Sources: DOE, Office of Conservation and Renewable Energy.

industrial production assumptions, capital stock characteristics and financial parameters.

Industrial Production Assumptions

Growth in industrial production is the underlying cause of increased energy use in industry. The total industrial production assumptions were given in Table 5.2. As evidenced by the 1980s, however, consumption need not increase as rapidly as output, due to the effects of energy management, conservation, changes in manufacturing processes and materials, and shifts in the industrial mix. Energy management and conservation investments are price-induced and treated through behavioral response and conservation supply curves. Changes in processes, materials, products, and mix are addressed through industrial product/process change curves.

Three factors are captured in the industrial product/process change curves. The first factor is the mix of industrial output. Because energy intensity varies by industry, relative growth among different industries can significantly affect total consumption. For instance, the trend of faster growth in light industries is expected to continue, resulting in less total energy consumption per unit of output. The second factor is the shift in product mix within each industry. Energy intensity can vary by product, so changes in product mix can also affect total consumption. An example is the continuing trend in the chemical industry away from basic chemicals and toward more refined chemical products, which will reduce total energy consumption. The third factor is changes in industrial processes. New processes installed to raise productivity can often substantially reduce energy consumption. An example is the shift from open hearth furnaces to mini-mills in the steel industry. The industrial product/process change curves used in the Fossil2 Model are adapted from the ISTUM-2 Industrial Energy Model, based on results of the Energy Modeling Forum work on industrial energy demand (EMF 8). They are updated biannually by Applied Energy Services, Inc., based on macroeconomic inputs from Data Resources, Inc. The current assumptions are given in Table 5.7. Feedstocks are treated exogenously in the industrial sector and therefore do not have a product/process change multiplier.

Capital Stock Assumptions

As stated earlier, the industrial sector has five basic end uses: steam, process heat, machine drive/electrolytic processes, cogeneration, and feedstocks. The steam service demand sector represents the demand for process steam, which may be satisfied by boilers or by cogeneration. Other heat represents direct heat applications in specific industrial processes such as glassmaking, calcining, petroleum refining, and chemical refining. The machine drive/electrolytic processes end-use category includes most industrial electricity consumption. Feedstocks are also represented to complete the energy accounting.

Table 5.7. Industrial Product/Process Change Multipliers

Year	Steam/Cogeneration (1980=1.00)	Machine Drive/ Electrolytic (1980=1.00)	Process Heat (1980=1.00)
1990	0.60	1.00	0.81
2000	0.53	1.04	0.81
2010	0.50	1.11	0.78
2020	0.50	1.15	0.69
2030	0.50	1.16	0.69

Sources: AES 1986; updated annually using DRI industrial forecasts.

Feedstocks demand, however, is an exogenous assumption based on the detailed industrial macroeconomic inputs. Industrial feedstocks assumptions are given in Table 5.8. Capital stock turnover structures in the industrial sector calculate fuel use and average efficiencies over time by adding and retiring stock. As old, inefficient stock is replaced by new efficient stock, overall energy efficiency increases. Stock lifetimes are given in Table 5.4.

Financial/Behavioral Assumptions

The energy service cost is used in the industrial sector to compute technology market shares. Electricity that is cogenerated is assumed to be sold to utilities, and these technologies are given an electricity sales credit when their fuel costs are calculated. Electricity may also be generated in the machine drive/electrolytic service demand sector, but this electricity is assumed to be used internally, and the cost of generation is compared to the industrial electricity price. Conservation investment and short-term level-of-use adjustments are made the same way as for buildings, but the short-term adjustments are referred to as "energy management" in the industrial sector, and the fuel bill is compared to the industrial gross domestic product.

Conservation investment for each end use is calculated in the industrial sector on the basis of fuel prices, the consumer discount rate, existing stock efficiencies, and characteristics of new conservation technologies. Fuel prices are generated within the model and are given in Table 5.10. Consumer discount rates for each end use are given in Table 5.9. Conservation characteristics for each end use are represented by the conservation marginal cost curve and the conservation total cost curve. The conservation marginal cost curves represent the total savings from technology measures that fall below a given marginal capital cost (in $/mBtu); the conservation total cost curves represent the total cost per home of installing these measures on a unit basis.

The industrial conservation marginal cost curves represent the additional efficiency gains available as of 1988. As with the residential and commercial curves, each curve is an aggregation of individual conservation measures and end-use technologies ordered by marginal capital cost in $/mBtu of savings. As additional conservation investments are made in an end-use category, additional conservation measures

Table 5.8. Industrial Feedstocks Assumptions

Year	Asphalt (mbd)	Liquids Other (mbd)	Total	Gases (TCF)	Met.Coal (MST)
1990	0.5	1.9	2.4	1.1	46
2000	0.5	2.0	2.6	1.1	45
2010	0.6	2.2	2.8	1.1	40
2020	0.6	2.4	3.0	1.1	35
2030	0.6	2.6	3.2	1.0	25

Sources: DOE/EIA 1990b; DOE/EIA, Office of Energy Markets and End Use.

Table 5.9. Discount Rate Assumptions

Sector and End-Use Category	Consumer Discount Rate
Residential sector:	
Space heating	0.20
Space cooling	0.25
Thermal	0.25
Lighting and appliances	0.25
Commercial sector:	
Space heating	0.25
Space cooling	0.35
Thermal	0.60
Lighting and appliances	0.60

Sources: Residential, commercial, heating: DOE/EIA 1990b, DOE/EIA, Office of Energy Markets and End Use. Other commercial: AES 1986.

Table 5.10. Industrial Fuel Prices (1989$/mBtu)

Year	Distillate	Residual Fuel	Natural Gas	Steam Coal	Electricity
1990	4.43	2.77	3.04	1.54	14.00
2000	6.59	4.59	4.97	1.72	14.36
2010	8.38	6.10	6.55	1.93	15.57
2020	9.45	7.00	7.95	2.18	16.04
2030	10.25	7.67	8.86	2.54	16.40

Source: NES Current Policy Base Case.

are purchased. Each curve represents a large number of measures for many industries; therefore, specific measures are not listed.

The primary use of renewable energy in the industrial sector is boiler fuel to produce steam. Dispersed (i.e., not grid-connected) renewable energy consumption also occurs.

Transportation Sector

The transportation sector of the Fossil2 Model consumes five fuels (motor gasoline; diesel fuel; jet fuel; residual fuel; and natural gas, electricity, and alcohol fuels) in four travel modes (personal, freight, air, and other). Consumption in each mode is driven by fuel prices, the price elasticity of travel, and assumptions about base travel demand and fleet efficiencies.

Highway Travel Assumptions

Personal and freight travel depends travel demand, fleet efficiency and fuel prices. Demand in vehicle-miles travelled (VMT) through 2010 is calculated from base VMT projections supplied by a more detailed transportation model (DOE/EIA 1990b). This base demand is adjusted slightly, based on fuel prices and the elasticity assumed. After 2010, the rate of growth in travel is estimated to decline as population and labor growth rates decline. In addition, highway saturation effects are assumed to cause the per capita highway travel demand growth rate to fall to zero by 2030. Consumption is calculated as the travel demand over the vehicle fleet efficiency. Efficiency assumptions are taken from ORNL and are based on EIA growth rates after 2010 (DOE/EIA 1990b). Highway travel assumptions are given in Table 5.11. Fuel prices, based on reference world oil price assumptions, refinery markups, and delivery charges, are given in Table 5.12.

The consumption of alcohol fuels in personal travel is projected to continue at the current levels used in gasoline additives through 2010. Consumption rises modestly thereafter, absent major policy intervention, reaching 0.5 quads by 2030. These results are based on staff estimates from the DOE Office of Conservation and Renewable Energy.

Air Travel Assumptions

Like highway travel, air travel depends on travel demand, fleet efficiency and fuel prices. Current Policies Case jet fuel prices are given in Table 5.12. Travel demand in airline seat-miles is calculated from base travel assumptions using a constant 61% average load factor. These assumptions are taken from the EIA PC-AEO Transportation Model. This base demand is adjusted slightly, based on fuel prices and the elasticity assumed. Consumption is calculated as the travel demand over the airline fleet efficiency. Efficiency assumptions in mBtu/seat-mile are taken from EIA. Travel and efficiency assumptions are given in Table 5.13.

5.2.3 Energy Supply Assumptions

The Fossil2 Energy Model has four major supply sectors: oil, gas, coal, and electricity. Renewables that produce electricity are incorporated in the electricity sector; non-electric renewables are incorporated into each end-use demand sector. The oil and gas sectors have similar structures and a common investment subsector; therefore, they are discussed together.

Petroleum and Natural Gas Supply

The oil and gas sectors of the Fossil2 Model estimate petroleum and natural gas production and

Table 5.11. Highway Transportation Assumptions

	Passenger Vehicles			Freight Vehicles		
Year	Vehicle Stock (million)	Total Vehicle Miles (billion)	Road MPG	Vehicle Stock (million)	Total Vehicle Miles (billion)	Road MPG
1990	165	1764	18.8	25	313	8.4
2000	193	2148	20.6	29	402	9.2
2010	221	2667	21.3	34	507	9.5
2020	241	3060	22.7	38	613	9.9
2030	255	3185	23.2	41	724	10.3

Sources: 1990-2010: ORNL; DOE/EIA 1990b (modified by revised economic growth rates); Oak Ridge National Laboratory (efficiency estimates). 2010-2030: DOE/EIA 1990b; vehicle travel based on DOE staff estimates.

Table 5.12. Transportation Fuel Prices (1989$/mBtu)

Year	Gasoline	Diesel Fuel	Residual Fuel	Jet Fuel
1990	7.87	7.00	2.78	4.27
2000	10.02	9.03	4.60	6.63
2010	11.87	10.76	6.15	8.64
2020	12.92	11.75	7.04	9.79
2030	13.66	12.44	7.66	10.60

Source: NES Current Policy Base Case.

Table 5.13. Air Transportation Assumptions

Year	Airline Seat-miles (seat-miles/mBtu)	Airline Fleet Efficiency (1988=1.00)
1990	745	1.02
2000	1134	1.19
2010	1606	1.29
2020	2111	1.46
2030	2635	1.62

Sources: 1990-2010: DOE/EIA 1990b. 2010-2030: DOE/EIA, Office of Energy Markets and End Use.

imports and natural gas wellhead prices. The sectors discover new reserves and develop new production capacity in response to demand (determined by the building, industrial, and transportation sectors) and calculate wellhead gas prices, based on market equilibration between gas supply and demand. Base world oil prices are input assumptions, although the model adjusts the oil price in response to changes in demand. These prices are then used to calculate product prices, which are, in turn, fed back in each time period to the demand sectors to determine oil and gas demand in the next period. The sectors allocate joint oil and gas industry investment among extraction and conversion technologies on the basis of marginal production costs and industry return on investment. For extraction technologies, investment is allocated between wildcat and development drilling. Wildcat drilling discovers resources and increases proven and probable reserves; development drilling increases proven reserves through revisions and extensions. Investment in conversion technologies (e.g., coal liquids) is allocated to facility construction. Resource categories included in the model are listed in Table 5.14.

The most important oil and gas assumptions are the undiscovered resources. These inputs are given in Table 5.15. Of particular importance for the period

Table 5.14. Oil and Gas Resource Categories

Oil Resources	Gas Resources
Conventional onshore	Conventional onshore
Stripper wells	Gulf of Mexico offshore
Gulf of Mexico offshore	Onshore associated
Thermal enhanced oil recovery	Gulf of Mexico offshore associated
Other enhanced oil recovery	Unconventional (coal bed methane, tight gas, Devonian shale and infill drilling)
Onshore natural gas liquids (NGL)	High-cost unconventional (hydrates, very tight sands and deep gas)
G··lf of Mexico offshore NGL	Synthetic gas from coal
Tar sands	Alaskan
Synthetic coal liquids	Pipeline imports
Alaskan	NGL imports
Imports	

Table 5.15. Petroleum, Natural Gas and Coal Resources

Resource	Resource Base
Oil:	
L-48 Conventional	33 BBOE undiscovered
Alaskan	17 BBOE undiscovered
Thermal EOR	12 BBOE - based on NPC study
Other EOR	22 BBOE - based on NPC study
Tar Sands	54 BBOE - measured plus speculative; costs based on Canadian data + 50%
Gas:	
L-48 Conventional	324 TCF undiscovered
Unconventional	378 TCF technically recoverable $2.00/mcf-$9.00/mcf
High-Cost Unconventionals	500 TCF technically recoverable at $4.50/mcf-9.00/mcf

Sources: Conventional resources: USGS 1989.
Enhanced oil recovery resources: NPC 1984.
Tar sands resources: Interstate Oil Compact Commission 1984. (economically recoverable resources are substantially lower)
Unconventional gas resources: DOE 1988.
High-cost unconventional gas resources: DOE staff estimate.

2010 to 2030 are the unconventional gas and high-cost unconventional gas assumptions. The first resource base is fairly well documented (DOE 1988), but little data exist for the high-cost unconventional gas. However, several studies suggest that large additional quantities of gas are recoverable at costs in excess of $4.50/million cubic feet (mcf). For this analysis, a resource base of 500 trillion cubic feet (tcf) has been assumed. This is a critically important assumption, as conventional gas production in the Current Policies Case declines substantially after 2010. Large quantities of high-cost unconventional gas are produced after about 2015, causing a rough stabilization of natural gas prices from 2020 to 2030.

Find rates for these resource categories are based on several sources. Conventional oil and gas find rates are based on API and AGA data (pre-1980) and EIA annual new field reserve additions (DOE/EIA 1990c, d). Future find rates are estimated by applying USGS growth rates to the historical data. Detailed find rate assumptions by resource category are available in EEA (1990).[a]

Oil imports provide the difference between consumption and production in this analysis. Total oil consumption rises slowly over the 40-year period and peaks around 2020, while oil production falls steadily. The net result is rising imports; total crude and product imports reach 12 million barrels per day (mbd) in 2010 and 15 mbd in 2030. It is assumed that this quantity of U.S. oil imports will be met by commensurate increases in OPEC production capacity.

(a) Energy and Environmental Analysis, Inc. (EEA). 1990 (forthcoming). Fossil2 Energy Policy Model Oil and Gas Sector Documentation. EEA, Arlington, Virginia.

Natural gas pipeline imports are assumed to reach pipeline capacity in the early 1990s. Capacity is assumed to expand to 2.1 tcf by 2000. These imports are assumed to be constrained in the mid-term by pipeline capacity and in the long term by Canadian resources and domestic consumption. The gas flows from Canada are based on initial reserves of 94 tcf, undiscovered recoverable resources of 321 tcf, and a domestic consumption growth rate of 1% per year. Imports of Canadian gas increase to a maximum of 2.1 tcf by 2005 and decline thereafter. Imports to the U.S. from Mexico are projected to grow steadily to 0.75 tcf by 2025.

Liquefied natural gas (LNG) imports are constrained by the price of the fuel and the capacity of import facilities. The U.S. has four LNG facilities with a total capacity of 0.9 tcf, but current imports total less than 0.1 tcf. However, several additional LNG contracts are now under negotiation. Additional contracts are assumed to be established if gas prices were to continue to rise. Imports are assumed to reach 0.4 tcf in 1995 and 1.5 tcf by 2010. It is assumed that natural gas facilities will be financed and built as they become economical.

The principal assumptions for the conversion technologies are the capital and operating and maintenance (O&M) costs for the production facilities. These inputs are given in Table 5.16. Coal liquids and shale oil figures are adapted from NRC (1989); coal gas figures are based on costs from the Great Plains synthetic gas facility.

Table 5.16. Synthetic Fuels Cost Assumptions (1988$)

Source	Capital Cost	Operating Cost
Coal Liquids	$16.20/mBtu capacity	$1.65/mBtu produced
Shale Oil	$20.79/mBtu	$2.98/mBtu produced
Synthetic Gas	$37.40/mBtu capacity	$2.60/mBtu produced

Sources: Coal liquids, shale: adapted from NRC 1989. Synthetic gas: DOE, DOE/EIA.

Coal Supply

The coal production sector of the Fossil2 Model estimates coal production capacity and minemouth prices. Production capacity is built over time, based on coal demand and industry return on investment. It is assumed that there are no long-term capacity constraints in the forecast period, with production meeting domestic and export needs. Minemouth prices are estimated from production levels, production costs, and labor productivity. Labor productivity is assumed to increase by 1% per year until 2000 and by 0.5% per year thereafter.

The demonstrated reserve base of coal is assumed to be 260 billion short tons (DOE/EIA 1990d). This resource is sufficiently large to avoid any economic scarcity effects, even over a 40-year analysis horizon.

Coal exports to 2010 are taken from the EIA International Coal Trade Model. Post-2010 exports are estimated by EIA, based on total world demand and non-U.S. coal export capacity. The rate of growth in U.S. coal exports is expected to slow after 2015, due to increased use of nuclear power and higher electricity generation efficiencies throughout the world.

Electricity Generation

The electricity supply sector of the Fossil2 Model estimates electricity supply and prices. The sector builds new capacity in response to expected future demand, dispatches capacity to satisfy current demand (determined by the buildings and industrial sectors) and sets electricity rates in accordance with utility rate regulations. These prices are then fed back to the demand sectors to determine current and future electricity load growth.

The sector estimates the expected quantity of new capacity required in each time period based on a forecast of load growth and the levels of capacity, both existing and under construction. The model includes costs and performance characteristics for the 23 different technologies listed in Table 5.17.

Table 5.17. Electricity Generation Technologies

Coal	Oil/Natural Gas	Nuclear	Renewable
Coal steam	Oil steam	Light-water reactors	Hydroelectric
Coal steam with FGD	Gas steam	Advanced light-water reactors	Photovoltaics
Atmospheric fluidized bed	Gas combined cycle	Second generation reactors	Solar thermal
Pressurized fluidized bed	Combustion turbines		Wind
Integrated gasification combined cycle (IGCC)	STIG		Geothermal
Coal gasification steam-injected turbines (SITG)	Intercooled steam-injected turbines (ISTIG)		Biomass
Coal gasification fuel cells	Gas fuel cells		

In addition to the technologies listed, the model can explicitly life-extend oil, gas, and coal steam plants, "repower" coal plants using the IGCC technology, and convert gas combined cycle plants to IGCC by installing a coal gasifier. The levelized cost per kilowatt-hour is calculated for each technology in each time period, based on capital costs, O&M costs, fuel costs and design capacity factors. The technology characteristics used in the model are given in Tables 5.18, 5.19, and 5.20; utility sector Current Policies Case fuel prices are given in Table 5.21. New capacity construction decisions are then made on the basis of these costs, resulting in a mix of "least-cost" technologies. (Detailed information on the market shares and electricity rate algorithms is available in AES 1990.)

A national-level load duration curve, together with technology costs, determines the capacity dispatching order. In a given time period, technologies within the capacity mix are dispatched on the basis of increasing fuel and variable operation and maintenance costs. This typically translates into a dispatch order of nuclear, base-load coal, base-load oil and gas, renewables, "intermediate" coal, "intermediate" oil and gas, and finally pumped storage hydro and combustion turbines for the peak load. Capacity factors are determined from this dispatching order. Base load is defined as the portion of the load below the annual minimum; peaking load is assumed to be 8% of total load.

The levelized cost calculation for the capacity construction decision requires price expectations for residual fuel, natural gas, coal, and nuclear fuel. For the period 1990 to 2030, model-derived utility sector prices are used. Beyond 2030, residual fuel, gas, and coal prices are assumed to rise by 0.5% per year in real terms; nuclear fuel costs are assumed to be flat.

Electricity imports are an exogenous assumption in the model. Imports are expected to increase by 150% between 1990 and 2010, as Canadian electricity continues to be an attractive supply option. After 2010, Canadian imports are assumed to retain the same share of U.S. electricity demand as they did prior to 2010. Several Canadian provinces currently have large undeveloped resources--it is assumed that these will be developed, in part for U.S. markets. Electricity imports from Mexico into the Southwest are also expected to begin after 2010. Total electricity imports are given in Table 5.22.

Other important assumptions in the electricity generation sector are capability reserve margins and transmission and distribution losses. These inputs are given in Table 5.22.

As the need for new capacity grows, utilities are expected to explore innovative demand side management (DSM) programs. DSM savings assumptions are given in Table 5.23. These estimates are taken

Table 5.18. Fossil and Nuclear Electricity Technologies: Technology Costs and Characteristics

Technology	Capital Cost[a,b] (1989$/kW) 2000	2010	2020	O&M Cost[c] (m/kWh)	Commercial Year[d]	Heat Rate (Btu/kWh)	Load Use	Capacity Factor[e]
Coal steam	$1355	$1355	$1355	4.3	-------	11,000	Base/Int	0.65
Coal steam w/FGD	$1535	$1535	$1490	11.7	-------	10,339	Base/Int	0.65
Oil steam	$ 960	$ 960	$ 960	5.3	-------	9,800	Inter	0.30
Gas steam	$ 960	$ 960	$ 960	5.3	-------	9,800	Inter	0.30
Gas combined cycle	$ 680	$ 640	$ 640	2.1	-------	7,570	Inter	0.30
Combustion turbines	$ 310	$ 310	$ 310	5.2	-------	13,500	Peaking	0.10
AFB	$1300	$1300	$1300	10.2	1990	9,750	Base	0.70
PFB	$1440	$1200	$1200	13.0	1996	8,400	Base/Int	0.70
IGCC	$1415	$1280	$1280	8.9	1994	9,220	Base/Int	0.70
STIG/ISTG	$ 600	$ 600	$ 600	2.1	1990	7,260	Base/Int	0.70
Gasification STIG	$1455	$1240	$1025	6.4	2005	8,530	Base/Int	0.70
Gas fuel cells	$ 860	$ 705	$ 705	10.9	1997	6,450	Inter	0.47
Coal fuel cells[f]	$1335	$1335	$1235	10.9	2025	7,130	Base/Int	0.80
Light-water reactor (LWR)	$1785[g]	$1785[g]	$1785[g]	26.6[h]	-----	10,800	Base	0.65
Advanced LWR[i]	$1490	$1375	$1375	8.9	1996	10,200	Base	0.75
2nd generation nuclear[i]	$1775	$1480	$1480	13.0	2000	10,300	Base	0.75

(a) Represents the overnight construction costs.
(b) New technologies are subject to a 15% learning curve; costs in table reflect this.
(c) The fuel cost component varies with fuel prices and is therefore not given in this table; utility fuel prices are given in Table 5.21.
(d) Coal and nuclear plants are assumed to have a lifetime of 40 years; fuel cells and oil and gas plants are assumed to have a lifetime of 30 years.
(e) Capacity factors given for intermediate/peak load technologies are typical.
(f) The O&M costs and heat rates for this technology category are represented by several coal fuel cells and therefore change over time. O&M costs are 10.4 m/kWh in 2010 and 8.2 m/kWh in 2020. Heat rates are 7130 Btu/kWh in 2010, 6500 Btu/kWh in 2020, and 6500 Btu/kWh in 2030.
(g) Conventional nuclear is assumed to have a $77/kW decommissioning cost.
(h) Includes $65/kW or 10.5 m/kWh capital maintenance cost.
(i) New nuclear orders are assumed to require changes in policy and are therefore not included in the Current Policies Case; excludes $170/kWh decommissioning cost.

Sources: Oil, gas, coal steam, AFB: DOE/EIA 1990b. Advanced fossil technologies: DOE, Office of Fossil Energy. Nuclear: Oak Ridge National Laboratory.

from DOE/EIA (1990b) for the 1990 to 2010 period. After 2010, the impacts of utility DSM programs are uncertain. However, the contributions of electric utility DSM programs after 2010 are assumed to grow at the same rate as the demand for electricity.

Renewables

Two categories of renewable energy consumption are estimated in the model: centralized, or grid-connected, and dispersed. As already noted, utility and non-utility renewable electricity generation technologies compete with fossil and nuclear technologies to satisfy electricity demand. Renewable electricity technology costs are shown in Table 5.20. Dispersed renewables are estimated in each end-use sector.

The largest dispersed renewable uses are residential wood for space heating, industrial biomass for steam and cogeneration, and alcohol fuels for vehicles. Residential wood consumption assumptions are given in Table 5.6. Biomass competes with fossil fuels on a marginal cost basis to produce steam and electricity in the industrial sector. Current Policies Case costs are given in Table 5.10. As noted earlier, alcohol fuel for personal travel is assumed to

Table 5.19. Life Extension/Repowering Costs and Characteristics[a]

Technology	Capital Cost (89$/kW)	O&M Cost (m/kWh)	Commercial Year	Heat Rate (Btu/kWh)	Construct Time (years)
Coal steam[b]	$235	4.1	1990	10,400	3
Oil/Gas steam	$155	4.8	1990	9,500	3
Nuclear	$580	10.8	1990	10,200	3

(a) Full life extension is assumed for all fossil plants in excess of 200 MW capability; a 50% repowering rate is assumed in the Current Policies Case. Life-extended/repowered capacity equals 340 GW by 2010.
(b) Coal plants are converted to AFB or IGCC plants using a repowering ratio of 2.7.

Sources: Coal, oil, gas: DOE/EIA 1990b. Nuclear: Oak Ridge National Laboratory

continue at the current levels used in gasoline additives through 2010. Consumption rises modestly afterwards, reaching 0.5 quads by 2030.

Additional dispersed renewable are consumed in the residential, commercial, and industrial sectors. The amounts are given in Table 5.6.

5.3 CURRENT POLICIES CASE RESULTS

The implications of the assumptions just discussed with regard to energy prices, energy consumption, energy transformation, energy production and imports, and greenhouse gas emissions are reported in this section.

5.3.1 Energy Prices

This section discusses the energy price results of the Current Policies Case simulation conducted using the Fossil2 Model. Energy prices are shown in Table 5.24. The price results for the prices of primary energy resources--oil, natural gas, and coal--are described in more detail.

Oil Prices

Petroleum product prices are driven by the exogenously assumed world oil price. The world oil price trajectory is shown in Figure 5.1. The world oil price rises continuously throughout the analysis period from 1990 to 2030. The world oil price increases by about 180% between 1990 and 2030. This translates into an average annual rate of increase of 2.23% per year. The average annual rate of increase is greatest in the period 1995 to 2000, averaging 6.7% per year. The rate of increase declines slowly thereafter as prices start to stabilize. By the end of the simulation period, the average annual rate of increase has declined to 0.7% per year.

Refiner crude costs and refined petroleum prices follow the world oil price closely in the Current Policies Case. The refiner crude cost is assumed to become identical to the world oil price after 1990. The prices of refined petroleum products differ from the world oil price only by a relatively constant cost of refining. Gasoline prices are approximately $5.00 to $5.50 per million Btu greater than the world oil price. Residential sector distillate oil costs approximately $3.50 to $4.00 per million Btu greater than the world oil price. Commercial sector residual fuel oil is similar in price to world oil. As a consequence of the relatively constant differential between the price of gasoline and world oil price, the price of gasoline experiences a much smaller percentage increase than does the world oil price over the period to 2030, ending the simulation period 83% higher in the terminal year than in the initial year. The direction of gasoline price changes mirrors the world oil price,

Table 5.20. Renewable Electricity Technologies: Technology Costs and Characteristics

	1990	2000	2010	2020	2030
Photovoltaics					
Capital cost (1989$/kW)[a]	--	3,500	2,130	1,390	1,175
O & M cost (m/kWh)	--	2	2	2	1
Capacity factor	--	28%	28%	28%	28%
Solar Thermal[b]					
Capital cost (1989$/HW)[a]	2,135	1,800	1,600	1,840	1,840
O & M cost (m/kWh)	11	9	8	8	8
Capacity factor	37%	37%	37%	43%	43%
Wind Farms					
Capital cost (1989$/HW)[a]	1,100	1,000	965	915	850
O & M cost	18	12	9	8	8
Geothermal[c]					
Capital cost (1989$/HW)[a]	2,200	2,115	2,030	1,920	1,795
O & M cost (m/kWh)	26	19	13	10	9
Capacity factor	81%	85%	90%	95%	95%
Biomass Electric					
Capital cost (1989$/HW)[a]	1,600	1,600	1,600	1,600	1,600
O & M cost (m/kWh)	9	9	9	9	9
Capacity factor	70%	70%	70%	70%	70%
Heat rate (Btu/kWh)	13,000	13,000	13,000	13,000	13,000

(a) Represents the overnight construction costs.
(b) Solar thermal costs reflect the penetration of new technologies after 2010.
(c) Geothermal is a base-load technology; all others are intermediate or peak load.

Source: Science Applications International Corporation (SAIC). 1990. *Renewable Energy Technology Characterizations.* Alexandria, Virginia. (draft).

Table 5.21. Electric Utility Fuel Prices (1989$/mBtu)

Year	Liquid Fuels	Natural Gas	Coal	Nuclear Fuel
1990	2.96	2.52	1.58	0.81
2000	4.46	3.90	1.71	0.62
2010	6.60	6.02	1.94	0.60
2020	7.56	7.47	2.09	0.60
2030	8.23	8.51	2.30	0.60

Source: NES Current Policies Base Case.

and the maximum rate of increase occurs between 1995 and 2000 at 3.25% per year.

Natural Gas Prices

In the Fossil2 Model, the price of natural gas is related to the world oil price in a more complex manner than is the price of refined petroleum products. The wellhead price of natural gas is determined endogenously by the model. This price depends not only on the world price of oil through the competition between oil and gas, but also on the resource and available reserves of gas, and to a lesser extent, competition with coal.

Table 5.22. Electricity Generation--Miscellaneous Assumptions

Year	Imports (kWh)	Transmission Distribution Losses	Reserve Margin	Plant Lifetime (years)
1990	27	7.5%	17%	40
2000	59	7.5%	17%	40
2010	68	7.5%	17%	40
2020	85	7.5%	17%	40
2030	107	7.5%	17%	40

Sources: 1990-2010 imports: DOE/EIA (1990a).
2010-2030 imports: DOE/EIA, Office of Coal, Nuclear, Electric and Alternate Fuels. Other: DOE/EIA (1990b).

Table 5.23. Demand Side Management Savings Assumptions (billion kWh/yr)

Year	2000	2010	2020	2030
Residential	20	59	65	70
Commercial	17	53	66	78
Industrial	20	59	69	81
Total	57	171	200	229

Sources: 1990-2010: DOE/EIA (1990b). 2010-2030: DOE/EIA, Office of Coal, Nuclear, Electric and Alternate Fuels.

The wellhead price of natural gas, in Figure 5.2, rises fairly steadily from $1.78 per million Btu in 1990 to $7.46 per million Btu in 2030, where it peaks about 320% above its 1990 level. Residential gas prices track the wellhead price of gas and also peak in the year 2030. Although they both increase at a rapid rate, the residential price of natural gas tends to increase in lesser magnitude as compared to the wellhead price. The residential price of natural gas increases by a little more than 106% between 1990 and 2030, far less than the 320% for the wellhead price.

Table 5.24. Current Policies Energy Prices (1989$)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.87
1995	$3.51	$3.51	$2.27	$1.07	$8.54
2000	$4.85	$4.85	$3.57	$1.16	$10.02
2005	$5.79	$5.79	$4.25	$1.19	$11.07
2010	$6.51	$6.51	$5.18	$1.33	$11.87
2015	$7.03	$7.03	$6.33	$1.34	$12.46
2020	$7.46	$7.46	$6.57	$1.43	$12.92
2025	$7.85	$7.85	$7.01	$1.50	$13.36
2030	$8.12	$8.12	$7.46	$1.59	$13.66

Year	Residential Gas	Utility Coal	World Oil Average Elec	Price ($/bbl)
1990	$5.69	$1.58	$18.65	$16.85
1995	$6.31	$1.60	$18.54	$20.38
2000	$7.72	$1.71	$19.19	$28.11
2005	$8.46	$1.75	$20.09	$33.56
2010	$9.35	$1.94	$20.76	$37.74
2015	$10.48	$1.95	$20.87	$40.81
2020	$10.77	$2.09	$21.38	$43.25
2025	$11.26	$2.17	$21.68	$45.51
2030	$11.73	$2.30	$21.86	$47.09

Coal Prices

The minemouth price of coal, shown in Figure 5.3, remains relatively stable over the entire period. It rises by about 53% between 1990 and 2030. This represents an average annual rate of growth of 0.78% per year. This rate of growth is roughly one-third of that for the world price of oil.

The relationship between the minemouth price of coal and the price of end-use coal (industrial and utility coal) is approximately proportional. Percentage changes in industrial and utility coal prices are fairly similar to those of minemouth coal.

Electricity Prices

The price trajectory for electricity is shown in Figure 5.4. The path of electricity prices over time is

even more stable than that of coal prices, the most important input to electricity production. Prices remain at or near $20.00 per million Btu electric throughout the period of analysis. Simulated electricity prices climb to a peak of $21.86 in 2030. The generally flat character of electricity prices is due to two factors: first, the relatively stable nature of coal prices, and second, the simulated penetration of new, more efficient, clean coal technologies.

5.3.2 Energy Consumption

Total energy consumption, shown in Table 5.25, grows between 1990 and 2030 by slightly less than 70%, from 85.4 quads to 144.6 quads. The average annual rate of growth remains positive over the entire period, but slows continuously, declining from 1.4% per year in the first 5 years to 0.8% in the last 5 years of the simulation period.

Oil Consumption

Domestic oil consumption increases over the entire simulation period, from 34.4 quads in 1990 to 52 quads in 2030. The rate of growth of oil consumption is somewhat uneven, but generally trends downward from 1.5% per year for the period 1990 to 1995 to 0.3% per year for the period 2025 and 2030. The relative importance of oil does not change very dramatically over this period of time. In 1990, oil was the single most important energy source in the U.S. economy, accounting for 40% of total energy consumption. By 2030, coal has supplanted oil as the most important energy source; however, oil's share of total consumption is still about 36%, while coal consumption represents about 38% of total consumption. The crossover does not occur until between 2025 and 2030.

As shown in Tables 5.26 through 5.29, oil consumption is not distributed evenly throughout the economy. In 1990, about 63% of U.S. oil consumption was used by the transportation sector. By 2030, this fraction is expected to grow somewhat, to 68%. Industrial oil consumption is expected to hover between 25% and 27% of total consumption. Simulated utility consumption fell from about 4% in 1987 to just under 2% in 2030. Residential and commercial use of oil also falls from 8% to under 3% by 2030.

Gas Consumption

Natural gas follows a pattern of growth, peak, and decline. Simulated gas consumption increases from 19.2 quads in 1990 to 23.6 quads in 2000. For the next 15 years in the simulation period, natural gas consumption fluctuates somewhat, but remains essentially constant. Starting in 2015, natural gas consumption declines from 23.8 quads to 19.9 quads in 2030. Over the entire period, the share of natural gas

Table 5.25. Current Policies Energy Consumption (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	36.6	21.0	20.4	6.0	7.3	0.2	91.6
2000	38.7	23.6	23.4	6.2	8.1	0.2	100.2
2005	41.5	23.2	28.0	6.4	9.5	0.2	108.9
2010	44.8	23.0	33.3	6.4	10.7	0.2	118.3
2015	47.9	23.8	37.7	4.5	11.9	0.3	125.9
2020	49.6	22.4	43.4	3.5	13.5	0.3	132.6
2025	51.2	21.7	48.8	1.8	15.1	0.3	138.8
2030	52.0	19.9	55.0	0.4	16.9	0.4	144.6

Table 5.26. Current Policies Case Electricity Fuel Consumption by Fuel (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.9	5.1	17.5	6.0	4.5	35.0
2000	2.0	6.7	20.2	6.2	4.8	39.8
2005	1.8	6.4	24.3	6.4	5.6	44.4
2010	1.8	5.9	28.9	6.4	6.0	49.0
2015	2.3	7.0	32.8	4.5	6.6	53.3
2020	1.9	6.0	38.4	3.5	7.6	57.5
2025	1.6	5.4	43.9	1.8	8.5	61.1
2030	1.0	3.9	50.0	0.4	9.4	64.8

Table 5.27. Current Policies Case Residential Energy Consumption (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.6	4.9	0.1	0.9	3.2	10.7
1995	1.3	4.7	0.1	1.0	3.6	10.7
2000	1.2	4.8	0.1	1.1	4.0	11.3
2005	1.1	4.8	0.1	1.2	4.4	11.5
2010	1.0	4.8	0.1	1.4	4.7	11.8
2015	0.9	4.7	0.1	1.5	5.0	12.0
2020	0.9	4.5	0.1	1.6	5.4	12.2
2025	0.8	4.4	0.1	1.7	5.6	12.4
2030	0.8	4.3	0.1	1.8	5.9	12.6

Table 5.28. Current Policies Case Commercial Energy Consumption (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.0	2.8	0.1	0.1	2.9	6.9
1995	0.9	2.6	0.1	0.1	3.4	7.2
2000	0.9	2.7	0.1	0.1	4.0	7.8
2005	0.8	2.8	0.1	0.1	4.6	8.4
2010	0.8	2.8	0.1	0.2	5.1	9.0
2015	0.8	2.8	0.1	0.2	5.7	9.6
2020	0.8	2.9	0.0	0.3	6.3	10.3
2025	0.7	3.0	0.0	0.3	6.8	10.9
2030	0.7	3.0	0.0	0.4	7.4	11.5

Table 5.29. Current Policies Case Industrial Energy Consumption (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	8.7	8.2	2.8	1.8	3.1	24.6
1995	9.5	8.4	2.6	1.8	3.6	25.8
2000	9.6	8.9	2.9	2.1	4.2	27.8
2005	10.0	8.8	3.5	2.4	4.9	29.5
2010	10.7	8.8	4.1	2.9	5.5	32.0
2015	11.4	8.6	4.5	3.3	6.1	33.9
2020	12.1	8.3	4.7	3.6	6.8	35.5
2025	12.9	8.2	4.7	4.0	7.4	37.1
2030	13.8	7.8	4.6	4.4	7.9	38.6

consumption declines from about 22% in 1987 to just under 14% in 2030. By the year 2030, natural gas holds approximately the same share of domestic consumption as renewable energy sources.

The increase in gas consumption over the period to 2000 is primarily the result of an escalation in the use of gas to produce electricity. In 1990, the utility share of natural gas consumption was approximately 10%. During the period beginning in 1995 and extending to 2010, there is a rapid installation of gas combined cycle, STIG and ISTIG turbine capacity. By 2015, simulated natural gas consumption by the utility sector increased from 2.7 quads in 1990 to 7.0 quads, or about 2.5 times 1990 levels. The surge in utility gas consumption tapers off after 2015, falling to 3.9 quads in 2030. This decline in gas consumption by the electricity sector is due largely to the rapid conversion of gas turbine technologies to coal through the application of a coal gasifier to the front end of the technology.

Natural gas consumption in the remaining sectors of the economy either remains about constant, or declines slightly throughout the simulation period.

Coal Consumption

Coal consumption triples from 19 quads per year in 1990 to 55 quads per year in the year 2030. This increases coal's percentage from a quarter of the total national energy consumption to 40% by 2030. In 1990, coal and natural gas provided approximately equal shares of the total, and together coal and gas were only slightly more important in overall energy consumption than oil alone. By 2030, simulated coal consumption overtakes oil consumption to become the single most important energy source in the U.S. economy. The primary reason for this is that the marginal cost (i.e., price) of coal remains relatively constant over the simulation period, while the marginal cost of other energy resources increases, creating incentives for sectors to switch fuels from oil and natural gas to coal.

Coal consumption is dominated by use in electric power generation. Throughout the course of the analysis, utility coal consumption accounts for 85% to 90% of total coal use. The remainder of coal consumption occurs in the industrial sector, with direct coal use in residential and commercial application virtually extinguished by the year 2020.

5.3.3 Energy Transformation

Electric Power Generation

The demand for electric power, shown in Figure 5.5, grows by about 112% between 1990 and 2030, from 9.2 quads to 18.4 quads per year. Consumption is relatively evenly divided between residential commercial and industrial customers. Residential consumption doubles over this period, growing somewhat less rapidly than commercial and industrial

consumption, both of which almost triple over the same period. As a consequence, the relative fraction of electricity production accounted for by commercial and industrial consumption rises while the residential share falls. This differential is driven primarily by the fact that the number of households grows less rapidly than either the industrial production index or the commercial floor space.

The coal fuel share increases from 54% in 1990 to 77% in 2030. Coal use, shown in Figure 5.6, triples over this period. Natural gas consumption increases up to the year 2000, doubling, but falls off sharply with higher fuel prices; the rate of gas usage is only slightly higher in 2030 than in 1987. The use of oil as a fuel for generating power increases by about 53% between 1987 and 2000, remains flat for the next 15 years, and then declines sharply thereafter. Oil consumption by the electric utility sector is 23% below 1987 levels by 2030. The use of nuclear power in the Current Policies Case increases by one-third between 1987 and 2010, but then decreases to practically zero as existing nuclear plants are retired and relatively lower-cost coal plants take their place. The use of renewable energy sources increases steadily and is almost two-and-one-half times 1987 levels by 2030.

Synfuels Conversion

By the year 2030, a very small synfuels industry has materialized. This industry has two components: oil used to produce syngas, and renewable energy sources used to produce synthetic oil, principally alcohol fuels. In addition, there is a synfuels conversion activity that occurs in the electric power industry with the application of coal gasifiers in conjunction with new high-efficiency gas turbines. The output of synfuels liquids increases from 0.1 quad in 1990 to 0.5 quad in 2030.

5.3.4 End-Use Energy Consumption

The end-use energy consumption results are presented in Tables 5.26 through 5.30. Total end-use energy consumption, as shown in Figure 5.7, increases from 64.6 quads in 1990 to just over 100 quads in 2030. The shares of both the industrial and transportation sectors remain about constant, around 38% for the entire period. At the same time, the residential share decreases from 17% to 13%, and the commercial share increases from 10% to 12%. As a result, there is very little change in the sectoral composition of energy use.

Residential Sector

Total end-use energy consumption in the residential sector grows by approximately 21% between 1990 and 2030. This is somewhat slower than total energy end-use, which increases 55% over this same period. As the occupied housing stock grows by 41% over this same period, the energy intensity of this sector drops by approximately 15%.

Table 5.30. Current Policies Case Transport Energy Consumption (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	21.6	0.7	0.0	0.1	0.0	22.4
1995	22.9	0.7	0.0	0.1	0.0	23.6
2000	24.9	0.7	0.0	0.1	0.0	25.7
2005	27.7	0.7	0.0	0.1	0.0	28.5
2010	30.4	0.7	0.0	0.1	0.0	31.2
2015	32.4	0.7	0.0	0.1	0.0	33.2
2020	33.8	0.7	0.0	0.2	0.0	34.7
2025	35.0	0.8	0.0	0.3	0.0	36.1
2030	35.6	0.9	0.0	0.5	0.0	37.1

The largest change in residential energy demand is the doubling of electricity use, as shown in Figure 5.8. Electricity grows from a 30% share of residential consumption to slightly less than half (47%) of all residential end-use energy consumption. Coal use remains low throughout the period. Oil use declines from 1.6 quads per year to 0.8 quads per year. Natural gas use decreases slightly, from 4.6 quads per year to 4.3 quads by the year 2030.

Commercial Sector

Commercial end-use energy consumption is shown in Figure 5.9. It grows rapidly and is about 67% higher in 2030 than it was in 1990. Because the number of square feet of floor space increases by 109% over this same period, there is a roughly 20% decrease in energy intensity in this sector.

Fuel share patterns in the commercial sector look similar to those in the residential sector. Electricity grows from a 42% fuel share in 1990 to 64% in 2030. Coal ceases to be used at all in the commercial sector by 2020. Oil becomes steadily less important, declining from 1 quad per year in 1990 to 0.7 quad per year in 2030, and from 14% of the total in 1990 to 6% in 2030. Natural gas consumption increases steadily over the simulation period, from 2.8 quads per year to 3.0 quads per year. Renewable energy consumption quadruples, but remains less than one-half quad (0.4 quads in 2030).

Industrial Sector

Energy use in the industrial sector, shown in Figure 5.10, grows by approximately 56%, from about 25 quads to 39 quads per year between 1990 and 2030. This energy growth is driven by a 156% increase in the index of industrial production. This implies a roughly 39% decrease in the energy intensiveness of this sector.

Electricity consumption by the industrial sector increases by 155% between 1990 and 2030, with the electricity fuel share increasing from 13% to 20%. The direct use of coal also increases from 2.8 quads per year to 4.6 quads, a 64% increase. The use of renewable energy grows almost as rapidly, from 1.8 quads per year to 4.4 quads per year. Oil consumption also increases, from 8.7 quads per year to 13.8 quads per year. Natural gas consumption decreases to 7.8 quads in the year 2030, down from a level of 8.2 quads in 1990.

Transportation Sector

The transportation sector runs on oil, as shown in Figure 5.11, and the analysis of its fuel choice is therefore the least complicated of all of the sectors. The oil fuel share is always above 95% in the analysis. Small amounts of natural gas and electricity are used, mostly in pipeline transport and rail transportation. The energy intensiveness of the transportation sector, measured as million Btu per thousand vehicle miles of travel, declines by 13% between 1990 and 2030. Average road mpg for all highway vehicles increases from 15.9 mpg to 18.9 mpg over this same period.

5.3.5 Energy Production and International Trade

The composition of domestic energy production, as shown in Table 5.31, changes dramatically over the period between 1990 and 2030. In 1990, 70 quads of energy were produced in the United States. In that year, coal and oil production each provided approximately 30% of the total. Natural gas provided approximately 25%, and the remainder was divided roughly equally between nuclear, 8%, and renewable, 10%. The changes in the composition of domestic energy production that are projected to occur from this base are described below.

Domestic Oil and Gas Supply

Domestic production of oil declines steadily from 17.9 quads in 1990 to 8.8 quads in 2030. Thus, by 2030, production is more than 50% below 1990 levels. The importance of North Alaskan oil declines rapidly from contributing 3.7 quads per year in 1990 to 0.5 quads in 2030. Continental U.S. production shows a declining pattern as well, falling from 11.6 quads to 4.9 quads.

Table 5.31. Current Policies Case Energy Supply (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.6	19.2	23.0	6.0	7.3	71.1
2000	14.7	21.2	26.7	6.2	8.1	76.9
2005	13.7	20.4	32.4	6.4	9.5	82.3
2010	13.3	20.2	39.1	6.4	10.7	89.6
2015	12.8	21.0	44.1	4.5	11.9	94.3
2020	11.7	19.9	50.2	3.5	13.5	98.8
2025	10.3	19.1	55.9	1.8	15.1	102.3
2030	8.8	17.3	62.1	0.4	16.9	105.5

Natural gas production rises over the period to 2000, surpassing oil production between 1990 and 1995. Natural gas production grows 19% between 1990 and 2015, from 17.8 quads to 21.2 quads. Growth is rapid between 1990 and 2000, averaging 1.9% per year. Production levels off in the year 2000 and remains stable over the next one-and-one-half decades. Subsequently, production declines steadily at an average annual rate of about 1.3% per year. By the year 2030, oil and gas production together contribute approximately 25% of total domestic energy production. Thus, their combined contribution to production is slightly lower in the year 2030 than that of oil alone in 1990.

Domestic Coal Supply

Coal production triples in the Current Policies Case between 1990 and 2030, growing from 21.6 quads to 62.1 quads. The rate of growth averages 2.7% per year over this period, but is more rapid between the years 2000 and 2020 and somewhat slower prior and subsequent to that period. During the period of this analysis, coal moves to be the dominant source of domestic energy production, accounting for almost 60% of domestic production.

Nuclear and Renewable Production

Nuclear energy production increases until 2010 and then declines sharply as old plants are retired. New nuclear is phased out in the Current Policies Case. By 2030, only 0.4 quad of energy is produced by nuclear powerplants.

Renewable energy sources such as hydroelectric, biomass, wind, solar electric, geothermal, and others show a steady increase in supply between 1987 and 2030, increasing their contribution from 6.8 quads per year to 16.9 quads per year. This increase of about 150% builds slowly at first, averaging 1.2% per year to 2000, but then accelerates in the latter half of the period of analysis, averaging more than 2.5% per year after 2000. The character of the renewable resource changes over this period as well. Although renewable energy production is dominated by hydroelectric power generation and dispersed biomass consumption in 1987, by 2030 a significant expansion occurs in other renewable energy forms such as geothermal, biomass in electric power generation, solar thermal, wind, landfill and sewer gas, and agricultural waste.

International Trade

Throughout the period to 2025, the U.S. becomes increasingly dependent on foreign sources for oil and gas. Oil imports, shown in Table 5.32 and Figure 5.12, grow from 16.5 quads per year in 1990 to 43.2 quads per year in 2030. As domestic production declines, this leads to an increasing dependence on foreign oil, which grows from 48% of domestic consumption in 1990 to 83% in 2030.

Table 5.32. Current Policies Case Energy Trade (quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	16.5	1.4	(2.6)	0.1	0	15.4
1995	21.0	1.9	(2.6)	0.2	0	20.4
2000	24.0	2.4	(3.3)	0.2	0	23.3
2005	27.8	2.8	(4.3)	0.2	0	26.5
2010	31.5	2.8	(5.8)	0.2	0	28.8
2015	35.1	2.8	(6.4)	0.3	0	31.7
2020	37.9	2.4	(6.8)	0.3	0	33.8
2025	40.8	2.5	(7.1)	0.3	0	36.6
2030	43.2	2.6	(7.2)	0.4	0	39.0

Natural gas imports, which were 1.4 quads per year in 1990, increase to 2.8 quads by the year 2005, remain constant until 2015, and then fluctuate downward to 2.6 quads in 2030. This leads to a modest shift in the natural gas sector. In 1990, 92% of U.S. consumption was domestically produced. However, by 2030, 85% of total U.S. consumption is produced domestically.

The trend in coal trade is the reverse of that for oil and gas. Coal is a U.S. export, and net coal exports increase from 2.6 quads per year in 1990 to 7.2 quads per year in 2030. The share of domestic production that is exported is virtually stable: 14% in 1990 and 13% by 2030.

Overall, U.S. energy dependence increases from 18% to 24% between 1990 and 2005, but then stabilizes, roughly, due to the stabilization of oil consumption, the decline in natural gas consumption, and the continued growth in coal exports.

5.3.6 Greenhouse Gas Emissions

Carbon

Carbon emissions are calculated as described in Chapter 4. Fossil fuel carbon emissions, shown in Table 5.33 and Figure 5.13, are gross emissions, but do not include the impact of carbon sequestration from the President's Tree Planting Program. The emissions almost double between 1990 and 2030, growing from 1299 TgC/yr to 2543 TgC/yr. This represents an average annual growth rate of about 1.6% per year. This growth rate is higher in the middle years, peaking at 2.0% per year between 2000 and 2015, but declines to 1.2% per year by 2030.

Emissions from natural gas rise by 22% between 1990 and 2005, from 274 TgC/yr to 332TgC/yr, but by 2030, they decline to 274 TgC/yr. During this period, the natural gas contribution to carbon dioxide emissions falls from 21% of total emissions to 11%. Emissions from oil increase by 55%, from 546 TgC/yr in 1990 to 851 TgC/yr in 2030. During the same period, the share of oil-related carbon dioxide emissions drops from 41% to 34%. The great increase in total carbon emissions over the period of analysis is associated with the use of coal, whose emissions increase by just under 200% over the period from 1990 to 2030, from 477 TgC/yr to 1399 TgC/yr. In the process, coal's share of total carbon dioxide emissions increases from 38%, on a par with oil in 1990, to 55% in 2030. Of particular importance is the use of coal in energy transformation activities, principally electric power generation, but later in the production of synthetic liquid fuels.

Residential and commercial sectors have relatively stable fossil fuel CO_2 emissions during the simulation

Table 5.33. Current Policies Case Carbon Emissions by Fuel (TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total
1990	546	274	477	2	1299
1995	580	296	522	3	1401
2000	616	332	596	4	1549
2005	664	324	715	7	1709
2010	718	318	849	9	1892
2015	773	328	960	12	2073
2020	805	308	1105	17	2234
2025	834	298	1244	18	2394
2030	851	274	1399	19	2543

period 1990 to 2030. Transportation and utility sectors have an increasing number of emissions, with the utility sector increasing most dramatically near 2030 (see Figure 5.14).

Factors Affecting Carbon Emissions

The mechanism by which emissions could be reduced is a matter of some interest. The principal issue is the extent to which emissions reductions can be accomplished by different response modes. Emissions reductions can be disaggregated usefully into five different response mode categories:

1. *Energy Conservation and Activity Mix:* Reducing the energy required to provide any energy service, such as space heating, goods transport, or electric power generation. Energy conservation does not mean doing without or changing the composition of energy-using activities. An example of this change in activity would be replacing the production of goods that use ferrous metals with those which use plastics or moving away from goods and toward services.

2. *Fossil Fuel Substitution:* Changing the mix among fossil fuels to increase the proportion of low CO_2-emitting fuels relative to high CO_2-emitting fuels, for example, from coal to natural gas, or from natural gas to nuclear or renewable energy.

3. *Non-Fossil Fuel Substitution:* Substituting non-fossil fuels for fossil fuels to increase the proportion of non-CO_2-emitting fuels relative to CO_2-emitting fuels, for example, substituting coal for nuclear or renewable energy.

4. *Demand Scale:* Changing the scale of the overall human and energy systems. Examples include changing population or the level of overall economic activity, or simply doing without and thereby having less of the fruits of energy use.

5. *Carbon Removal and Recovery:* Removing carbon after combustion via traditional scrubbing or tree planting and disposing of it in a permanent repository, or removing the carbon before the fuel is combusted and then disposing of the carbon.

The effects of all emissions reductions options can be associated with one or more of the above principles. For example, the nuclear and renewable power options are non-fossil fuel substitution options, while lifestyle changes would exert an influence through several avenues, including energy conservation and activity mix and fossil fuel, biomass, and non-fossil fuel substitution. It is important to note that carbon removal and recovery technologies were not examined in this report.

In the Current Policies Case, there is little change in either the CO_2-to-fossil-fuel ratio or the fossil-fuel-to energy ratio.[a] The CO_2-to-fossil-fuel ratio is 18.7 kilograms of carbon per million Btu in 1987 and 19.9 kilograms of carbon per million Btu in 2030. This difference indicates a slight increase in the carbon intensity of fossil fuels, resulting from the increase in importance of coal in the mix of fossil fuel consumption. The fraction of energy accounted for by fossil fuels increases slightly, from 85% to 88%, during the simulation period, indicating very modest growth in the contribution of fossil fuels to total energy-related carbon dioxide emissions. The only factor in the scenario acting to reduce the emission of carbon per dollar of GNP is an overall decrease in the energy intensiveness of the economy of about 30%. Had there been no improvement in the energy-to-GNP ratio, the increase in U.S. fossil fuel CO_2 increase would have been approximately 200% rather than slightly under 100%.

(a) It is possible to quantify the relative contribution of each of the first five modalities as follows. The rate of fossil fuel carbon emissions can be written as the product of the carbon-to-fossil-fuel consumption ratio (CO_2/FF), the fossil-fuel-to-energy ratio (FF/E), the energy-to-GNP ratio (E/GNP), and the GNP, that is

$$CO_2 = (CO_2/FF) \cdot (FF/E) \cdot (E/GNP) \cdot GNP.$$

A measure of the relative contributions of the four factors just discussed can be obtained by examining the percentage changes in each of these factors relative to the percentage change in CO_2 emissions. Alternatively, one can rewrite the above equation in terms of logarithms and work with the ratio of differences in logarithms. The latter approach yields very similar results to the simpler percentage change approach, but has the one advantage that the percentage changes sum to 100 percent. We have used the latter approach.

Methane

As Table 5.34 and Figure 5.15 show, total CH_4 emissions from fossil fuel use grow from approximately 12 $TgCH_4$/yr in 1990 to approximately 20 $TgCH_4$/yr in the year 2030 in the Current Policies Case. This growth is similar to that of CO_2 emissions, though the scale of emissions is two orders of magnitude smaller for CH_4. Total emissions have three major components: methane emissions from coal mining, from oil and natural gas production and from natural gas transmission and distribution. U.S. methane emissions from landfills are included in the global warming potential computations.

The contribution of coal mining grows steadily in the Current Policies Case, from 35% of the fossil fuel contributions in 1990 to 60% in the year 2030. In absolute terms, the emissions from coal more than triple, going from 4.1 $TgCH_4$ in 1990 to nearly 12 $TgCH_4$ in 2030, precisely paralleling the domestic coal production profile.

Table 5.34. Current Policies Case Methane Emissions ($TgCH_4$/yr)

Year	Coal Mines	Natural Gas Prod	Nat. Gas Trans.& Dist.	Total
1990	4.1	2.1	5.6	11.8
1995	4.4	2.2	6.1	12.8
2000	5.1	2.5	6.9	14.5
2005	6.2	2.4	6.8	15.3
2010	7.5	2.4	6.7	16.5
2015	8.4	2.5	6.9	17.8
2020	9.6	2.3	6.5	18.4
2025	10.7	2.2	6.3	19.2
2030	11.9	2.0	5.8	19.7

Natural gas emissions peak in the year 2000 at about 9 $TgCH_4$, then remain level for about 15 years, later diminishing to slightly less than the 1990 total of 8 $TgCH_4$. Over two-thirds of the total is attributable to transmission and distribution loss, which is a function of gas consumption. The other segment, production losses, drops off more rapidly in later years, reflecting the growing role of imports. For reference purposes, these fossil-fuel-associated emissions account for one-quarter of the nation's total anthropogenic methane releases in 1990.

Global Warming Potential (GWP)

The GWP of the seven major groups of contributors to global warming is shown in Table 5.35 and Figure 5.16. Overall, the total GWP value increases by about 50%, from 7458 $TgCO_2e/yr$ in 1990 to 10,523 $TgCO_2e/yr$ in 2030. Two different forces account for this increase. The first has been detailed in previous sections: the increase in fossil fuel emissions of carbon dioxide, carbon monoxide, methane and nitrous oxide. This is driven primarily by the increase in electricity production and the dramatic expansion of coal use by that sector. The combination of electricity demand growth, fuel switching by the electric utility sector, and growth in the transportation sector in oil causes an almost 90% increase in CO_2, CO, CH_4, and N_2O. Juxtaposed to this growth is an even more dramatic 90% decrease in the contribution of CFCs and HCFCs to the GWP total as a result of U.S. compliance with the international agreements and domestic law to regulate and reduce these gases. Had CFCs and HCFCs not changed at all during the period, the GWP total would have increased by about 70% instead of 41%. Since the GWP from CFCs and HCFCs is reduced to just 174 $TgCO_2e/yr$ in 2030, this means that any further dramatic reductions in the GWP total will have to come from reductions in the other major greenhouse gases, primarily through policies to reduce electricity demand and policies that cause electric utilities and transportation to rely less on coal and oil.

5.4 NES ACTIONS CASE ASSUMPTIONS

The NES Actions Case (DOE 1991) uses all of the assumptions in the above Current Policies Case with modifications to the underlying assumptions of the model. The additional model assumptions and modifications to the Current Policies Case assumptions necessary for the NES Actions Case in the Fossil2 Model are provided below.

5.4.1 Clean Coal Technologies (CCTs) Market Incentives

Regulatory reforms and market incentives are expected to result in an accelerated penetration of certain CCTs into the marketplace. The model

Table 5.35. Current Policies Case GWP-Weighted Energy-Related Greenhouse Gas Emissions ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs	HCFCs	Total
1990	4527	455	626	17	1,689	144	7,458
1995	4854	488	640	19	1,062	326	7,388
2000	5313	534	728	21	360	299	7,255
2005	5811	584	790	24	326	254	7,789
2010	6383	641	828	28	179	366	8,425
2015	7012	705	838	31	58	458	9,102
2020	7574	761	824	35	5	470	9,668
2025	8130	817	813	38	3	350	10,151
2030	8649	869	789	42	2	172	10,523

represents these incentives with earlier commercialization dates for these technologies than in the Current Policies Case. In the NES, the integrated gasification combined cycle (IGCC) is commercialized in 1994, rather than the year 2000; the pressurized fluidized bed in 1996, instead of 2000; and coal gasification ISTIG (intercooled steam-injected turbine) in 2000, rather than in 2005.

5.4.2 Clean Air Act Amendments of 1990 (CAAA-90) *Controls on NO_x and SO_2 Emissions*

The CAAA-90 requires that SO_2 emissions from electric utilities not exceed a cap of 8.9 million tons by the year 2000, with a permanent cap on SO_2 emissions at that level thereafter. Installation of devices for controlling emissions of NO_x from existing coal-fired electric utility powerplants will also be implemented. Utility NO_x emissions must also be reduced 2 million tons by the year 2000.

5.4.3 Nuclear Regulatory Reform

Reform of the U.S. Nuclear Regulatory Commission (NRC) licensing process will reduce the lead time and financial risk associated with building nuclear powerplants. It accelerates the introduction of advanced design nuclear powerplants and standard powerplant designs. The reform of the nuclear regulating institutions allows nuclear technologies to compete for new base-load electricity generating requirements. In the model, an advanced light-water reactor (ALWR) is assumed to be commercially available in 1996 with a capital cost of $1490/kW (1989 dollars). In the Current Policies Case, the technology is made available in the year 2000, but it is not until the year 2020 that it is available at the same cost. In the NES scenario, a generic second generation technology is assumed to be available in the year 2000 with a capital cost of $1775/kW (1989 dollars). The attractiveness of this second technology is enhanced because it has a lower financial risk factor than does the ALWR, due to its passive safety features and smaller size. In the model, these two technologies are allowed to compete at their respective capital costs with the other generating technologies for base-load power generation. In addition to new nuclear plants, the model assumes that, under the NES Actions, 70% of existing light-water reactor (LWR) plants are life-extended to operate an additional 20 years. Life-extension is captured in the model by decreasing the LWR retirement rates accordingly and capitalizing the life-extension costs.

5.4.4 Hydroelectric Regulatory Reform

The NES proposes to streamline the Federal Energy Regulatory Commission (FERC) regulatory process to increase hydroelectric capacity and generation when it is economically feasible and when its environmental effects are limited. Hydroelectric production from large facilities is exogenous to the model, but small hydroelectric facilities (independent powerplants or IPP) compete with other technologies for base-load generation. The NES Actions are expected to increase hydroelectric capacity by about 16 gigawatts (GW) by the year 2030. In addition, improvements to the regulatory environment and R&D advances in mitigation strategies will also help retain the 22 GW of capacity due for Federal relicensing by 2010.

5.4.5 Additional Municipal Solid Waste (MSW) Electric Generating Capacity

Because MSW construction in the marketplace is, to a large extent, driven by non-energy cost considerations such as landfill capacities and refuse tipping fees, total MSW generation capacity is treated exogenously by Fossil2. With the NES Actions to encourage the conversion of MSW to energy, waste-to-energy (WTE) plants are expected to provide up to 2.1 quads of energy for electricity generation by the year 2010.

5.4.6 Advanced Oil Research and Development

Under the NES, research and development funding will promote the development of the advanced oil recovery technologies that will increase domestic reserves and production rates. The proposed R&D measures would result in additional oil production that would reach 1.4 million barrels/day (mbd) by 2000 and reach 3.0 mbd to 3.4 mbd in 2010. A

15% tax credit for tertiary enhanced oil recovery is also included. Modifications of the percentage depletion rules that will primarily benefit marginal production are incorporated directly into the model at a starting date of 1990. This depletion allowance is allowed on the incremental production resulting from new Enhanced Oil Recovery (EOR) techniques.

5.4.7 Access to Oil and Gas in Arctic National Wildlife Refuge (ANWR)

This option allows environmentally responsible oil and gas exploration in the ANWR area. Oil production from the ANWR is exogenous to the model and is based on analysis provided by the EIA in 1987. The ANWR is activated in the model by setting the starting date for production, estimated to be the year 2001. Based on conservative estimates of conditional mean resources, production could amount to an additional 870,000 barrels of oil per day by 2005.

5.4.8 Access to Oil and Gas in the Restricted Areas of the Federal Outer Continental Shelf (OCS)

This option allows for oil and gas exploration in the restricted federal OCS regions. In the model, oil and gas production from OCS is treated exogenously. Under the NES, OCS oil and gas production begin in 2000 and are added to the remaining production totals from conventional offshore oil and gas production. The average estimate of recoverable resources from these areas is about 3.1 billion barrels of oil and 9.4 trillion cubic feet of natural gas. The OCS resource estimates are based on Department of Interior estimates.

5.4.9 Natural Gas Pipeline Production

This NES option will promote a more efficient, accessible natural gas transportation and distribution system. Reform of Federal regulations will allow timely construction of new pipeline capacity, liquefied natural gas facilities, and storage capacity. It will encourage more efficient pricing of pipeline service which will, in turn, will lower residential and commercial gas prices. In the model, these gas price changes are incorporated by reducing gas transportation margins. Another estimated effect of these options is a decreased financial risk for new gas production facilities, which is represented in the model by reduced capital charge rates for the new facilities. These reform actions are projected to increase natural gas consumption by about 0.9 tcf in 1995 and about 1.1 tcf in 2010. This increased demand is implemented in the model in each of the demand sectors by increasing the potential markets in which natural gas can compete.

5.4.10 Unconventional Fuels Tax Credit

The unconventional fuels credit was extended two years by the Omnibus Budget Reconciliation Act of 1990 and will be available for production sold before the year 2003 from wells drilled before 1993. The unconventional fuels credit applies to gas produced from tight formations, coal seams, and Devonian shale. This tax credit is incorporated directly into the financial structure of the model with a start date of 1990 and an end date of 1993.

5.4.11 Ethanol Tax Credit

Tax credits for ethanol production were renewed in 1990 by the Omnibus Budget Reconciliation Act of 1990. Ethanol production is estimated to increase due to the extension of the credits through the year 1996. Ethanol production is exogenous in the Fossil2 Model, although it is represented in the model by directly increasing the amounts of ethanol production to match the values in the estimated increase in production resulting from the tax credits.

5.4.12 Transportation Energy Efficiency R&D and Alternate-Fuel Vehicles

Advanced propulsion technologies and alternative fuels can be expected to significantly increase efficiency and reduce pollution. The NES provides for transportation energy-efficiency improvements and use of alternative transportation fuels that should allow continued growth in travel, but require less petroleum than is used today. Implementation of the NES is projected to reduce U.S. reliance on oil. The alternative fuel and energy-efficiency initiatives

included in the NES and the Clean Air Act Amendments of 1990 are expected to reduce U.S. oil imports by about 2 mbd by 2005 and 3.5 mbd by 2010. Estimates of oil import reductions range up to 8 mbd by 2030. This reduction in consumption is the single largest contributor to the cut in the oil imports projected. Significant production of domestic biofuels will begin around 2010, rising to about 50% of total alternative fuel use by 2030.

5.4.13 Energy Efficiency Standards for Federally Subsidized Buildings

State and local adoption and vigorous enforcement of the federal building standards designed to improve energy efficiency, including new industry efforts in quality control, could save up to 0.2 quad per year by 2010. Retrofits and other energy management improvements in public housing could save up to 0.02 quad, and up to 0.1 quad might be saved by 2010 in new and existing homes because of home buyer and builder responses to mortgage loans that give proper credit for energy cost savings. Total estimated savings from these programs is 1.0 quad in 2030.

5.4.14 Integrated Resource Planning (IRP)

The Integrated Resource Planning (IRP) actions are a variety of planning instruments designed to encourage the integration of resource planning through federal support of state programs, information-sharing, and demonstration projects. Increased federal support and state implementation of IRP activities are expected to reduce required capacity by about 54,000 megawatts (MW) of generating capacity in 2010 and 96,000 MW in 2030. This represents about a 6% reduction in required generating capacity in 2010, compared with the Current Policies Case.

5.4.15 Industrial Energy Efficiency Research and Development

The NES encourages cost-effective measures to reduce energy costs, increase energy efficiency, and reduce industrial waste generation. Increases in R&D funding for industrial energy efficiency are estimated to result in higher efficiency gains for available and new conservation technologies. With these actions, the industrial sector, on average, would be 5% more energy efficient in 2005, 10% more efficient in 2010, and more than 15% more efficient in 2030. This effect is modeled through the use of multipliers that adjust the conservation supply curves by increasing the amount of conservation available at the same costs.

5.5 NES ACTIONS RESULTS

This section presents the results of the simulations for the NES Actions Case. As in Section 5.3, results are reported for energy prices, energy consumption, energy transformation, energy production and imports, and greenhouse gas emissions.

5.5.1 Energy Prices

This section discusses the energy price results of the NES Actions Case simulation conducted using the Fossil2 Model. Energy prices are shown in Table 5.36. The results for the prices of primary energy resources--oil, natural gas, and coal--are described below in more detail.

Oil Prices

The world oil price trajectory is shown in Figure 5.17. The time path of world oil prices shown here follows the same general pattern as for the Current Policies Case, at first decreasing and then increasing at a slowly declining rate. The fundamental difference between the two cases is that the world oil price rises more gradually with the NES Actions in effect. Thus, by 2030, the world price of oil in the NES Actions Case is $7.07, as opposed to $8.12 in the Current Policies Case. Refiner crude costs and prices for refined petroleum products such as gasoline follow the world oil price closely in both the Current Policies and the NES Actions Cases. As a result,

Table 5.36. NES Actions Case Energy Prices

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.46	$3.46	$2.38	$1.07	$8.49
2000	$4.56	$4.56	$3.89	$1.12	$9.70
2005	$5.03	$5.03	$4.16	$1.15	$10.23
2010	$5.52	$5.52	$5.12	$1.25	$10.78
2015	$6.15	$6.15	$6.07	$1.31	$11.47
2020	$6.56	$6.56	$6.59	$1.37	$11.93
2025	$6.88	$6.88	$6.60	$1.42	$12.29
2030	$7.07	$7.07	$7.33	$1.47	$12.50

NES Actions Energy Prices (contd)

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.22	$1.69	$18.82	$20.06
2000	$7.67	$1.74	$20.02	$26.43
2005	$7.98	$1.78	$20.74	$29.20
2010	$8.89	$1.92	$21.04	$32.02
2015	$9.82	$2.00	$20.70	$35.66
2020	$10.35	$2.09	$21.57	$38.07
2025	$10.43	$2.15	$21.88	$39.93
2030	$11.13	$2.22	$21.77	$41.01

differences in these product prices closely mirror those differences in the price pattern of the primary resource.

Natural Gas Prices

The time trajectory of the wellhead price of natural gas, shown in Figure 5.18 is virtually identical to that depicted previously for the Current Policies Case. Natural gas prices in the NES Actions Case are slightly higher than in the Current Policies Case from 1990 to just before 2005. Thereafter, simulated natural gas prices under the NES Actions are somewhat lower than in the Current Policies Case. However, the differences are very small. In 2030, for example, the wellhead price of natural gas is just thirteen cents lower in the NES Actions Case than it was in the Current Policies Case.

Coal Prices

The minemouth price of coal, as shown in Figure 5.19, remains relatively stable over the entire period and, like the other price series discussed above, closely tracks, but remains below the price trajectory in the Current Policies Case. By the end of the simulation period, the minemouth price of coal in the NES Actions Case is only twelve cents below the

price of coal in the Current Policies Case. This represents less than 2% of the 2030 price value for either of the two cases.

Electricity Prices

The price trajectory for electricity is shown in Figure 5.20. As in the Current Policies Case, the path of electricity prices over time is even more stable than that of coal, the most important input to electricity production. Moreover, it is virtually identical to the price path of electricity in the Current Policies Case. In 2030, electricity prices in the NES Actions Case are just nine cents below the price of electricity in the Current Policies Case.

5.5.2 Energy Consumption

Between 1990 and 2030, total energy consumption grows by about 48% in the NES Actions Case, as opposed to 69% in the Current Policies Case (see Table 5.37). By 2030, total energy consumption in the NES Actions Case is 18 quads lower than in the Current Policies Case. The pattern of growth over time in both cases is the same, consisting of a continuing decline in the rate of growth over the entire period. However, in the NES Actions Case, the decrease in the rate of growth of consumption is more pronounced than in the Current Policies Case. The most important differences between the NES Actions Case and Current Policies Case are significantly reduced oil and coal consumption, which is partially replaced with higher nuclear and renewable energy consumption.

Oil Consumption

In the NES Actions Case, domestic oil consumption increases from 34.4 quads in 1990 to a high of 38.3 quads in 2015, then decreases to 35.6 quads in 2030, fully 16.4 quads below domestic oil consumption in the Current Policies Case in that year. In the process, the relative importance of oil changes very dramatically over this period of time. In 1990, oil is the single most important energy source in the U.S. economy, accounting for 40% of total energy consumption. By 2030, however, oil's share of total consumption has fallen to under 30% in the NES Actions Case, as opposed to 36% in the Current Policies Case.

Tables 5.38 through 5.41 show energy consumption by fuel for various sectors. As indicated, oil consumption is not distributed evenly throughout the economy. This is true in both the NES Actions and the Current Policies Case. However, in the NES Actions Case, the distribution of oil consumption among the various sectors changes in a different way.

Table 5.37. NES Actions Case Energy Consumption (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.7	22.2	20.0	6.0	7.7	0.8	91.5
2000	35.9	24.7	22.3	6.2	9.0	1.2	99.2
2005	37.3	23.9	25.0	6.5	10.3	2.1	105.3
2010	38.0	22.8	27.8	7.0	11.9	3.4	110.9
2015	38.3	23.8	28.9	6.9	14.5	3.4	115.9
2020	37.8	23.5	29.5	8.3	17.3	3.5	119.9
2025	36.6	21.9	31.0	10.5	20.2	3.5	123.7
2030	35.6	20.2	32.3	12.5	22.4	3.5	126.6

Table 5.38. NES Actions Case Electricity Fuel Consumption by Fuel (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.6	5.3	17.1	6.0	4.6	34.7
2000	1.0	6.7	19.2	6.2	5.5	38.7
2005	1.1	6.0	21.7	6.5	6.3	41.6
2010	1.1	5.1	24.2	7.0	7.1	44.5
2015	1.6	6.5	25.1	6.9	7.9	48.0
2020	1.5	6.7	25.8	8.3	9.4	51.7
2025	1.0	5.2	27.3	10.5	10.9	54.9
2030	0.7	3.9	28.7	12.5	12.3	58.1

Table 5.39. NES Actions Case Residential Energy Consumption by Fuel (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.6	4.9	0.1	0.9	3.2	10.7
1995	1.3	4.8	0.1	1.0	3.5	10.8
2000	1.2	5.1	0.1	1.1	3.8	11.3
2005	1.0	5.1	0.1	1.2	4.1	11.5
2010	0.9	5.1	0.1	1.4	4.3	11.8
2015	0.9	5.0	0.1	1.5	4.6	12.0
2020	0.8	4.8	0.1	1.6	4.9	12.2
2025	0.7	4.7	0.1	1.7	5.2	12.3
2030	0.7	4.6	0.1	1.8	5.4	12.5

Table 5.40. NES Actions Case Commercial Energy Consumption by Fuel (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.0	2.8	0.1	0.1	2.9	6.9
1995	0.9	2.7	0.1	0.1	3.4	7.2
2000	0.8	2.8	0.1	0.1	3.9	7.7
2005	0.8	2.8	0.1	0.1	4.4	8.2
2010	0.8	2.8	0.1	0.2	4.9	8.7
2015	0.8	2.8	0.0	0.2	5.5	9.3
2020	0.7	2.9	0.0	0.3	6.0	9.9
2025	0.8	2.9	0.0	0.3	6.5	10.5
2030	0.8	3.0	0.0	0.4	6.9	11.1

Table 5.41. NES Actions Case Industrial Energy Consumption by Fuel (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	8.7	8.2	2.8	1.8	3.1	24.6
1995	9.3	8.8	2.6	1.8	3.5	25.9
2000	9.6	9.2	2.7	2.1	4.1	27.6
2005	10.3	8.9	3.1	2.4	4.3	29.1
2010	11.3	8.5	3.4	2.7	4.4	30.2
2015	11.8	8.3	3.6	2.9	4.6	31.1
2020	12.5	7.9	3.5	3.2	5.0	32.0
2025	13.1	7.9	3.5	3.5	5.3	33.3
2030	14.1	7.5	3.4	3.8	5.7	34.5

Specifically, the industrial share of oil consumption increases from about 25% to 40% of total oil consumption, while the transportation share of oil consumption remains constant over the entire time period at about 63%. This is in sharp contrast to the Current Policies Case, where the transportation share increases and the industrial share remains nearly constant.

Gas Consumption

Natural gas follows a pattern of growth, peak, and decline almost identical to that in the Current Policies Case. Projected gas consumption increases from 19.2 quads in 1990 to 24.7 quads in 2000, about a quad higher than in the Current Policies Case. For the next 15 years of the simulation period, natural gas consumption fluctuates somewhat, but remains essentially constant. Starting in 2015, natural gas consumption declines from 23.8 quads to 20.2 quads, ending the period 0.2 quad higher than in the Current Policies Case. Over the entire period, the share of natural gas consumption declines from about 23% in 1990 to just over 16% in 2030, compared to 14% for the Current Policies Case. Finally, the distribution of gas across the various sectors does not change markedly from the Current Policies Case.

Coal Consumption

The most dramatic difference between the two cases is in coal consumption. In the Current Policies Case, coal consumption triples from 19 quads per year in 1990 to 55 quads per year in the year 2030. In the NES Actions Case, coal consumption still increases, but the rate of growth over the entire simulation period falls from about 200% to 80%. By 2030, coal consumption in the NES Actions Case is almost 20 quads less than in the Current Policies Case. In the process, coal's share in total consumption increases by just a small fraction, from about 23% to 26% in the NES Actions Case, compared to 38% under the Current Policies Case.

Renewable Energy Consumption

In the Current Policies Case, renewable energy consumption increases from 6.8 quads in 1990 to 16.9 quads in 2030. This growth is fairly evenly spread over the consuming sectors. In the NES Actions Case, consumption of renewables at the end of simulation period is 5.5 quads higher than in the Current Policies Case. In relative terms, its share of total consumption more than doubles in the NES Actions Case, from 8.8% in 1990 to 18% in 2030, fully

6.5% higher than its share in the Current Policies Case in 2030. Most of the additional growth in the consumption of renewables in the NES Actions Case is concentrated in the electric utility industry and the transportation sector.

Nuclear Consumption

Nuclear consumption in the Current Policies Case follows a pattern of decline as old nuclear powerplants are retired and this capacity is replaced by other fuels. However, under the NES Actions, the nuclear industry revives. In 1990, nuclear capacity constitutes just 5.9 quads of energy consumption, but by 2030, energy consumption associated with this fuel has increased to 22.4 quads in the NES Actions Case, 22 quads higher than in the Current Policies Case. In the process, its share of total consumption increases from about 7% in 1990 to 18% in 2030.

5.5.3 Energy Transformation

Electric Power Generation

The demand for electric power is shown in Figure 5.21. It grows by about 112% between 1990 and 2030, from 9.2 quads to 18.4 quads per year. This can be compared to the Current Policies Case results where electricity consumption grows by about 150%, or 21.2 quads, by 2030. Thus, the difference in total energy consumption between the two scenarios is relatively modest. In addition, this decreased consumption is spread relatively evenly over all of the electricity-consuming sectors in the economy.

In the NES Actions Case, average fuel efficiency increases very slightly, from 30% to about 31% between 1990 and 2030 as new "clean coal" technologies penetrate the market. This is slightly less than the growth in efficiency in the Current Policies Case because renewable and nuclear energy partially replace coal inputs to electricity production. The loss of growth is due to higher conversion losses associated with renewable and nuclear energy. Figure 5.22 shows electric utility energy consumption by fuel. Coal fuel share, which increased from 54% in 1990 to 77% in 2030 in the Current Policies Case accounts for only 49% in 2030 under the NES Actions Case. In fact, with the exception of renewable, which increases its share of fuel use by the electric utility sector from 13% to 21% over the period, all of the input shares of the remaining fuels (coal, oil, and natural gas) decrease.

5.5.4 End-Use Energy Consumption

The end-use energy consumption result is presented in Table 5.42. Total end-use energy consumption grows from 64.6 quads in 1990 to 84.8 quads in 2030 under the NES Actions Case, as opposed to 99.6 quads in the Current Policies Case. This decline in total energy consumption is due almost entirely to decreases in end-use energy consumption by the transportation sector and, to a lesser extent, the industrial sector, as seen in Figure 5.23.

Residential Sector

Total residential end-use energy consumption in Figure 5.24 grows by approximately 17% between 1990 and 2030 under the NES Actions Case, as opposed to 21% under the Current Policies Case. In absolute terms, this translates into a difference of less than one-half quad of energy in 2030. This small decrease in energy consumption in 2030 across the two cases is due largely to an equally small decrease in electricity consumption, which is partially offset by a small increase in gas consumption in the NES Actions Case.

Commercial Sector

Commercial end-use energy consumption is shown in Figure 5.25. Here, too, there is very little difference between the two cases. In 2030, commercial energy consumption is 0.4 quad lower in the NES than it is in the Current Policies Case. Again, this is due almost entirely to slightly lower electricity use by the commercial sector under the NES Actions Case.

Table 5.42. NES Actions Case Total End-Use Energy Consumption (quads)

Year	Res	Comm	Ind	Tran	Total
1990	10.7	6.9	24.6	22.4	64.6
1995	10.8	7.2	25.9	23.5	67.4
2000	11.3	7.7	27.6	25.6	72.3
2005	11.5	8.2	29.1	27.5	76.3
2010	11.8	8.7	30.2	28.9	79.7
2015	12.0	9.3	31.1	29.7	82.1
2020	12.2	9.9	32.0	29.5	83.6
2025	12.3	10.5	33.3	29.1	85.3
2030	12.5	11.1	34.5	27.9	86.0

Industrial Sector

Total energy use in the industrial sector, shown in Figure 5.26, grows by approximately 40%, from about 24.6 quads to 34.5 quads per year between 1990 and 2030. This can be contrasted with an overall rate of growth of 57% in the Current Policies Case. Nevertheless, by 2030, energy consumption by this sector in the NES Actions Case is only 6 quads less than in the Current Policies Case. This is due to lower consumption of electricity, coal, natural gas, and, remarkably, renewables in the NES Actions Case. Oil use is slightly higher in the NES Actions Case in 2030, but this difference is very small.

Transportation Sector

The NES Actions have a substantial impact on energy consumption by the transportation sector, whose energy consumption is shown in Figure 5.27. Under the NES Actions, transportation fuel use increases by 25% over the 40-year simulation period, as opposed to a 65% increase under the Current Policies Case. This translates into a 10-quad difference in energy consumption by the year 2030. This difference in the NES Actions Case is partially attributable to the consumption of alcohol and renewables as fuel in addition to oil for transportation. Oil consumption remains virtually constant in the NES Actions Case, while increasing by almost 15 quads in the Current Policies Case. By 2030, the renewable share of transportation energy consumption is 14% in the NES Actions Case, as opposed to about 1.5% in the Current Policies Case.

5.5.5 Energy Production and International Trade

The growth of total domestic energy production under the NES Actions Case, as shown in Table 5.43, is virtually identical to that projected for the Current Policies Case. Total energy supply in the NES Actions Case in 2030 is only 2.6 quads lower than in the Current Policies Case in the same year. However, the structural changes in total energy consumption are quite a bit different in the two cases. The rapid growth of coal production projected to occur in the Current Policies Case does not take place in the NES Actions Case. Instead, coal production grows at a more modest rate, while production from nuclear sources and renewable picks up dramatically.

Domestic Oil and Gas Supply

Under the NES Actions Case, domestic production of oil increases from 17.9 quads in 1990 to 21.9 quads in 2005, then declines steadily to 10.9 quads in 2030, about 2 quads higher than in the Current Policies Case. This arch in production is due to the development and use of untapped sources of domestic crude oil supplies. Natural gas production follows a similar pattern, finishing the period at 17.6 quads.

Table 5.43. NES Actions Case Energy Supply (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.8	20.3	22.6	6.0	7.7	72.4
2000	18.3	22.4	25.6	6.2	9.0	81.5
2005	21.9	21.1	29.4	6.5	10.3	89.3
2010	21.4	20.1	33.6	7.0	11.9	93.9
2015	17.6	21.2	35.3	6.9	14.5	95.5
2020	15.0	21.0	36.3	8.3	17.3	98.0
2025	12.5	19.6	38.0	10.5	20.2	100.9
2030	10.9	17.6	39.5	12.5	22.4	102.9

Domestic Coal Supply

Coal production triples in the Current Policies Case between 1990 and 2030, growing from 21.6 quads to 62.1 quads. However, in the NES Actions Case, coal production increases by slightly less than 100%, reaching 39.5 quads in 2030. Throughout this period, the domestic coal supply share of total production increases from 29% to 38% under the NES Actions Case, compared to 59% under the Current Policies Case.

Nuclear and Renewable Production

As previously indicated, both nuclear energy production and production from renewable resources increase much more rapidly under the NES than under the Current Policies Case. In the Current Policies Case, nuclear power is virtually zero by 2030, while in the NES Actions Case, it accounts for 12.5 quads, or about 12% of total domestic supply. Renewable production, which increased from 6.8 quads to 16.9 quads in the Current Policies Case, reaches 22.4 quads, or 22% of domestic production, in 2030 under the NES Actions Case.

International Trade

An important result of the NES Actions is that they are projected to make the U.S. less dependent upon foreign oil. In the Current Policies Case, oil imports grow from 16.5 quads per year in 1990 to 43.2 quads per year in 2030. In the NES Actions Case (see Table 5.44 and Figure 5.28), energy imports fluctuate between 15 quads and 19 quads over the period 1990 to 2010. Thereafter, imports increase slowly, reaching 23.7 quads in 2030, fully 15.4 quads below the Current Policies Case projection for that year. Natural gas imports and coal exports under the NES Actions Case are virtually identical to those projected for the Current Policies Case. Imports of alcohol (methanol for transportation fuel) rise from negligible levels in 1990 to 3.2 quads in 2030.

Carbon Dioxide

Fossil fuel carbon emissions, shown in Figure 5.29, increase by 33% between 1990 and 2030, growing from 1299 TgC/yr to 1707 TgC/yr (see Table 5.45). This can be contrasted with a roughly 100% rate of growth projected for the Current Policies Case over the same time period. Fossil fuel emissions under the NES Actions Case in 2030 are 836 TgC below the Current Policies Case value. Of this change, 31% is due to reduced emissions associated with oil and slightly less than 69% is due to reduced emissions associated with coal. Emissions associated with natural gas are negligible. The increase in fossil fuel carbon emissions occurs essentially between 1990 and 2015, with the added growth after 2015 equalling less than 1%.

Table 5.44. NES Actions Case Energy Trade (quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	16.5	1.4	(2.6)	0.1	0	15.4
1995	18.9	1.9	(2.6)	0.2	0.7	19.1
2000	17.6	2.3	(3.3)	0.2	1.0	17.8
2005	15.4	2.8	(4.3)	0.2	1.9	16.0
2010	16.6	2.8	(5.8)	0.2	3.2	17.0
2015	20.7	2.7	(6.4)	0.3	3.2	20.4
2020	22.7	2.4	(6.8)	0.3	3.2	21.9
2025	24.0	2.3	(7.1)	0.3	3.2	22.8
2030	24.8	2.6	(7.2)	0.4	3.2	23.7

Table 5.45. NES Actions Case Carbon Emissions by Fuel (TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total
1990	546	274	477	2	1299
1995	548	313	511	3	1376
2000	567	347	568	4	1487
2005	595	334	639	6	1573
2010	609	316	710	7	1640
2015	621	330	737	8	1695
2020	618	324	753	14	1710
2025	601	302	89	18	1710
2030	587	278	824	18	1707

Within the residential, industrial, and commercial sectors, the CO_2 emissions remained stable in the NES Actions Case during the period 1990 to 2030. Transportation had a minimal increase. The utility sector CO_2 emissions increased slightly near the year 2030, but not as much as in the Current Policies Case (see Figure 5.30).

Factors Affecting Carbon Dioxide Emissions

In the NES Actions Case, there is a small increase in the CO_2-to-fossil-fuel ratio, from 17.9 TgC/quad in 1990 to 18.6 TgC/quad, as seen in Table 5.46. Under the Current Policies Case, the CO_2-to-fossil-fuel ratio is 17.9 TgC/quad in 1990 and 20.0 TgC/quad in 2030. The fraction of energy accounted for by fossil fuels declined dramatically in the NES Actions Case, from 85% in 1990 to 72% in 2030. In the Current Policies Case, this fraction increased slightly, from 85% to 88% during the simulation period. The ratio of energy use per dollar of GNP also decreases 44% in the NES Actions Case, from 0.016 quads/billion 1989$ to 0.009 quads/billion 1989$, indicating a substantial improvement in the energy efficiency of the economy.

Methane

As Table 5.47 and Figure 5.31 show, total CH_4 emissions from fossil fuel use grow from approximately 12 $TgCH_4$/yr in 1990 to approximately 15 $TgCH_4$/yr in the NES Actions Case in 2030, as

Table 5.46. Carbon-to-Fossil-Fuel Ratio Comparison Between NES Actions and Current Policies Cases

Year	Current Policies Case (TgC/quad)	NES Actions Case (TC/quad)
1990	17.9	17.9
1995	17.9	17.9
2000	18.0	17.9
2005	18.4	18.2
2010	18.6	18.4
2015	18.8	18.5
2020	19.2	18.7
2025	19.5	18.8
2030	19.9	19.2

Table 5.47. NES Actions Case Methane Emissions ($TgCH_4$/yr)

Year	Coal Mines	Natural Gas Prod.	Nat. Gas Trans. & Dist	Total
1990	4.1	2.1	5.6	11.8
1995	4.3	2.4	6.5	13.2
2000	4.9	2.6	7.2	14.7
2005	5.6	2.5	7.0	15.1
2010	6.4	2.4	6.7	15.4
2015	6.7	2.5	7.0	16.2
2020	6.9	2.5	6.9	16.2
2025	7.3	2.3	6.4	16.0
2030	7.5	2.1	5.9	15.5

opposed to 20 $TgCH_4$/yr in the Current Policies Case. Almost all of this difference is accounted for by decreased emissions from coal mining. Methane emissions from landfills have been constrained by the Clean Air Act.

Global Warming Potential (GWP)

The GWP of the seven major groups of contributors to global warming is shown in Table 5.48 and Figure 5.32. Overall, the total GWP value decreases by about 5%, from 7458 $TgCO_2e$/yr in 1990 to 7082 in 2030. This is about 33% lower than the terminal GWP total in the Current Policies Case. Perhaps more interesting is the fact that total GWP actually decreases to 6843 $TgCO_2e$/yr in the year 2000, but then starts to increase slowly after that, peaking from 2015 to 2020 and then declining again. The NES Actions actually stabilize total GWP for the total analysis period below the 1990 level.

By far the largest contributor to greenhouse gas emissions reduction by the year 2030 was nuclear power. The second largest was transportation R&D and alternate-fuel vehicles. Other significant single contributors include industrial energy efficiency, and energy efficiency and IRP. In the year 2000, energy efficiency and IRP, transportation R&D and alternate-fuel vehicles, municipal solid waste, and natural gas reform were the largest single contributors to greenhouse gas emissions reductions (see Figures 5.33 and 5.34).

It is important to note that the difference in total GWPs across the two scenarios is not due to differences in CFC and HCFC production. Decreases in emissions from these two groups of greenhouse gases occur entirely under the Current Policies Case. No additional decreases occur under the NES Actions. This means that all of the differences in the GWP totals are accounted for by decreased emissions from other gases/fuels. Fully 85% of the difference between the two scenarios in 2030 is due to decreases in CO_2 emissions; about 9% is due to decreased CO emissions in the NES and about 6% to decreased CH_4 emissions.

The impacts of the NES Actions Case are substantially different from those of the Current Policies Base Case. The implementation of the National Energy Strategy has a profound effect on the future course of U.S. energy and greenhouse gas emissions. GWP-weighted emissions decrease 5% from 1990 to 2030 and never rise above 1990 levels. This is about 33% lower than the terminal GWP-weighted emissions anticipated under in the Current Policies Case.

Fossil fuel carbon emissions increase by 33% over the period between 1990 and 2030, compared to a roughly 100% growth projected for the Current

Table 5.48. NES Actions Case GWP-Weighted[a] Energy-Related Greenhouse Gas Emissions ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs[b]	HCFCs[c]	Total
1990	4527	455	626	17	1689	144	7458
1995	4765	479	493	18	1062	326	7143
2000	5096	512	556	20	360	299	6843
2005	5338	536	589	22	326	254	7064
2010	5506	553	605	23	179	366	7233
2015	5697	572	613	24	58	458	7422
2020	5747	577	608	24	5	470	7431
2025	5747	577	590	25	3	350	7293
2030	5737	576	569	26	2	172	7082

(a) 100-year integration period.
(b) CFCs include CH_3, CCl_3, CCl_4, and halons.
(c) HCFCs include HCFC and HFC.

Policies Base Case over the same time period. Of this reduction, 31% is due to reduced emissions associated with oil and 69% to reductions in coal-related emissions. Most of the difference between the two scenarios in 2030 is due to decreases in CO_2 emissions.

The most dramatic change in energy production and use between the Current Policies and NES Actions Cases is in coal production and use. In the NES Actions Case, coal consumption still increases, but the rate of growth over the entire simulation period falls from about 200% to 80%. Total primary energy consumption grows only 45% in the NES Actions Case, as opposed to 80% in the Current Policies Base Case. Oil consumption increases 9% by the year 2030. Natural gas follows a peaking pattern similar to that seen in the Current Policies Case, decreasing by 17% by 2030, compared to the 1987 levels. Renewable energy grows approximately 150% by the year 2030 in the NES Actions Case.

The importance of various policy instruments within the National Energy Strategy Actions package in reducing potential U.S. GWP-weighted emissions varies with time. Over the course of the next decade, integrated resource planning, energy efficiency actions, greater use of alternate-fuel vehicles, waste-to-energy plants, and natural gas reforms are important. By the year 2030, increased transportation fuel efficiency and expanded use of alternative fuels and alternative vehicles, expanded use of nuclear energy, energy efficiency and integrated resource planning efforts, and industrial energy efficiency improvements will all contribute to the significant reduction in emissions.

The results of the NES Actions Case (DOE 1991) form the point of departure for the analysis of further actions that follows.

5.6 SENSITIVITY ANALYSIS: NES ACTIONS WITHOUT NUCLEAR POWER

5.6.1 Assumptions

As discussed in the introduction to this chapter, a sensitivity analysis has been performed using the NES Actions Case without new or life-extended nuclear power as an alternative reference scenario. The results of this alternative also serve as a point of reference for sensitivity analyses in the chapters that follow.

In this case, the results with nuclear power are identical to those in the Current Policies Case; that is, existing nuclear plants continue to operate until they

reach retirement age, but no existing nuclear plants are life-extended, and no new nuclear plants are constructed. The purpose of this case is to illustrate the results of greenhouse gas emissions reductions policies in light of uncertainties in defining a starting point.

5.6.2 Summary of Results

Without new nuclear power, fossil fuels retain a considerable share of the market for electricity generation. Coal and renewable energy sources make up for much of the electricity that was generated with nuclear energy under the NES Actions. Table 5.49 shows the fuel inputs to electricity generation under the NES Actions Without Nuclear Case.

Table 5.50 shows carbon emissions for the NES Actions Without Nuclear Case. These carbon emissions form the reference point for the sensitivity analyses in the next chapters. The carbon emissions here are generally 10% to 20% higher than projected in the NES Actions Case. With this alternative case serving as the starting point, emissions reductions policies have farther to go in meeting emissions reductions targets. GWP-weighted emissions for the NES Actions Without Nuclear Case are also provided in Table 5.51.

Table 5.49. NES Actions Without Nuclear Electricity Fuel Consumption by Fuel (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.6	5.3	17.1	6.0	4.6	34.7
2000	1.0	6.8	19.2	6.2	5.5	38.7
2005	1.1	6.0	21.7	6.4	6.3	41.5
2010	1.1	5.2	24.5	6.4	7.1	44.4
2015	1.6	6.9	26.3	4.5	8.3	47.5
2020	1.2	6.2	29.6	3.5	10.1	50.6
2025	0.9	5.6	33.3	1.8	11.7	53.3
2030	0.5	3.8	38.1	0.4	13.2	56.1

Table 5.50. NES Actions Without Nuclear Carbon Emissions by Fuel (TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total
1990	546	274	477	2	1299
1995	548	313	511	3	1376
2000	567	347	568	4	1487
2005	594	334	641	6	1576
2010	609	317	719	7	1651
2015	621	334	766	10	1731
2020	611	318	849	18	1795
2025	599	310	943	20	1872
2030	583	276	1063	20	1942

Table 5.51. NES Actions Without Nuclear GWP-Weighted[a] Energy-Related Greenhouse Gas Emissions ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs[b]	HCFCs[c]	Total
1990	4527	455	626	17	1689	144	7458
1995	4765	479	493	18	1062	326	7143
2000	5096	512	556	20	360	299	6843
2005	5346	537	590	22	326	254	7074
2010	5543	557	607	24	179	366	7276
2015	5822	585	620	25	58	458	7568
2020	6046	607	620	27	5	470	7774
2025	6311	634	619	29	3	350	7946
2030	6557	659	606	31	2	172	8026

(a) 100-year integration period.
(b) CFCs include CH_3, CCl_3, CCl_4, and halons.
(c) HCFCs include HCFC and HFC.

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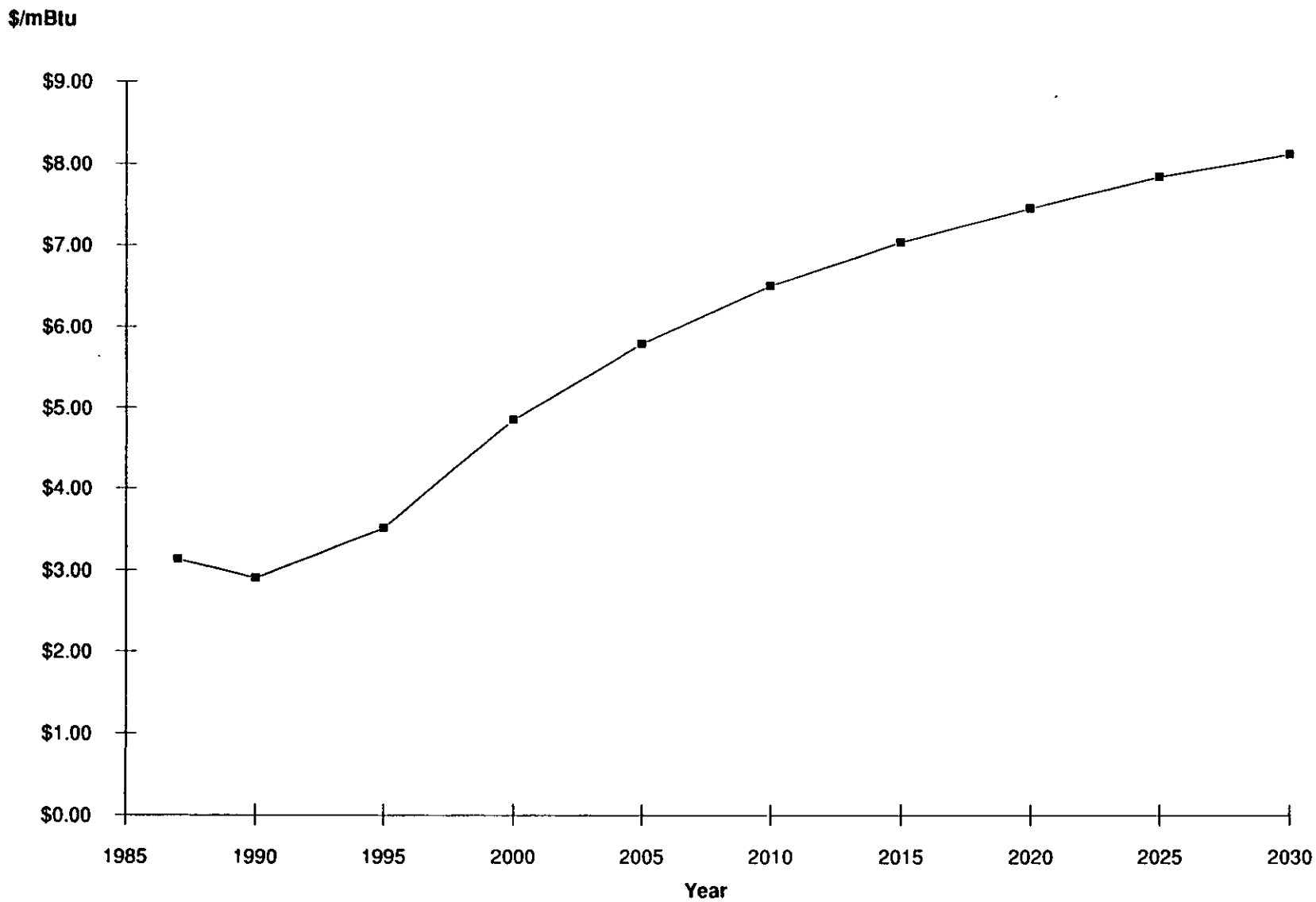

Figure 5.1. Current Policy Base Case: World Price of Oil ($/mBtu)

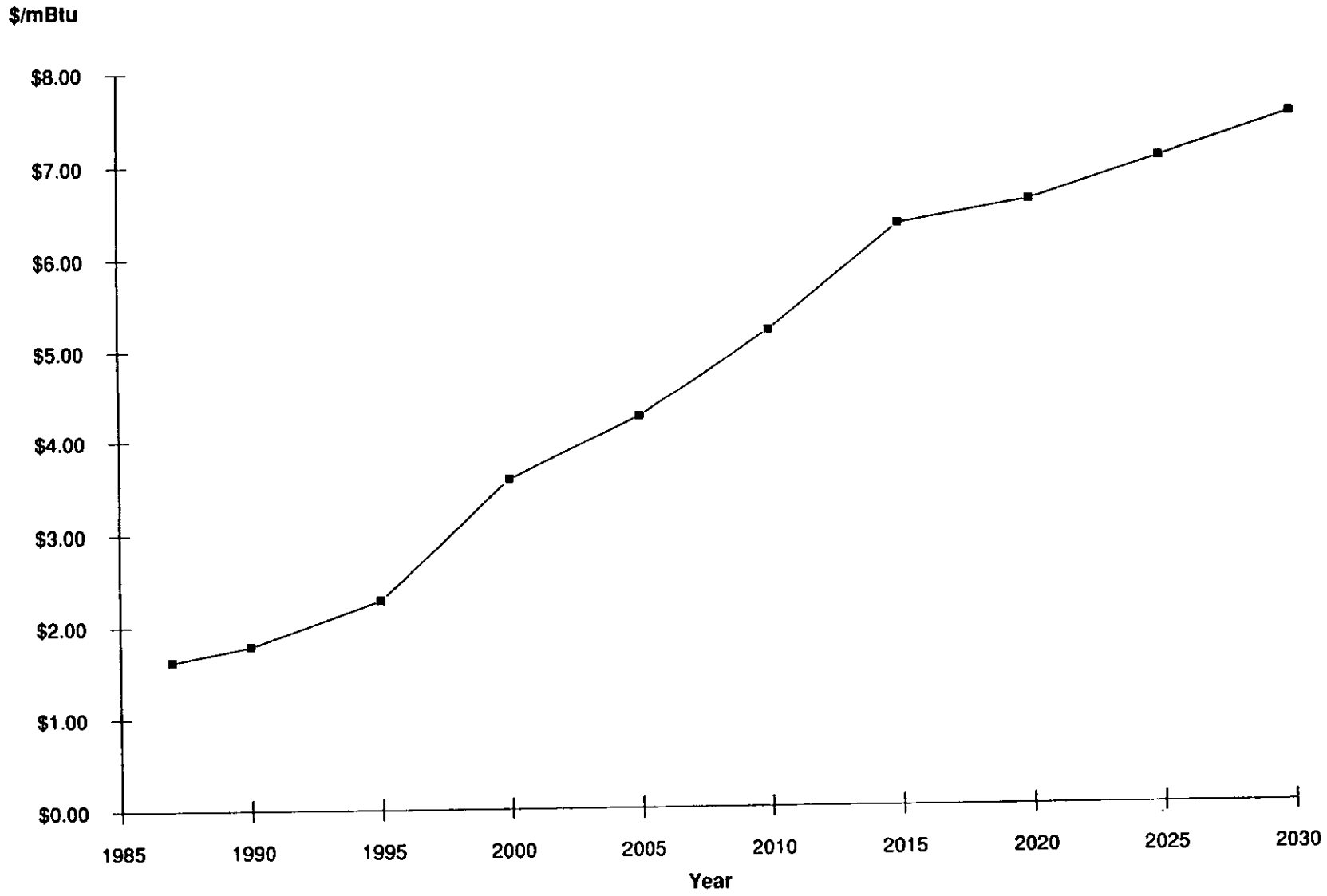

Figure 5.2. Current Policy Base Case: Wellhead Price of Natural Gas ($/mBtu)

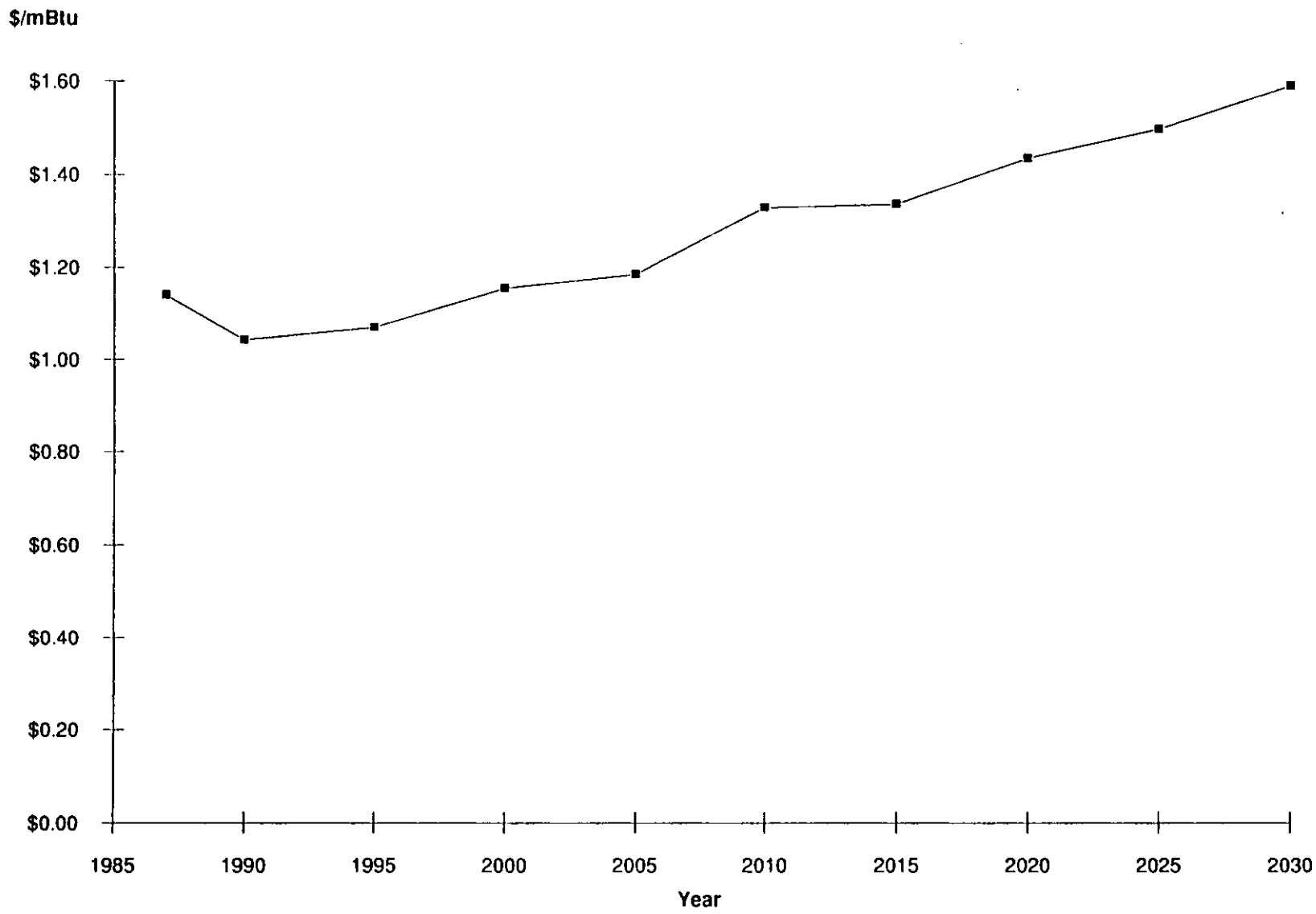

Figure 5.3. Current Policy Base Case: Minemouth Price of Coal ($/mBtu)

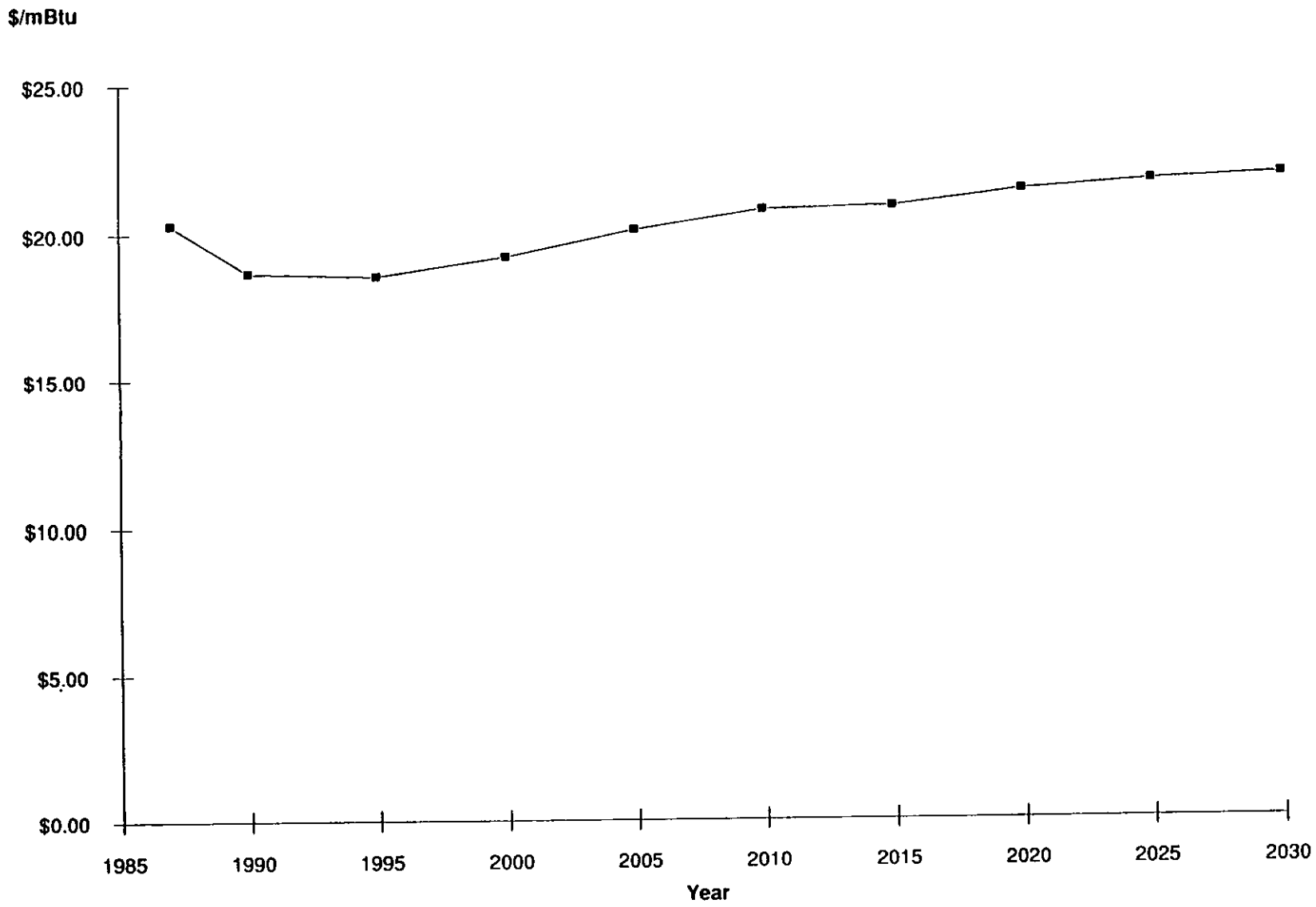

Figure 5.4. Current Policy Base Case: Average Price of Delivered Electricity ($/mBtu)

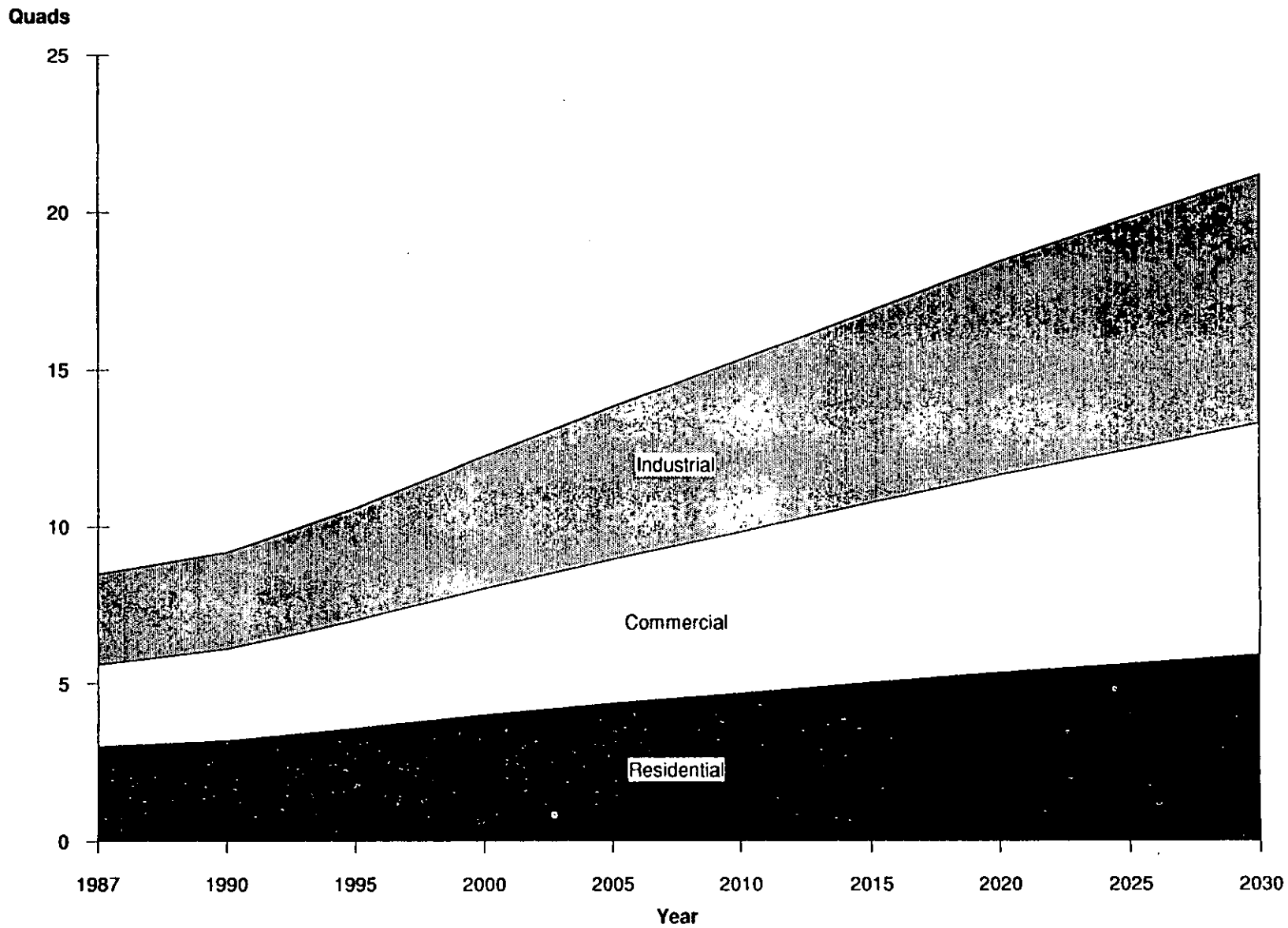

Figure 5.5. Current Policy Base Case: Total Electric Power Consumption, by Sector, 1987-2030 (quads)

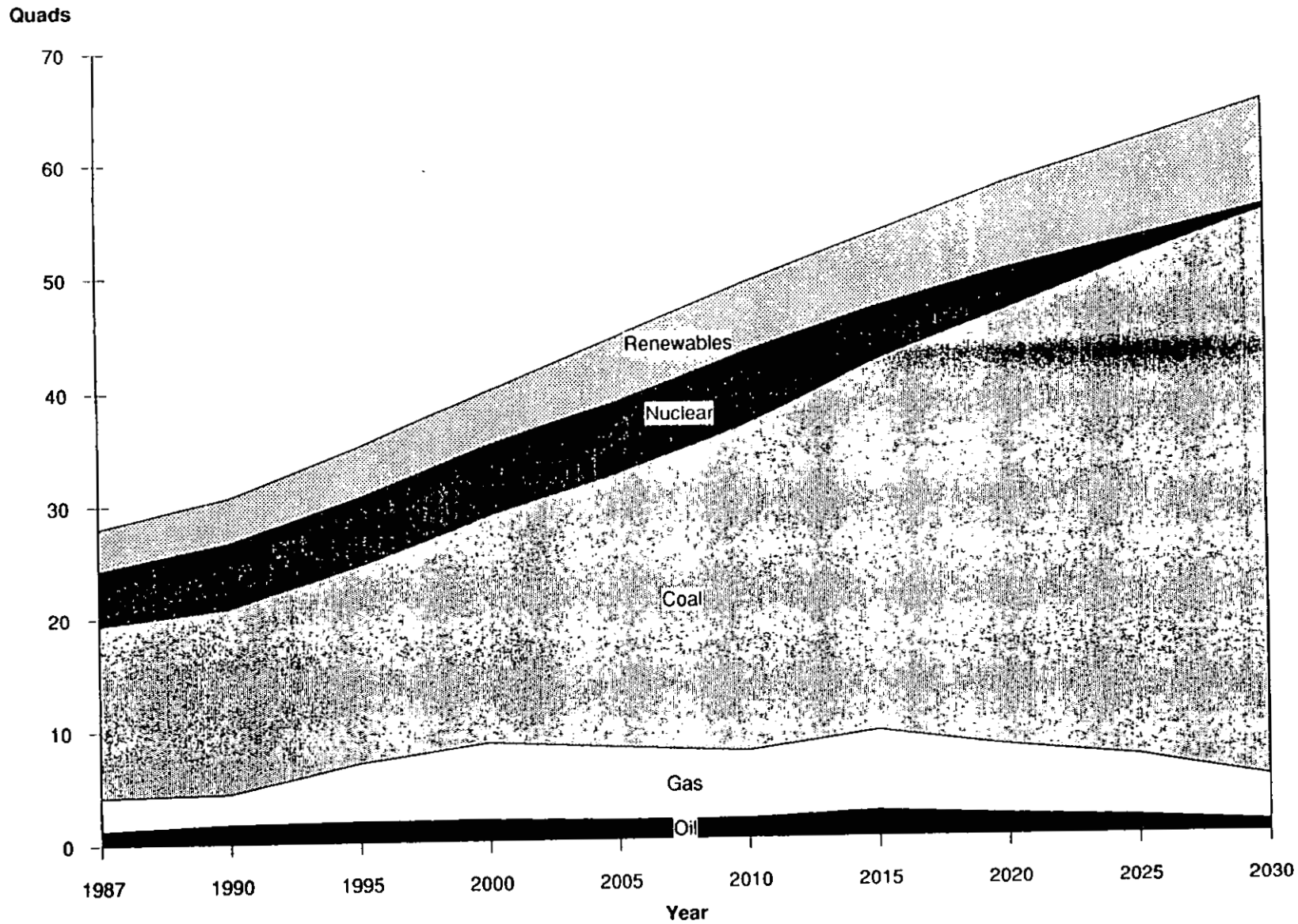

Figure 5.6. Current Policy Base Case: Electric Utility Energy Consumption, by Fuel, 1987-2030 (quads)

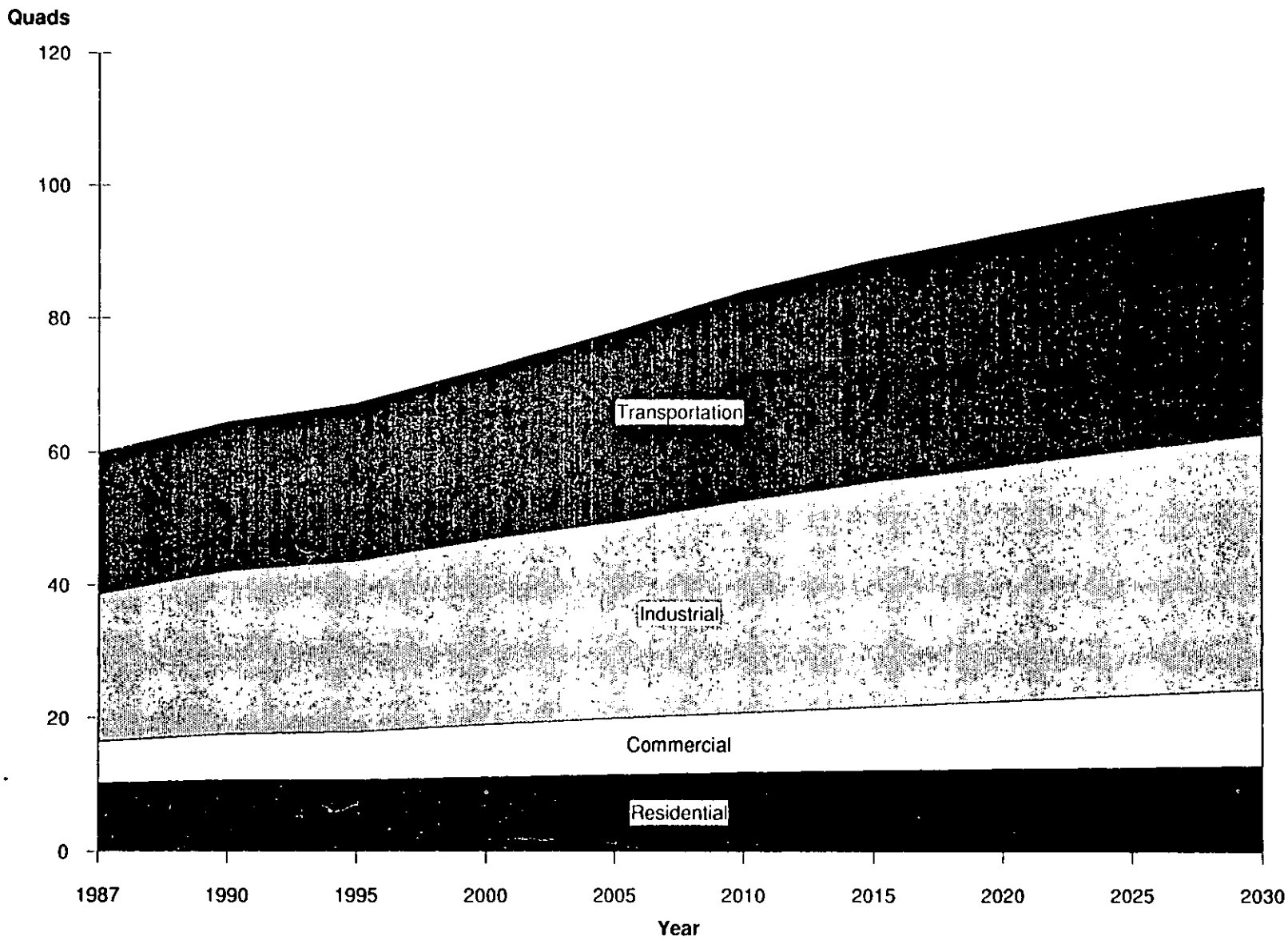

Figure 5.7. Current Policy Base Case: Total End-Use Energy Consumption, by Sector, 1987-2030 (quads)

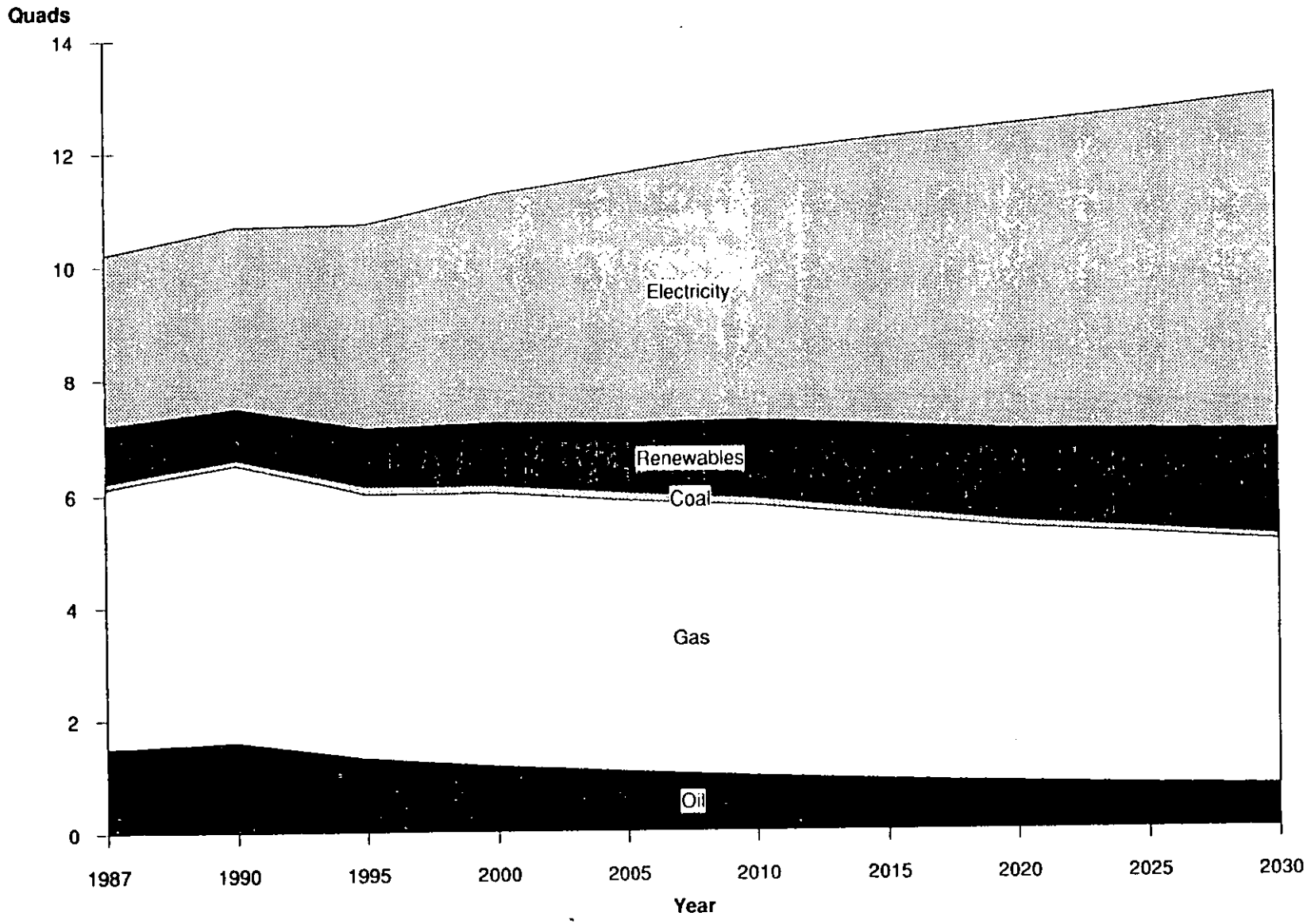

Figure 5.8. Current Policy Base Case: Residential Energy Consumption, by Fuel, 1987-2030 (quads)

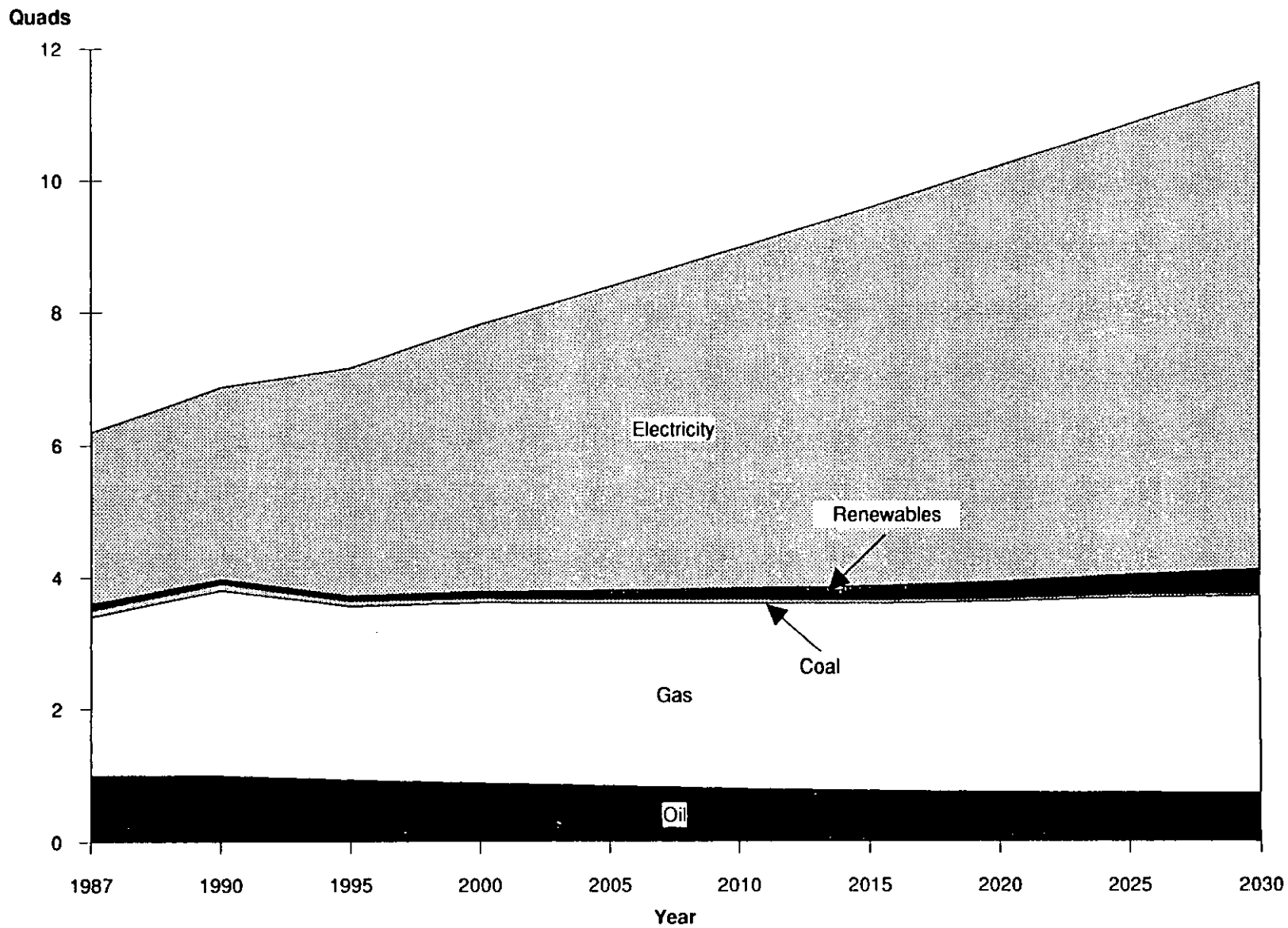

Figure 5.9. Current Policy Base Case: Commercial Energy Consumption, by Fuel, 1987-2030 (quads)

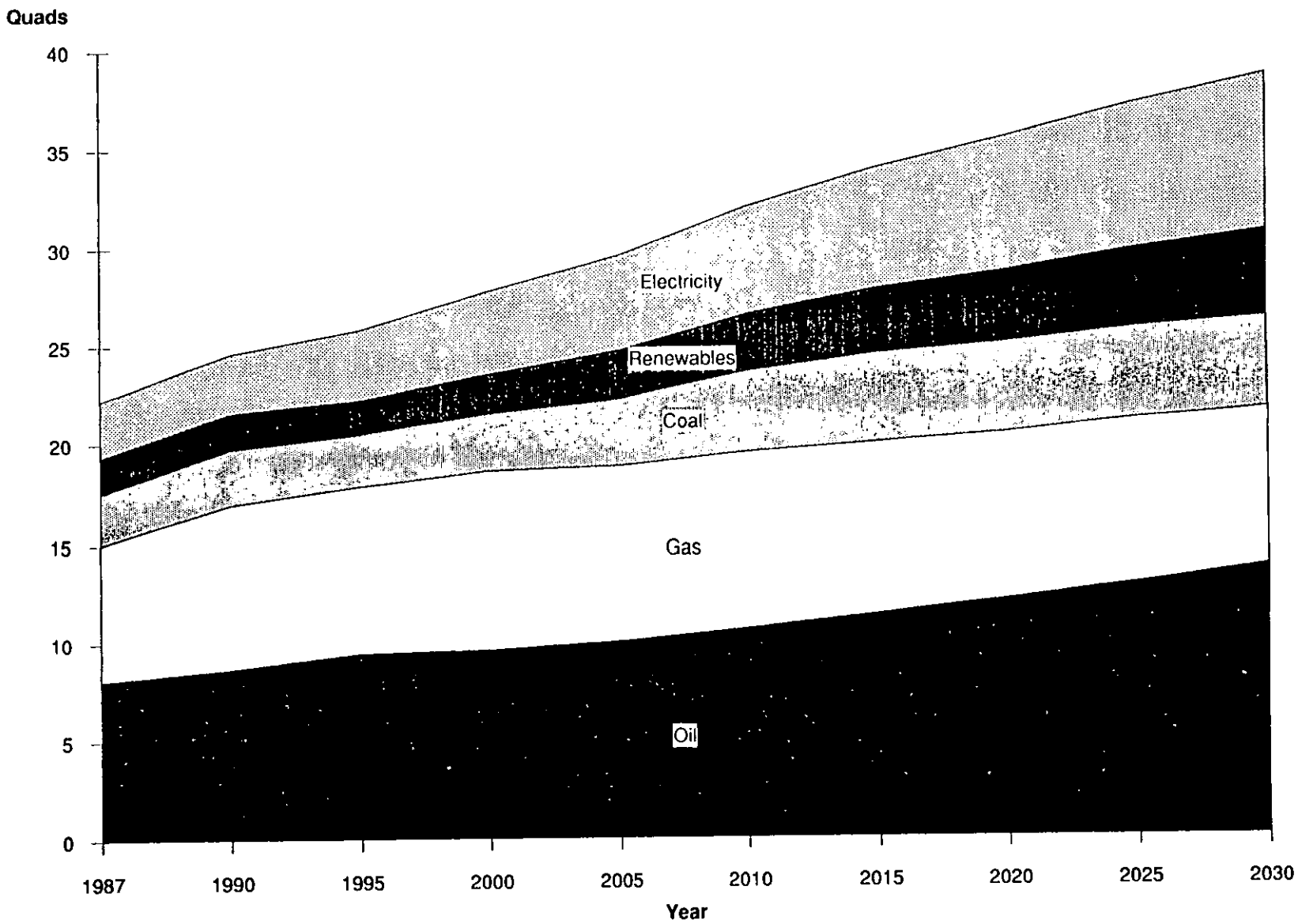

Figure 5.10. Current Policy Base Case: Industrial Energy Consumption, by Fuel, 1987-2030 (quads)

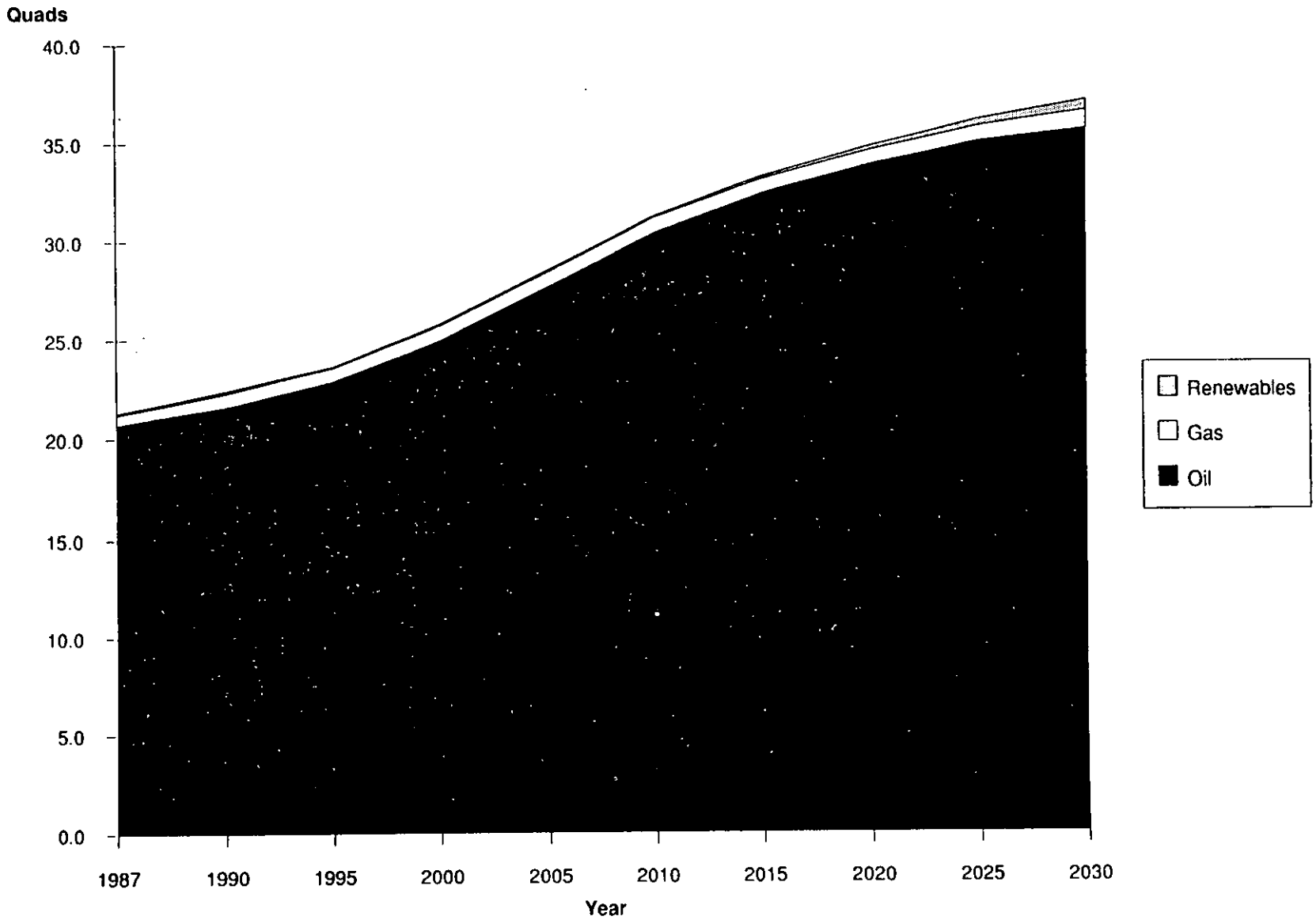

Figure 5.11. Current Policy Base Case: Transportation Energy Demand, by Fuel, 1987-2030 (quads)

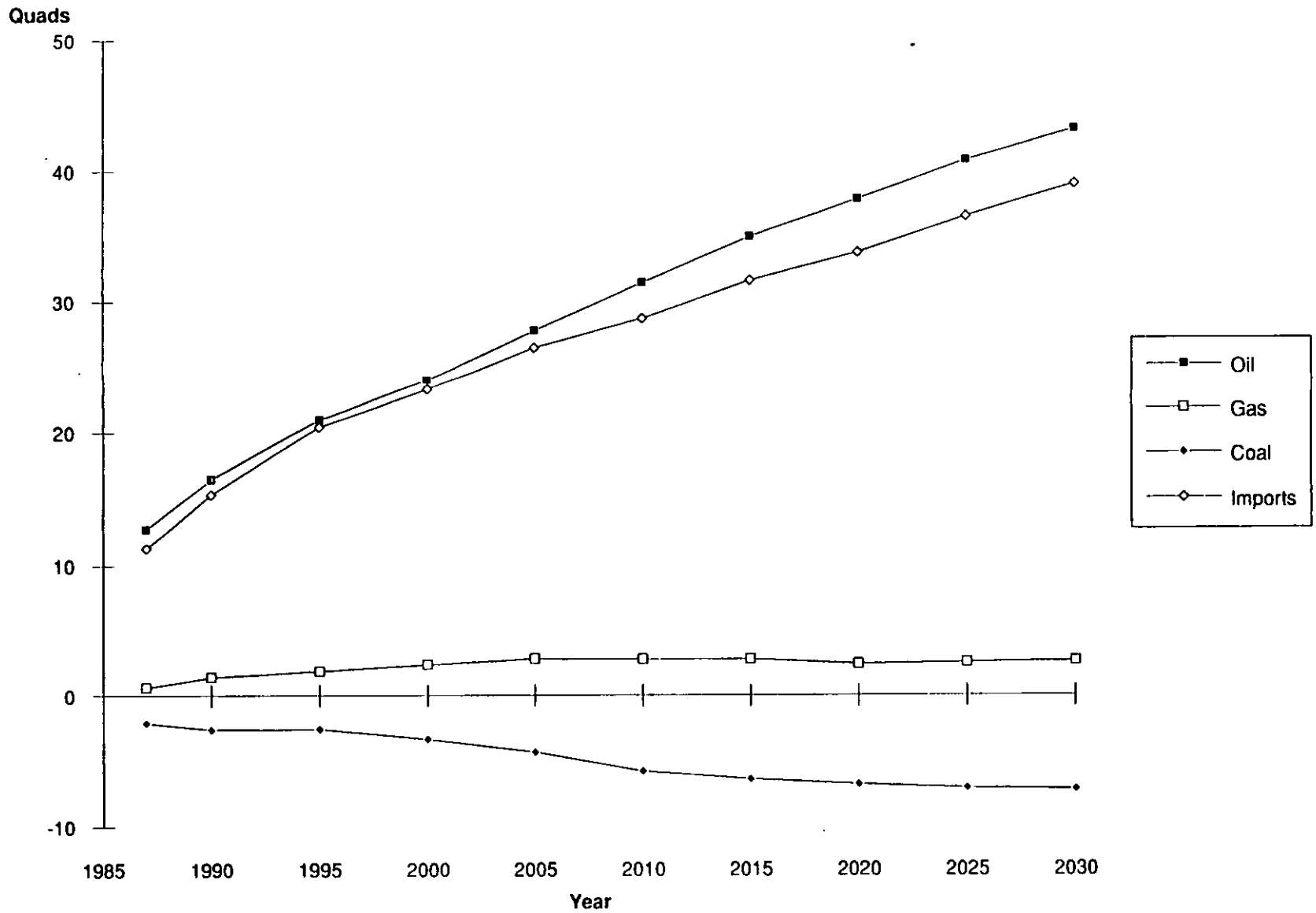

Figure 5.12. Current Policy Base Case: Net Fossil Fuel Imports, by Fuel, 1987-2030 (quads)

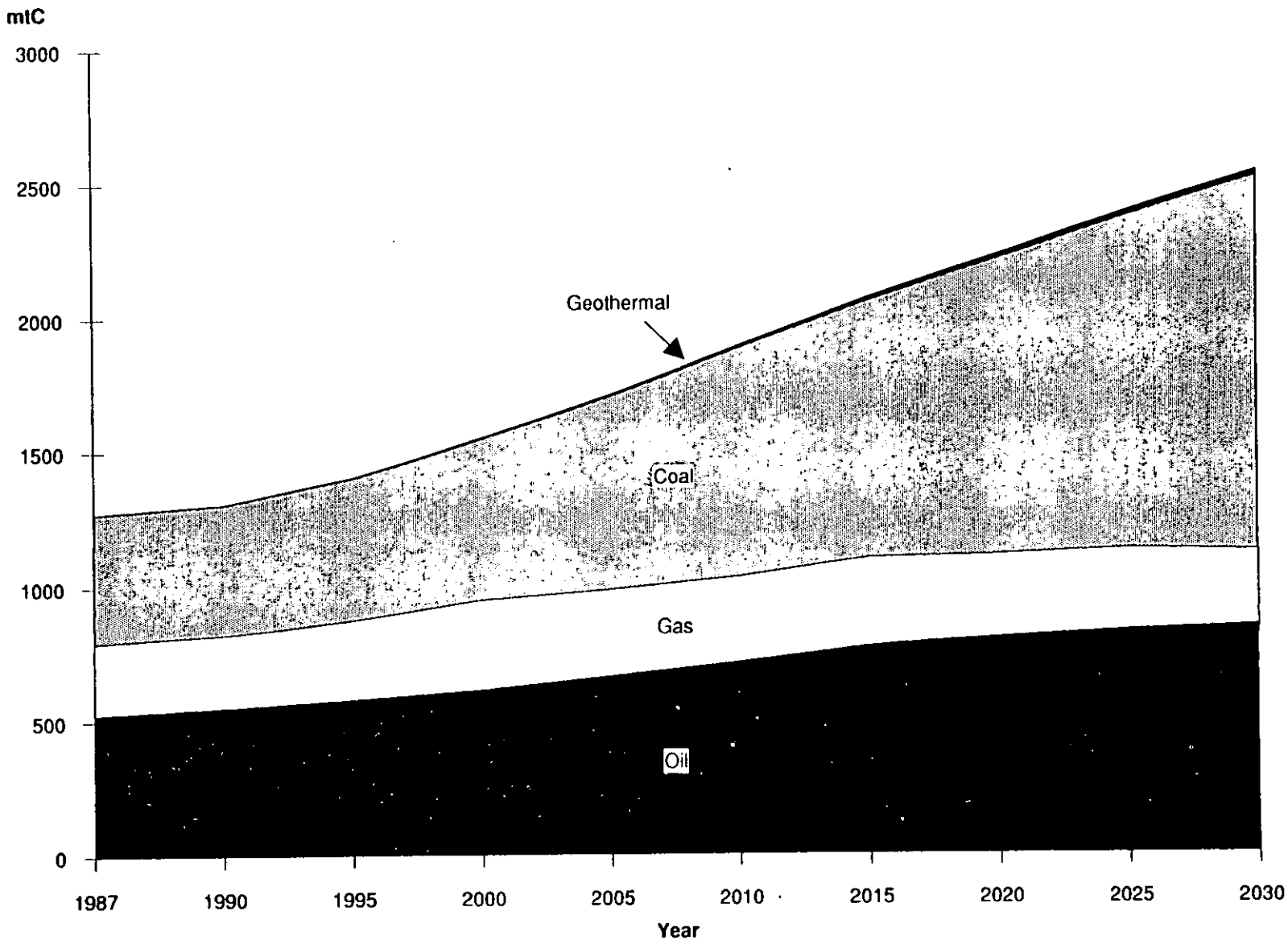

Figure 5.13. Current Policy Base Case: Fossil Fuel CO_2 Emissions by Fuel (millions of mtC/yr)

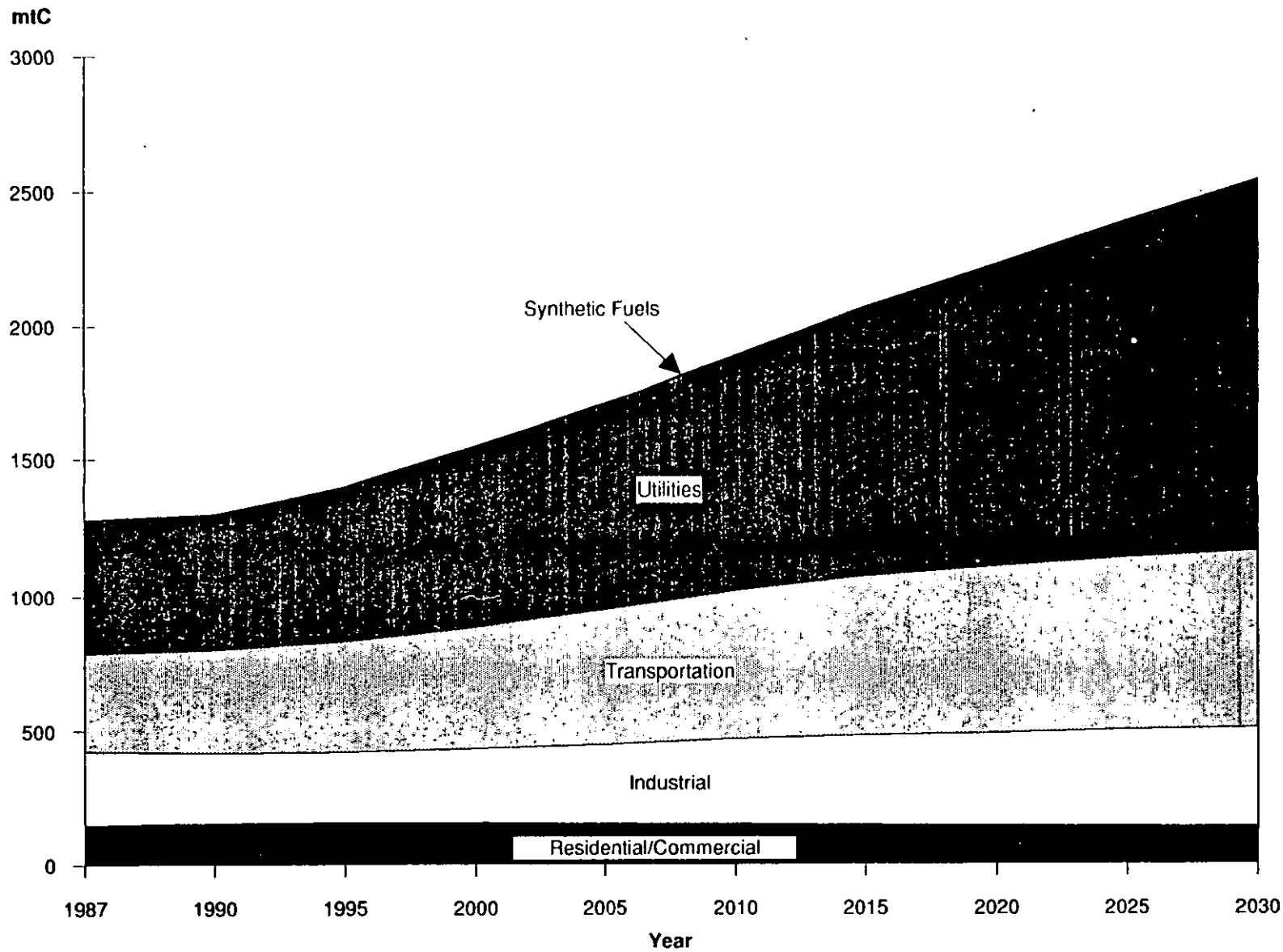

Figure 5.14. Current Policy Base Case: Fossil Fuel CO_2 Emissions by Sector (millions of mtC/yr)

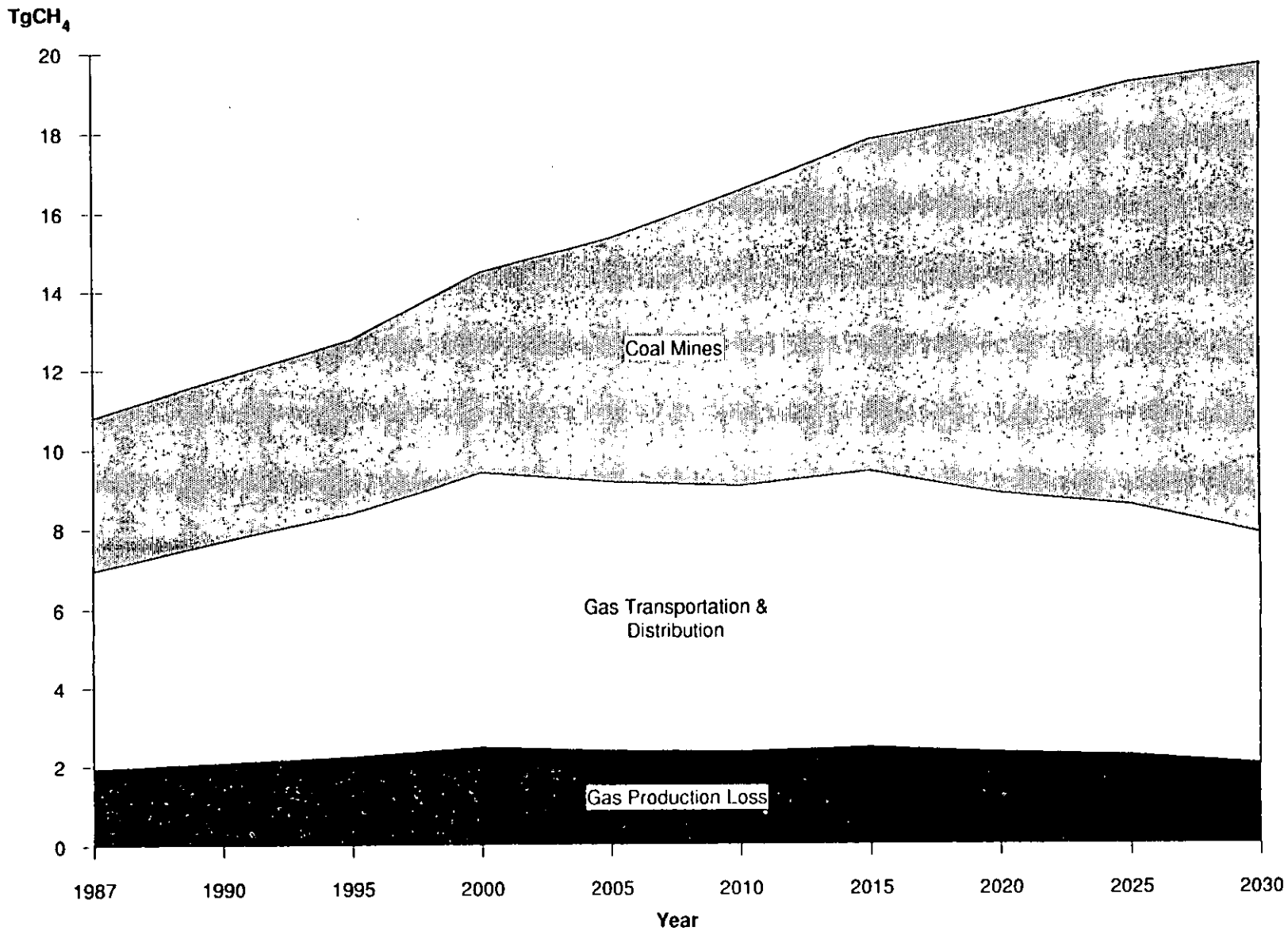

Figure 5.15. Current Policy Base Case: Methane Emissions ($TgCH_4$/yr)

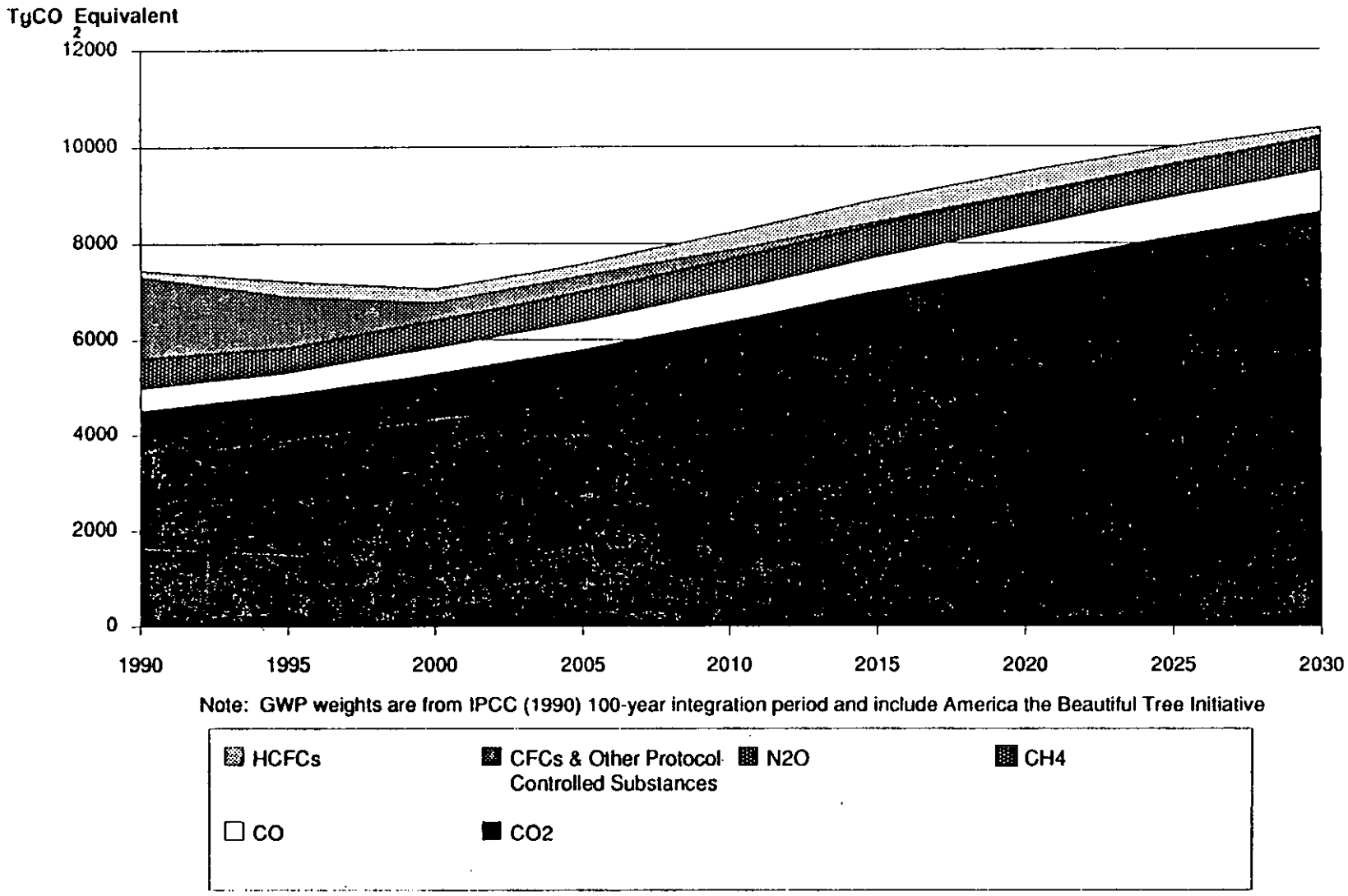

Figure 5.16. Current Policy Base Case: GWP-Weighted Energy-Related Emissions by Gas and by Year ($TgCO_2$ equivalent)

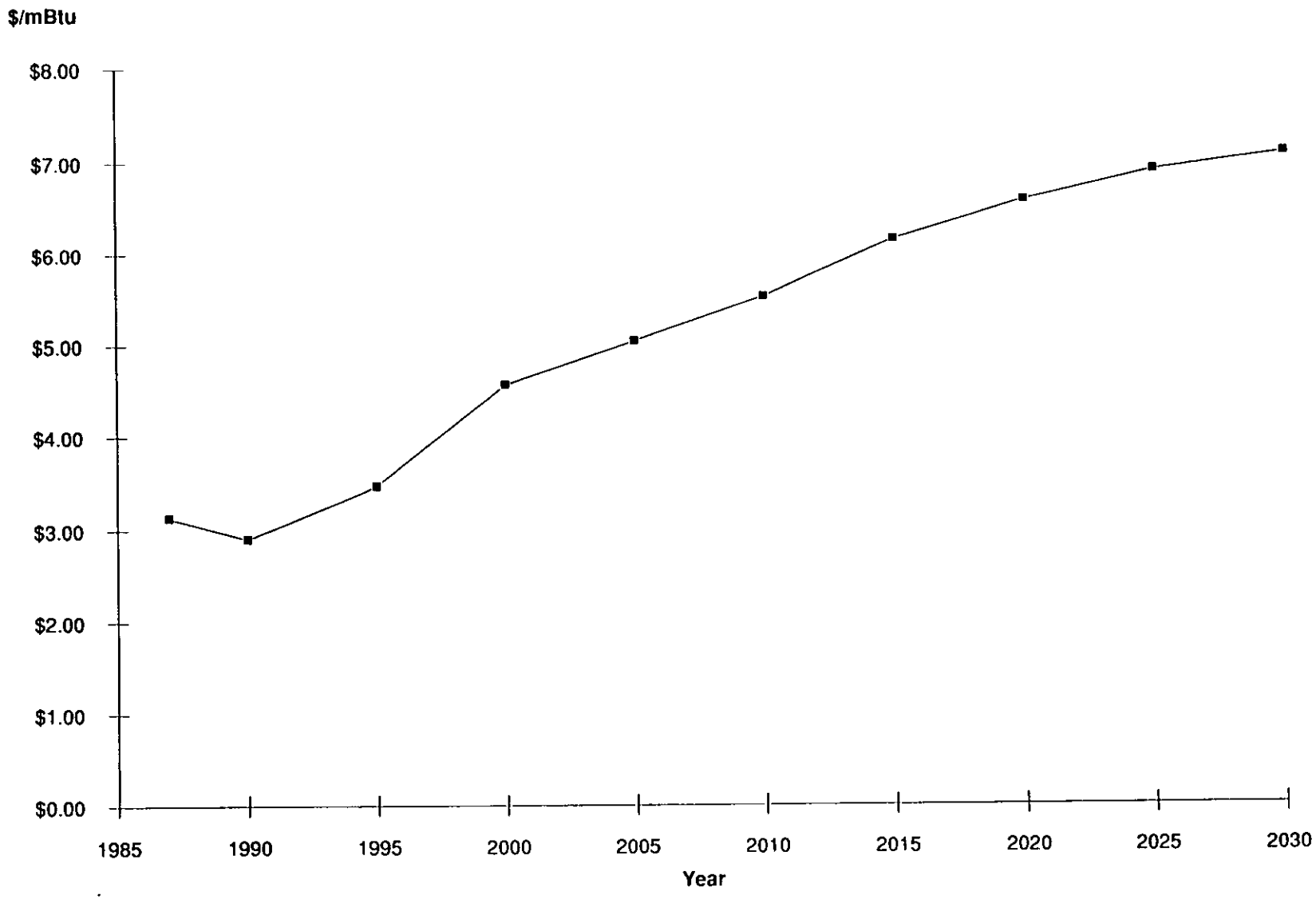

Figure 5.17. NES Actions Case: World Price of Oil ($/mBtu)

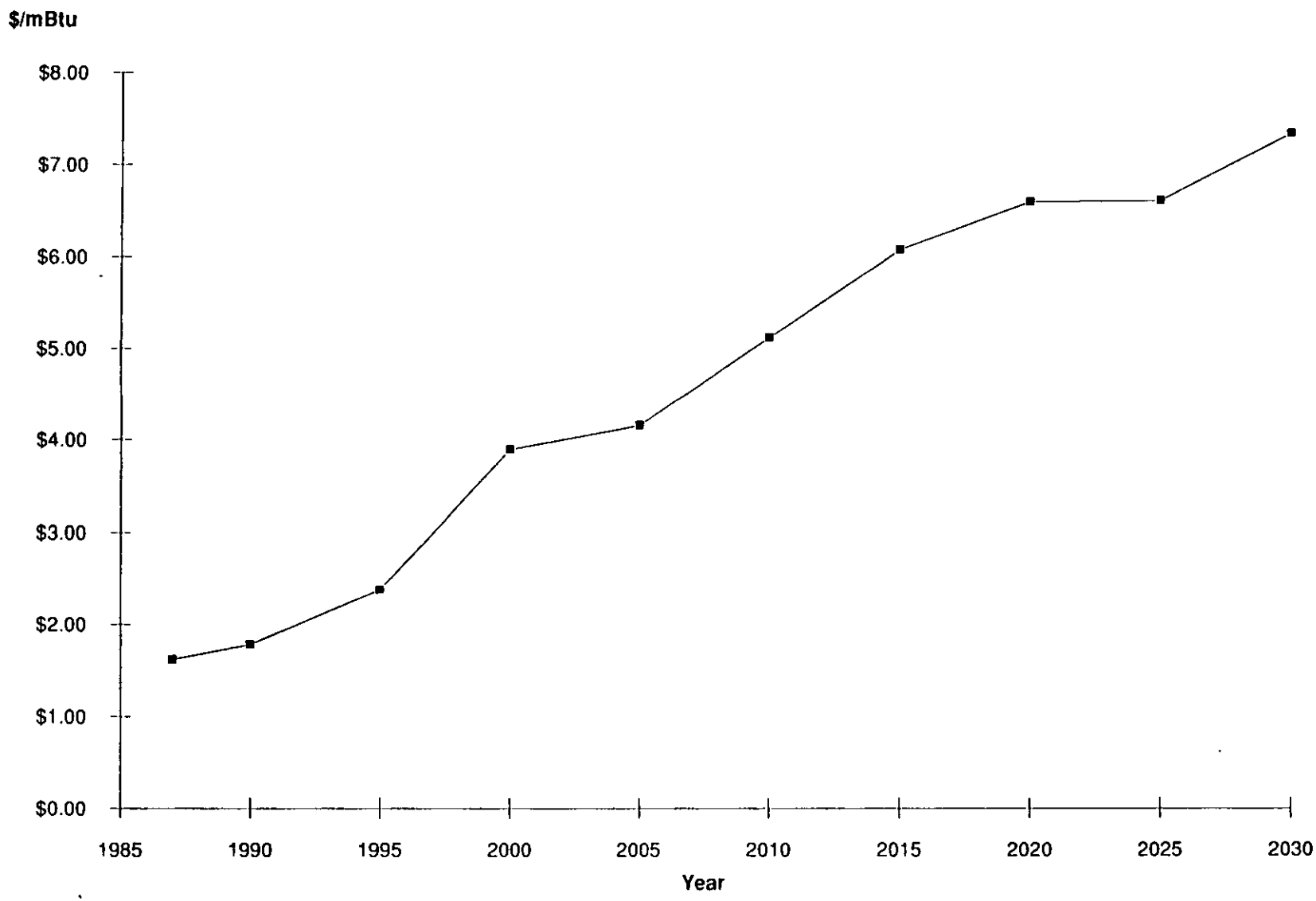

Figure 5.18. NES Actions Case: Wellhead Price of Natural Gas ($/mBtu)

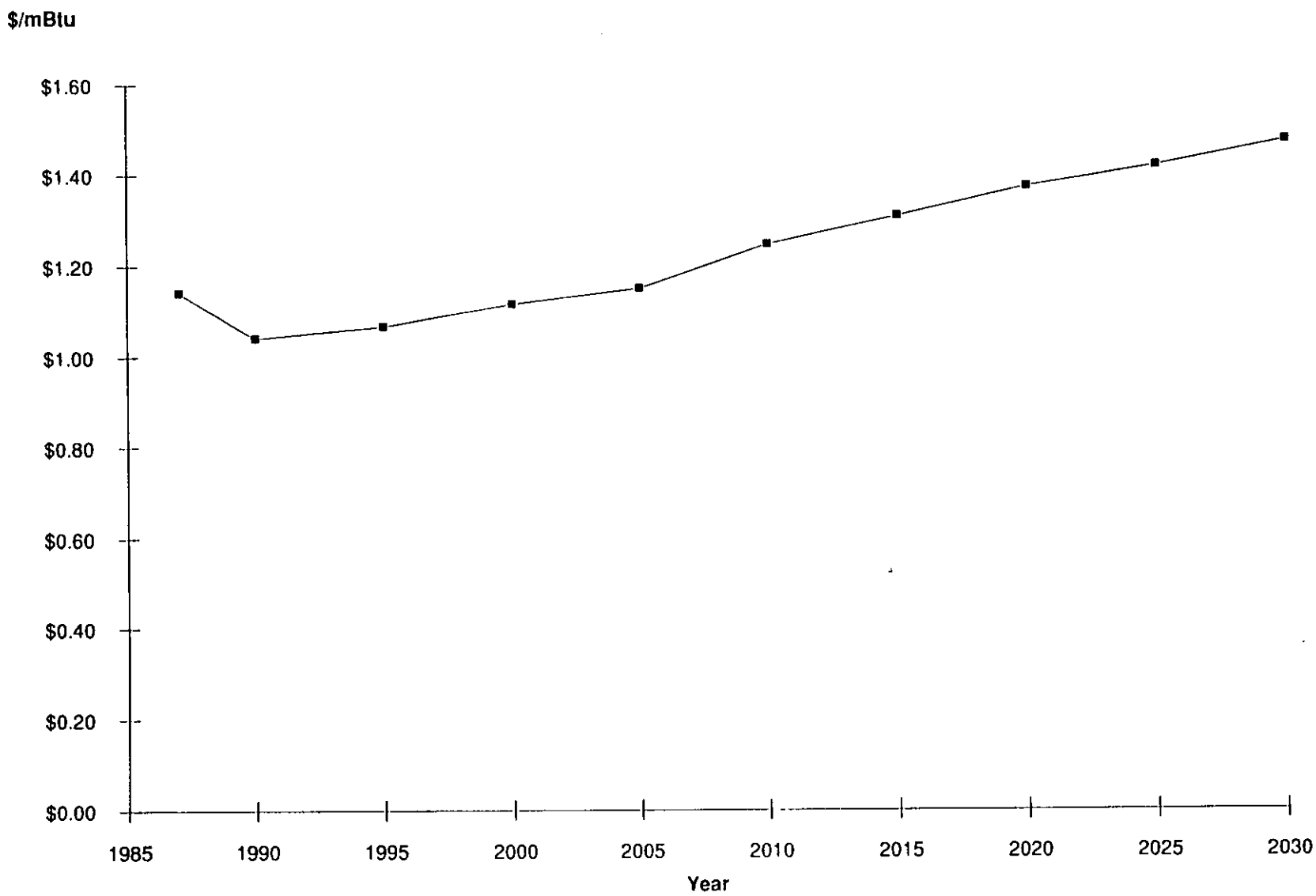

Figure 5.19. NES Actions Case: Minemouth Price of Coal ($/mBtu)

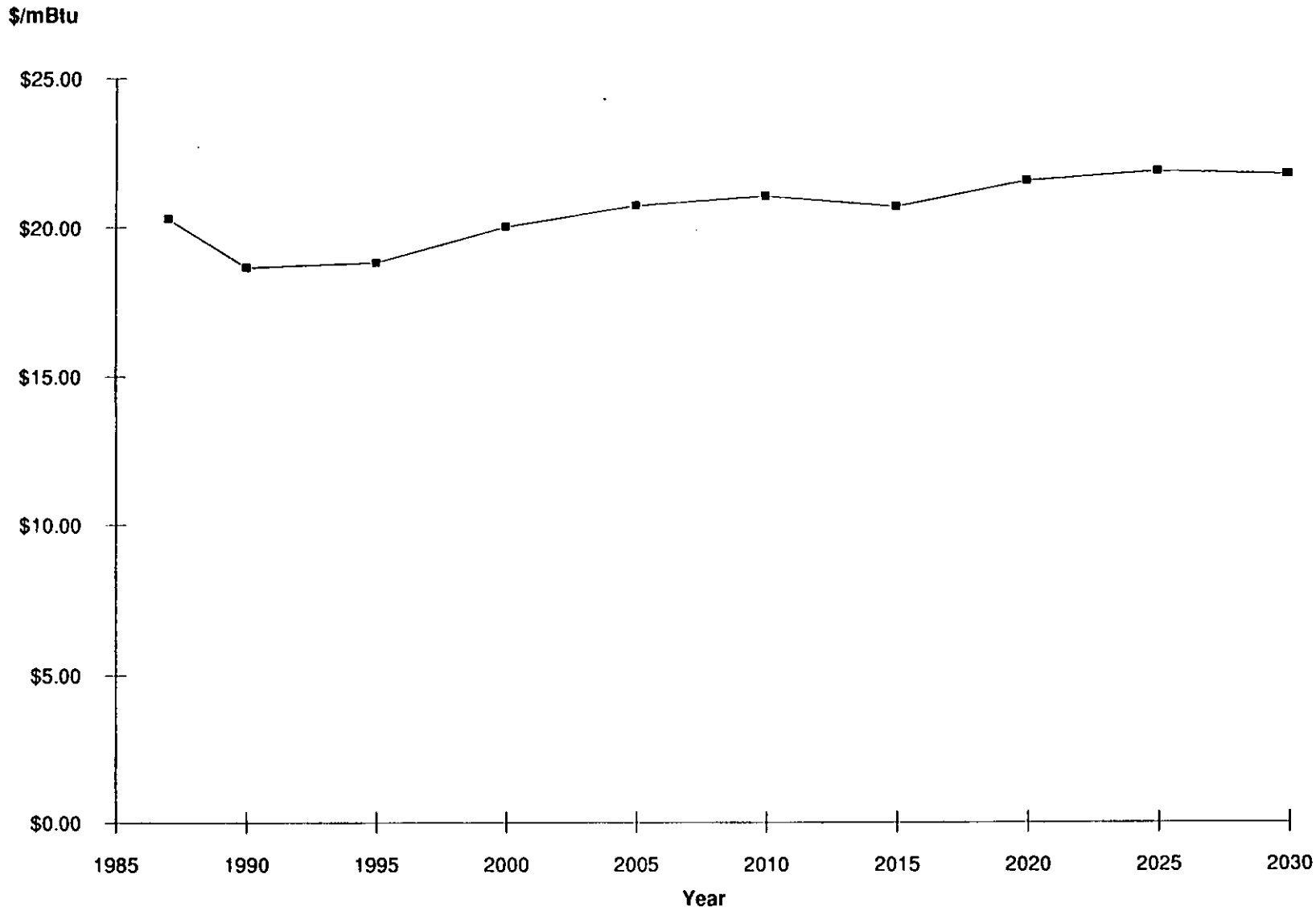

Figure 5.20. NES Actions Case: Average Price of Delivered Electricity ($/mBtu)

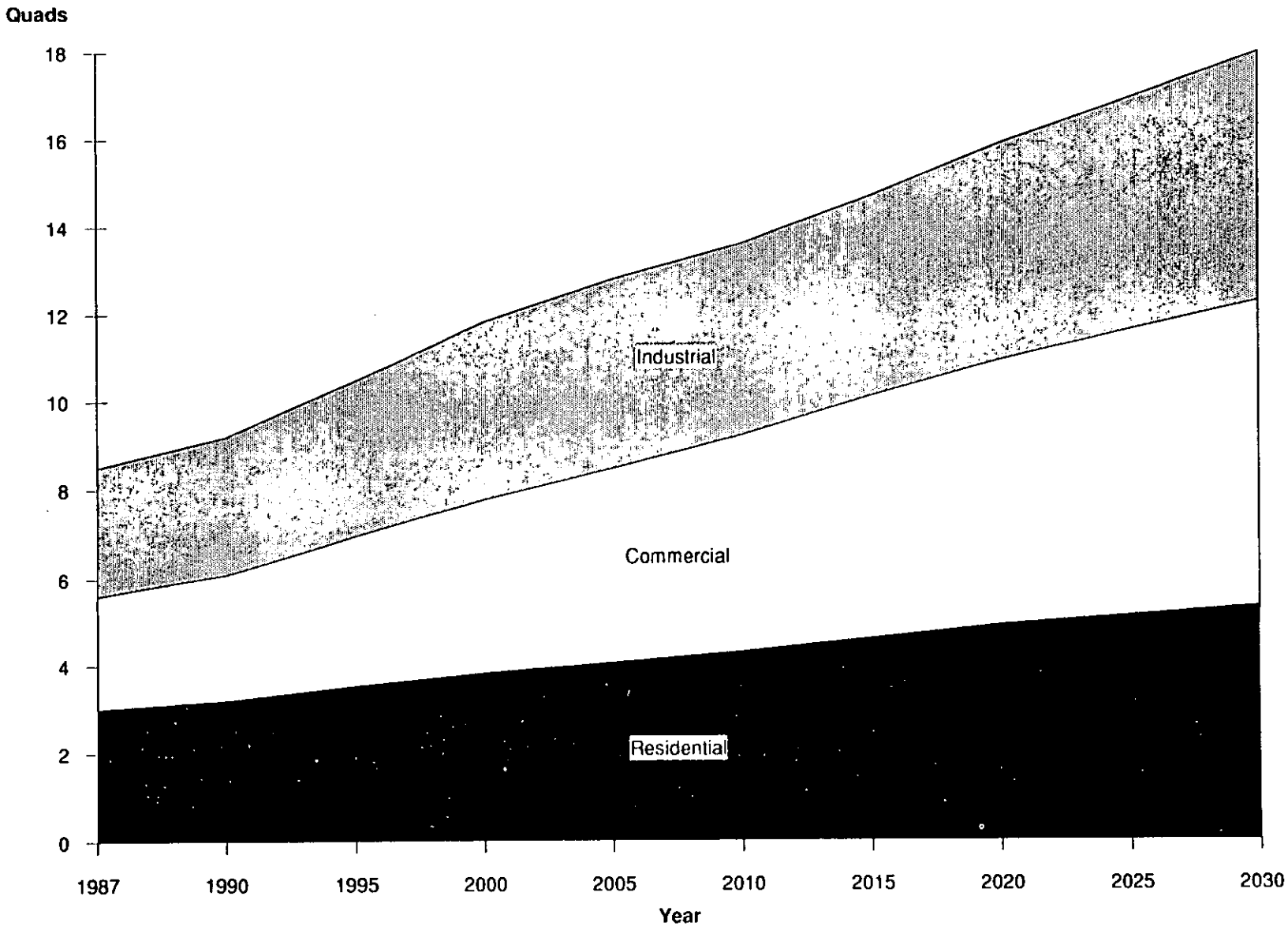

Figure 5.21. NES Actions Case: Total Electric Power Consumption, by Sector, 1987-2030 (quads)

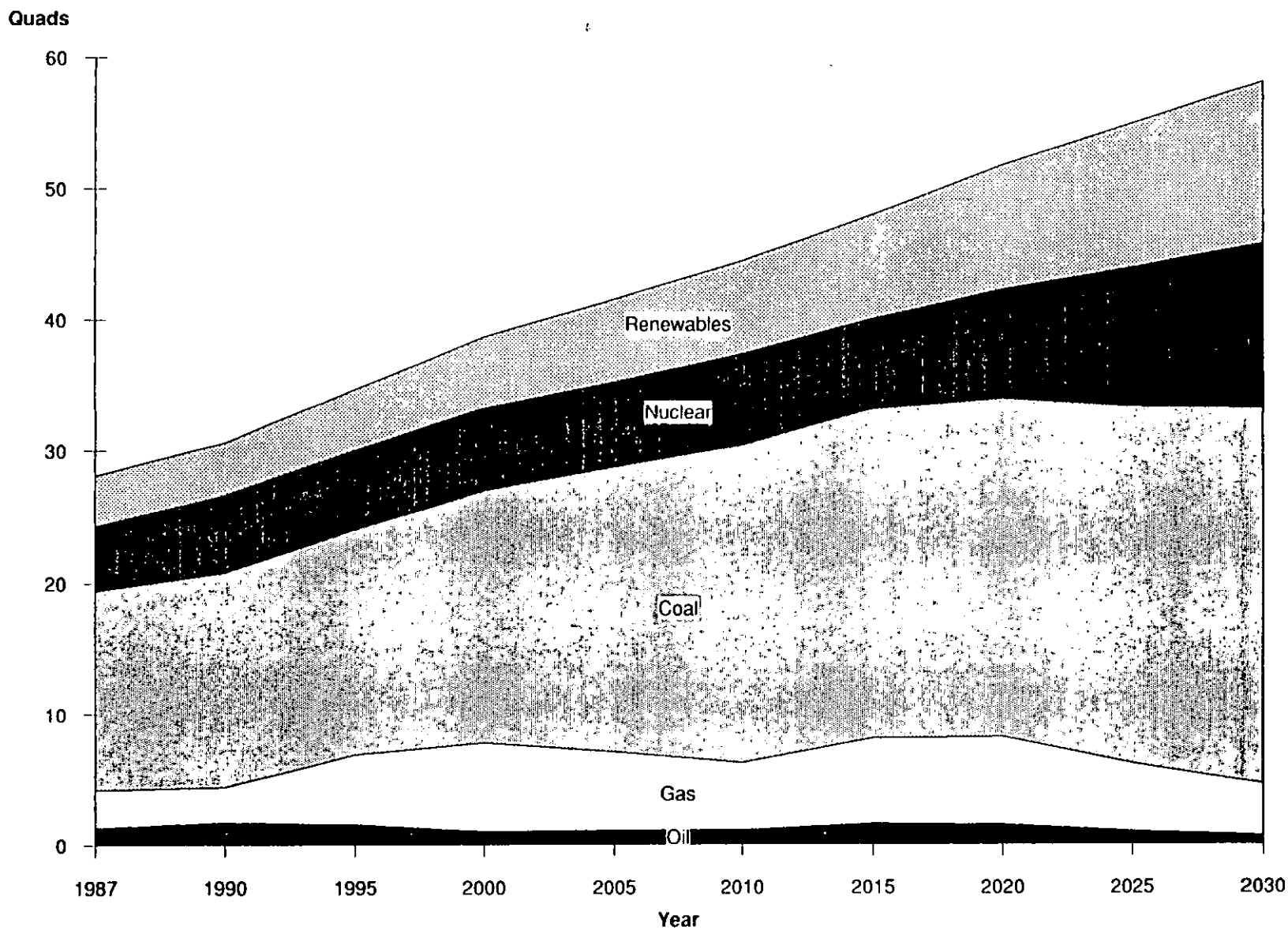

Figure 5.22. NES Actions Case: Electricity Utility Energy Consumption, by Fuel, 1987-2030 (quads)

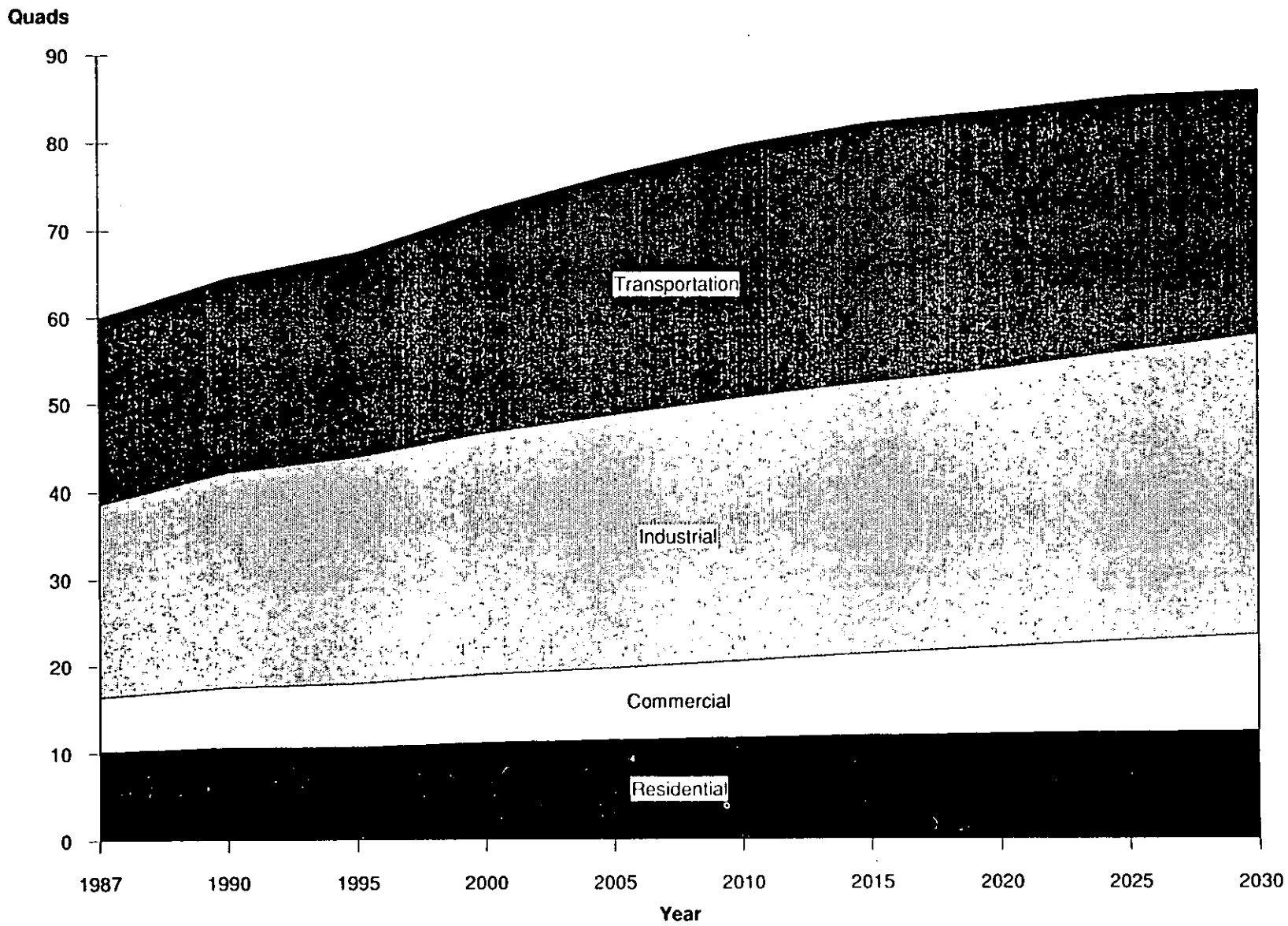

Figure 5.23. NES Actions Case: Total End-Use Energy Consumption, by Sector, 1987-2030 (quads)

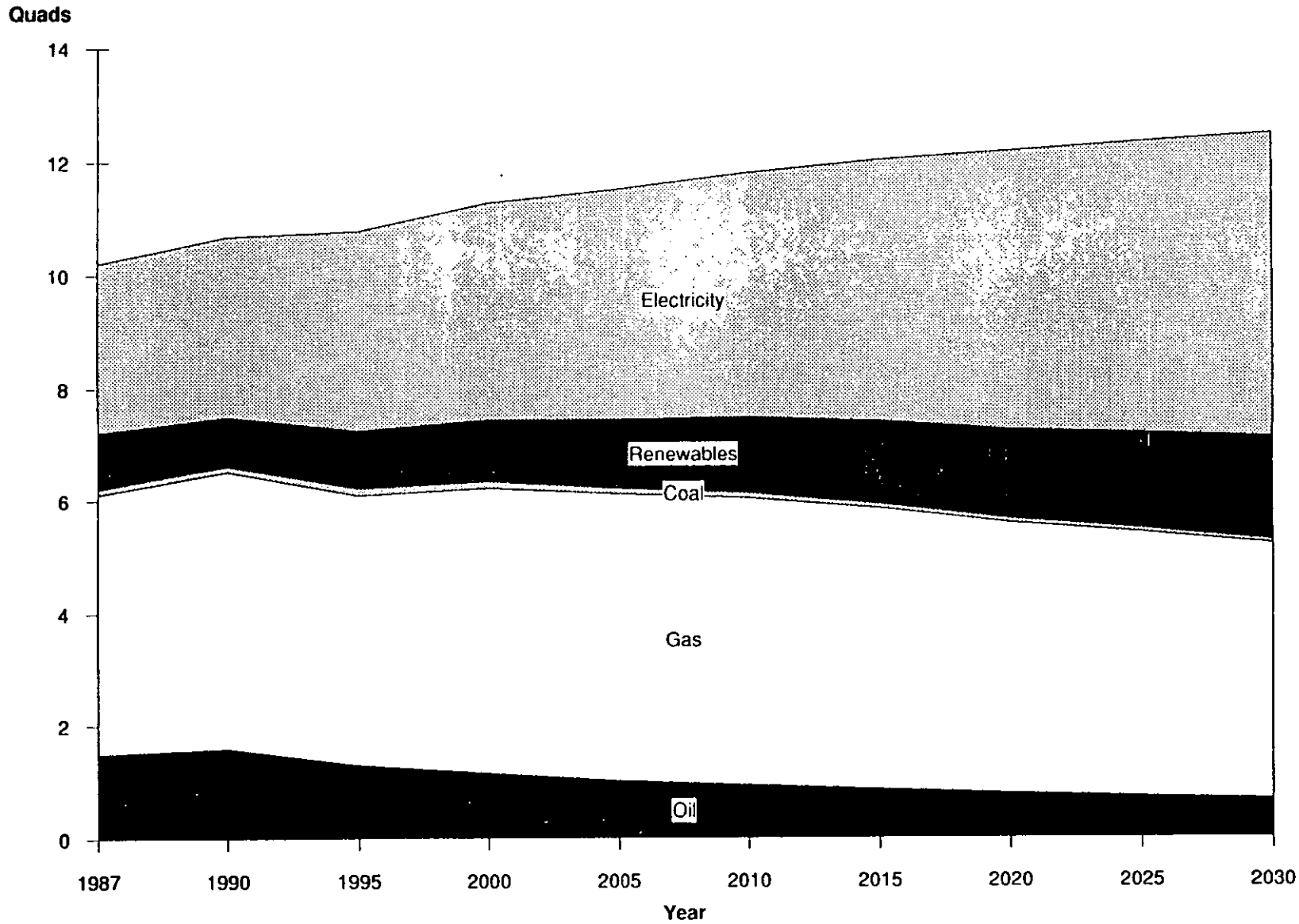

Figure 5.24. NES Actions Case: Residential Energy Consumption, by Fuel, 1987-2030 (quads)

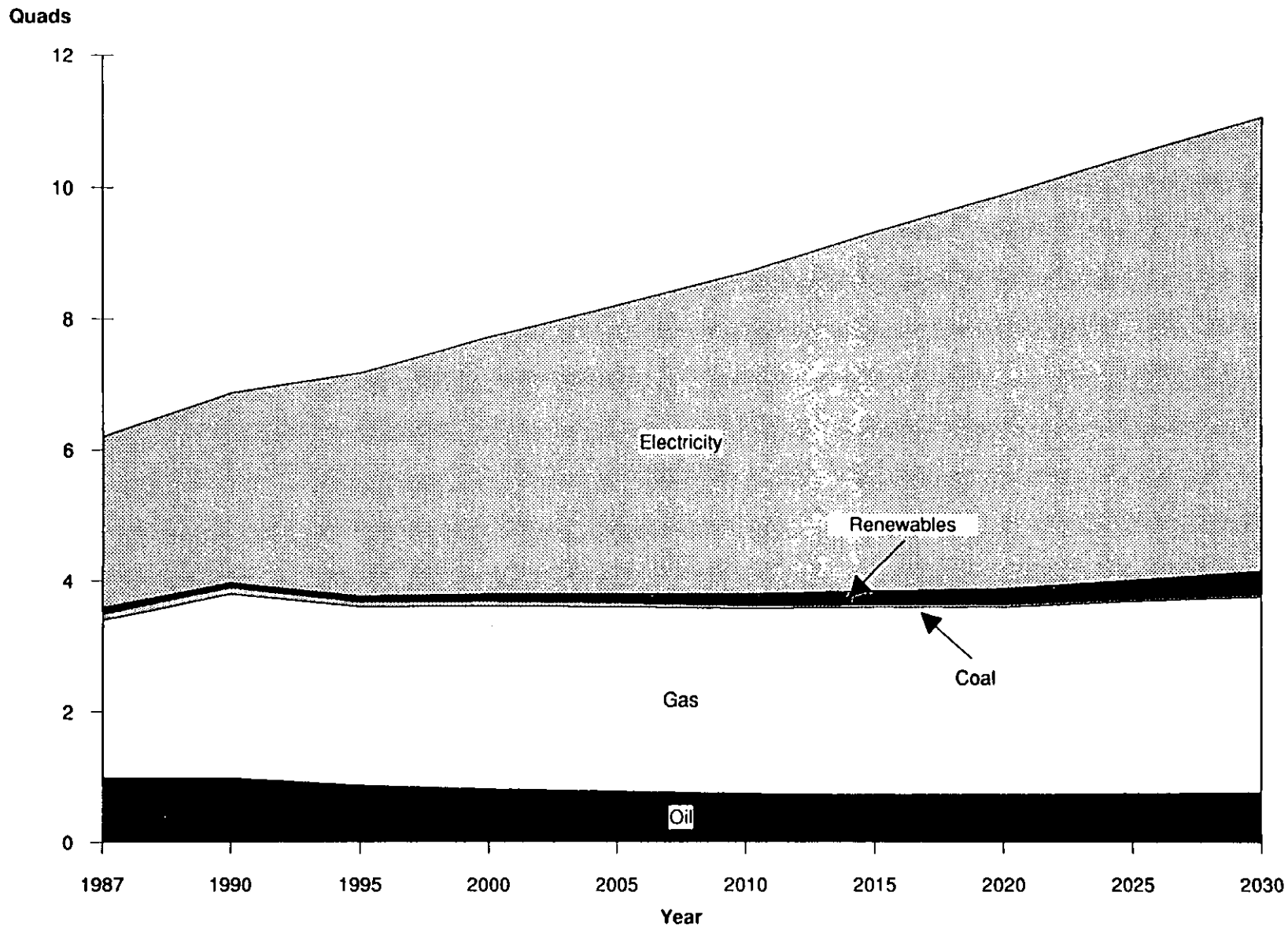

Figure 5.25. NES Actions Case Commercial Energy Consumption, by Fuel, 1987-2030 (quads)

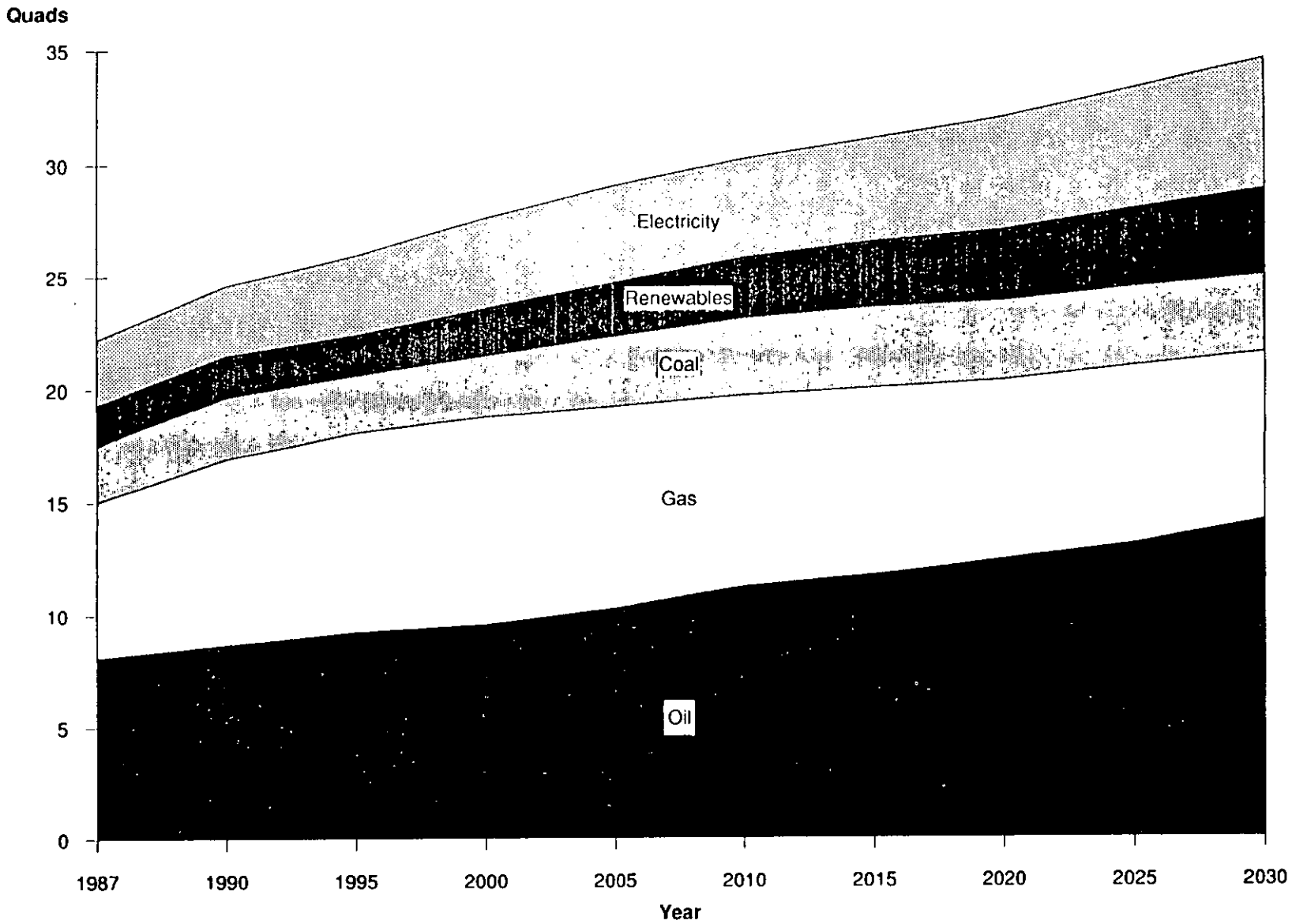

Figure 5.26. NES Actions Case: Industrial Energy Consumption, by Fuel, 1987-2030 (quads)

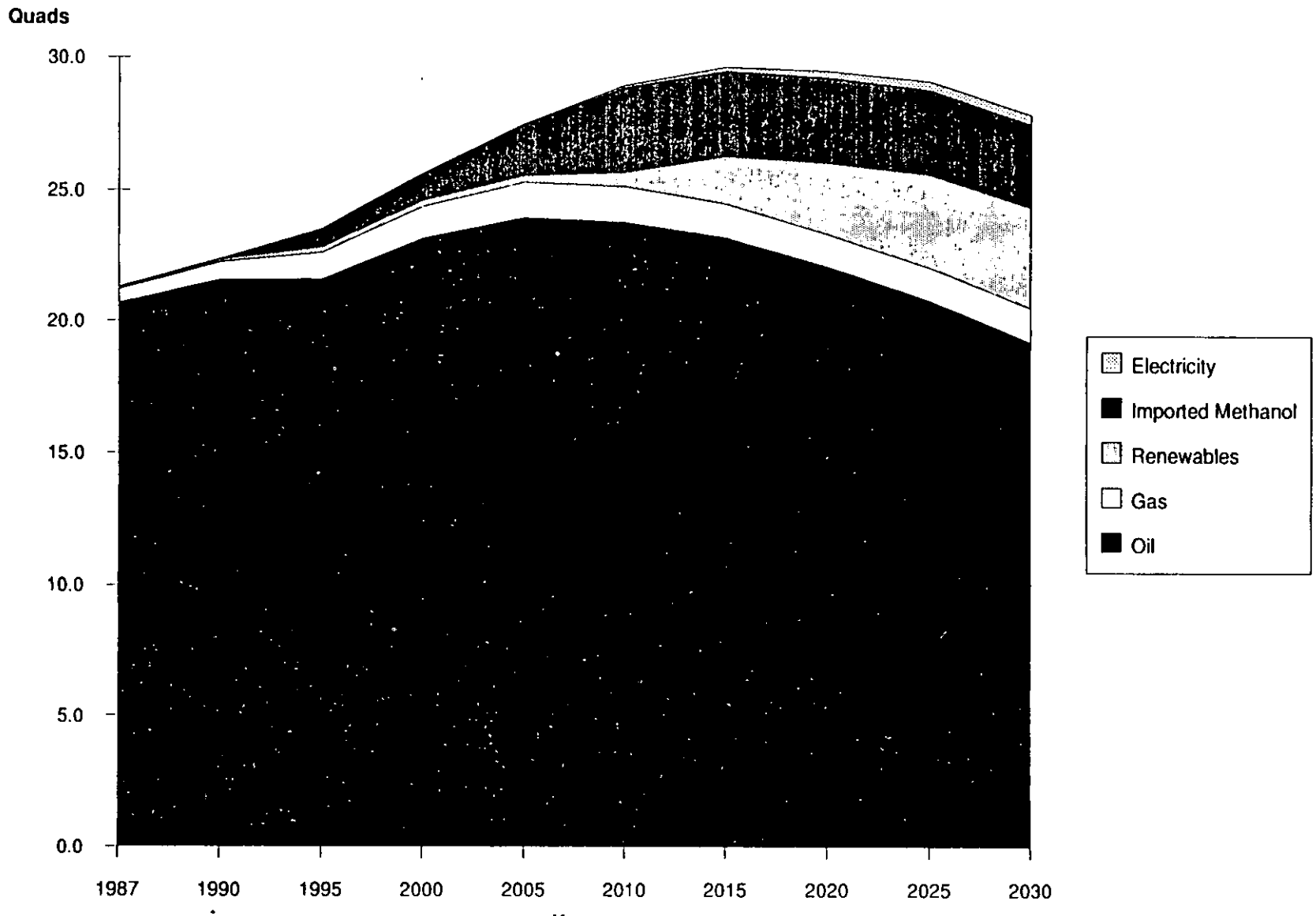

Figure 5.27. NES Actions Case: Transportation Energy Demand, by Fuel, 1987-2030 (quads)

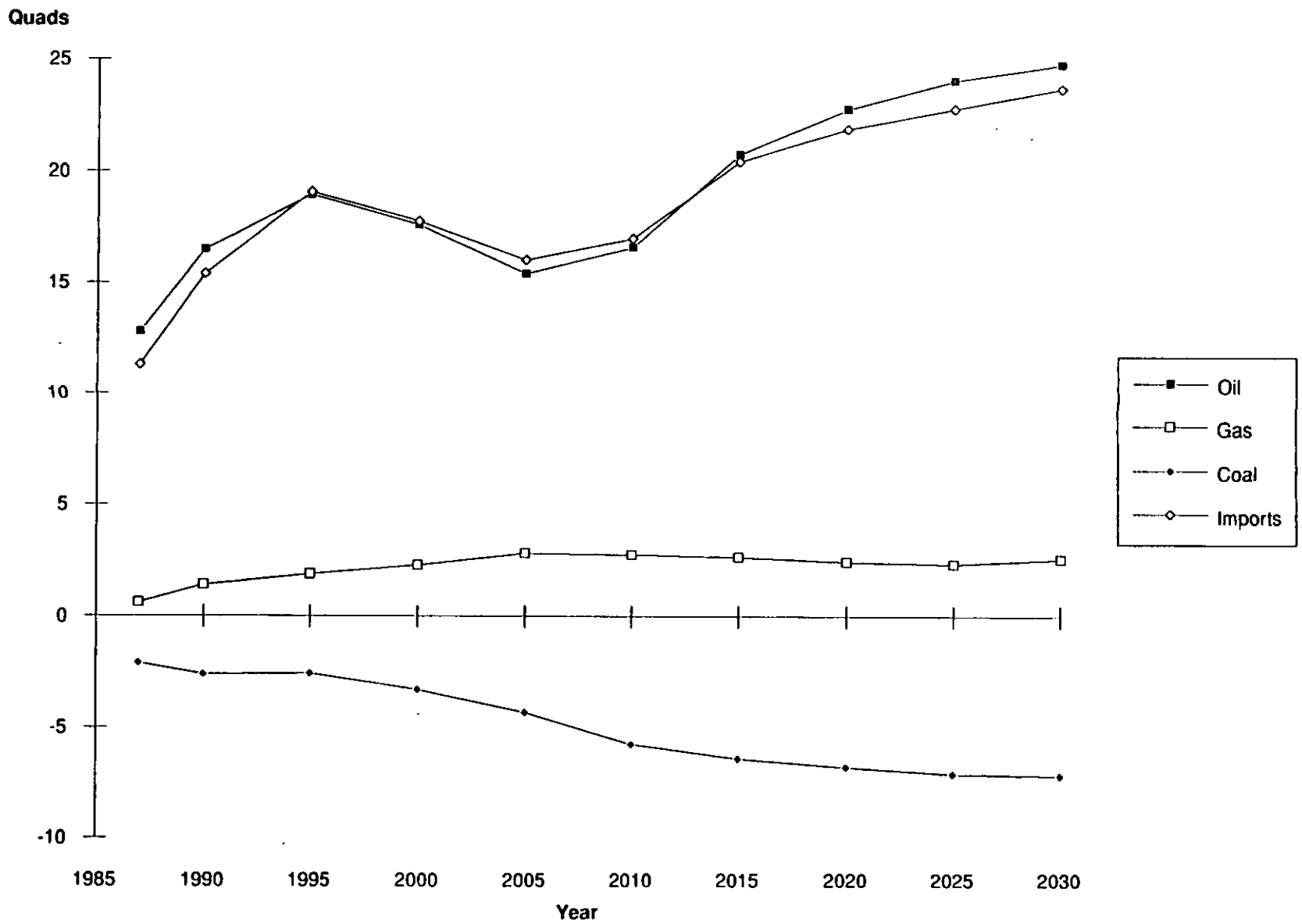

Figure 5.28. NES Actions Case: Net Fossil Fuel Imports, by Fuel, 1987-2030 (quads)

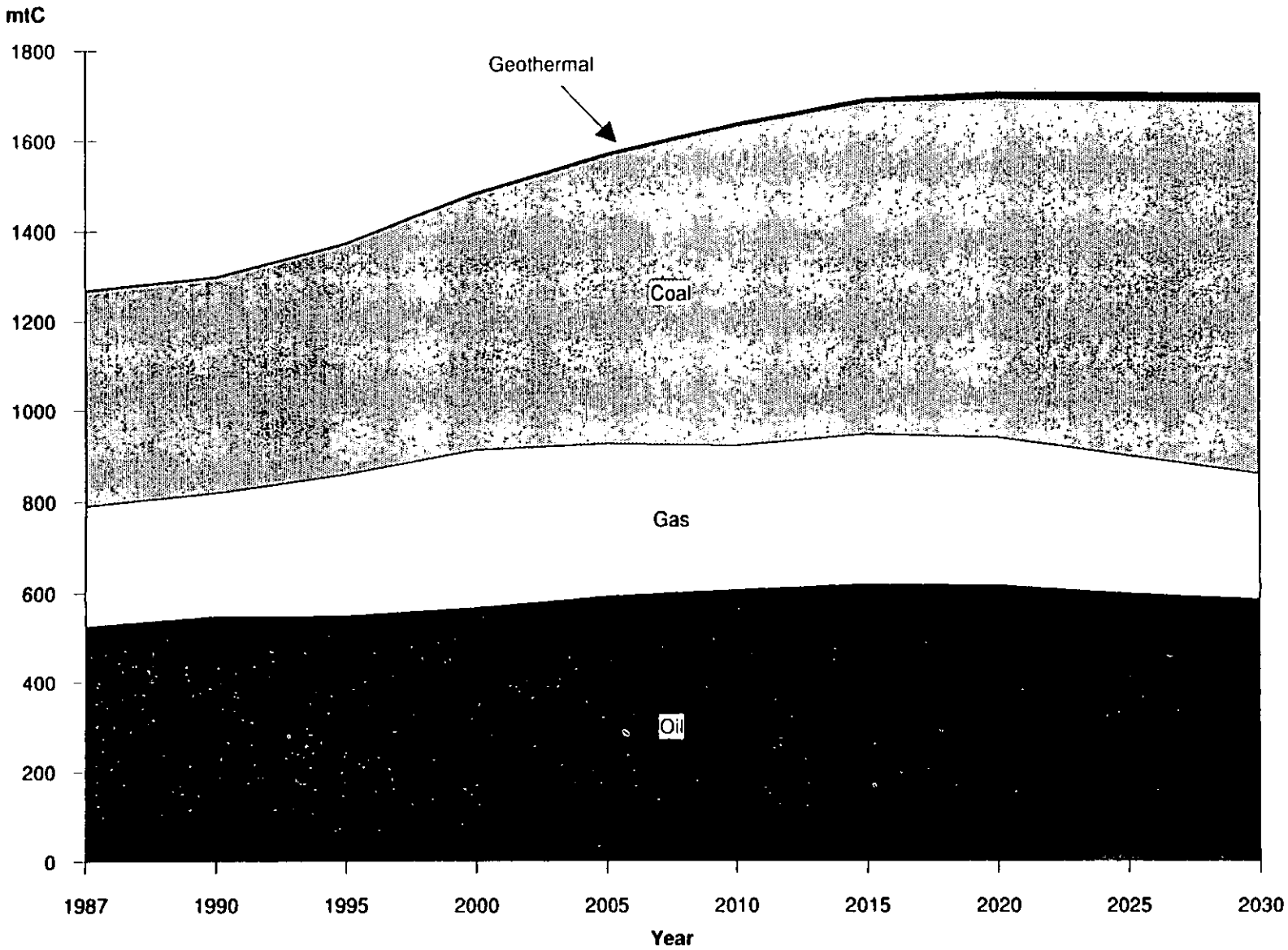

Figure 5.29. NES Actions Case: Fossil Fuel CO_2 Emissions by Fuel (millions of mtC/yr)

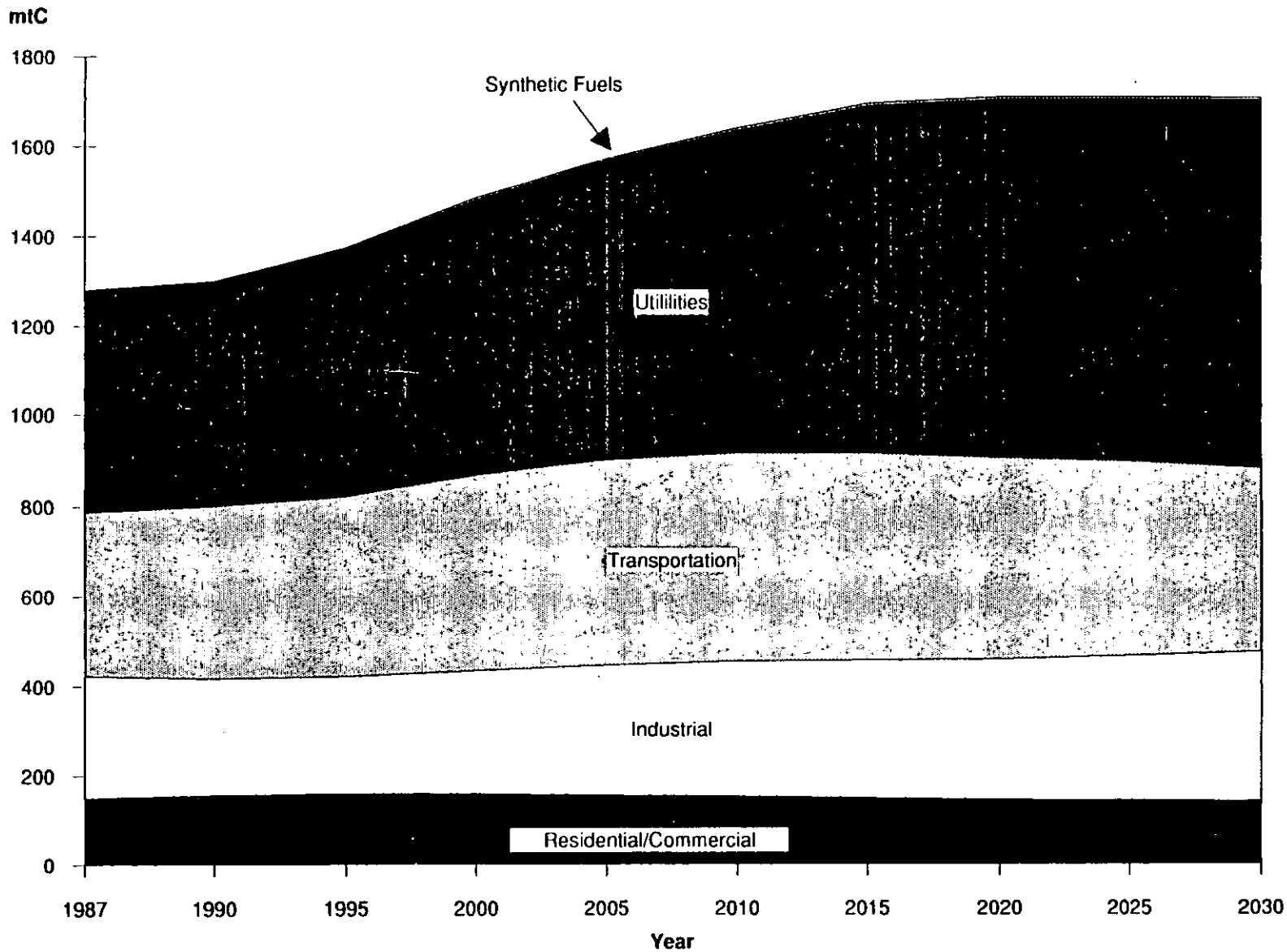

Figure 5.30. NES Actions Case: Fossil Fuel CO_2 Emissions by Sector (millions of mtC/yr)

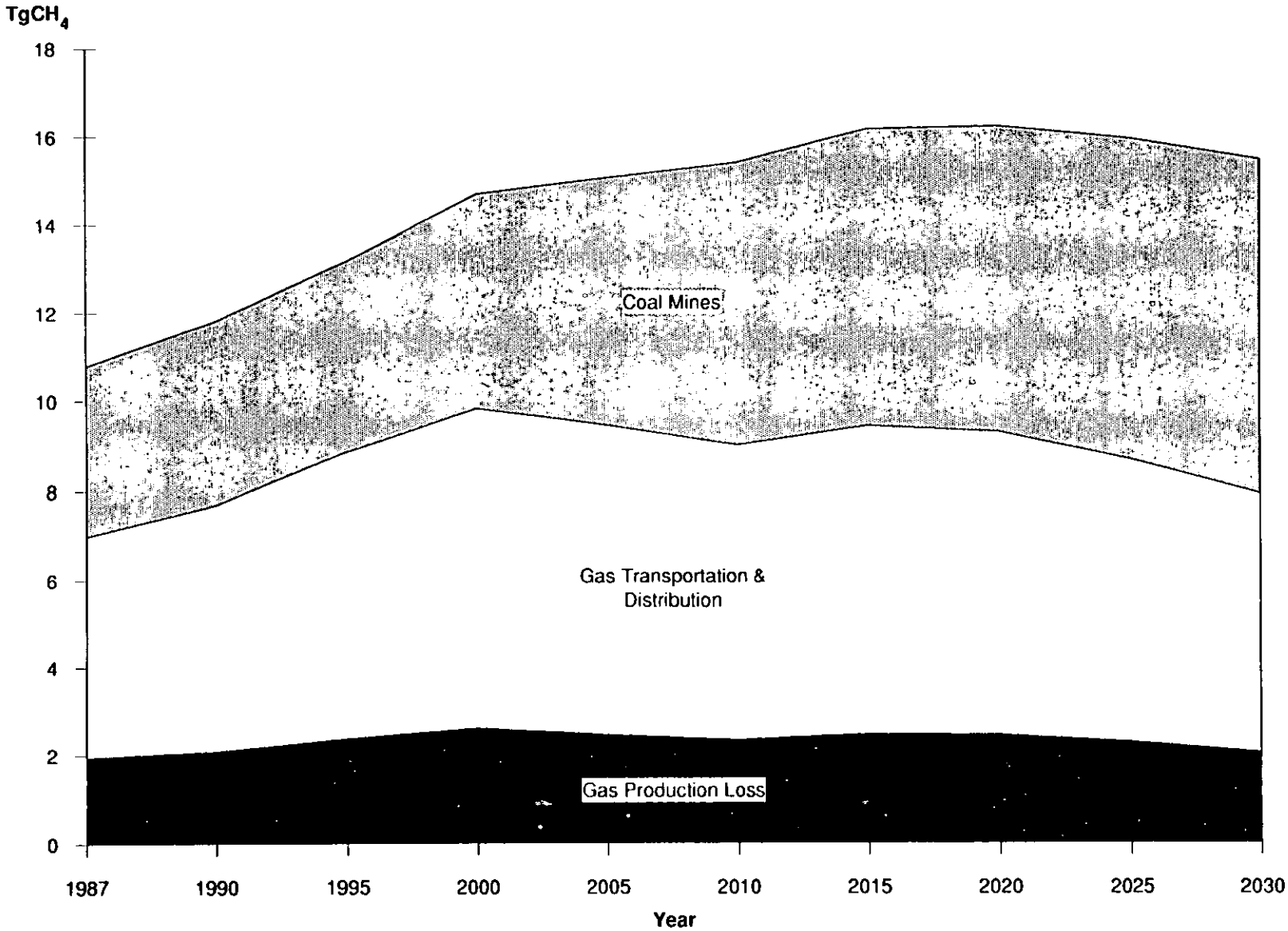

Figure 5.31. NES Actions Case: Methane Emissions ($TgCH_4$/yr)

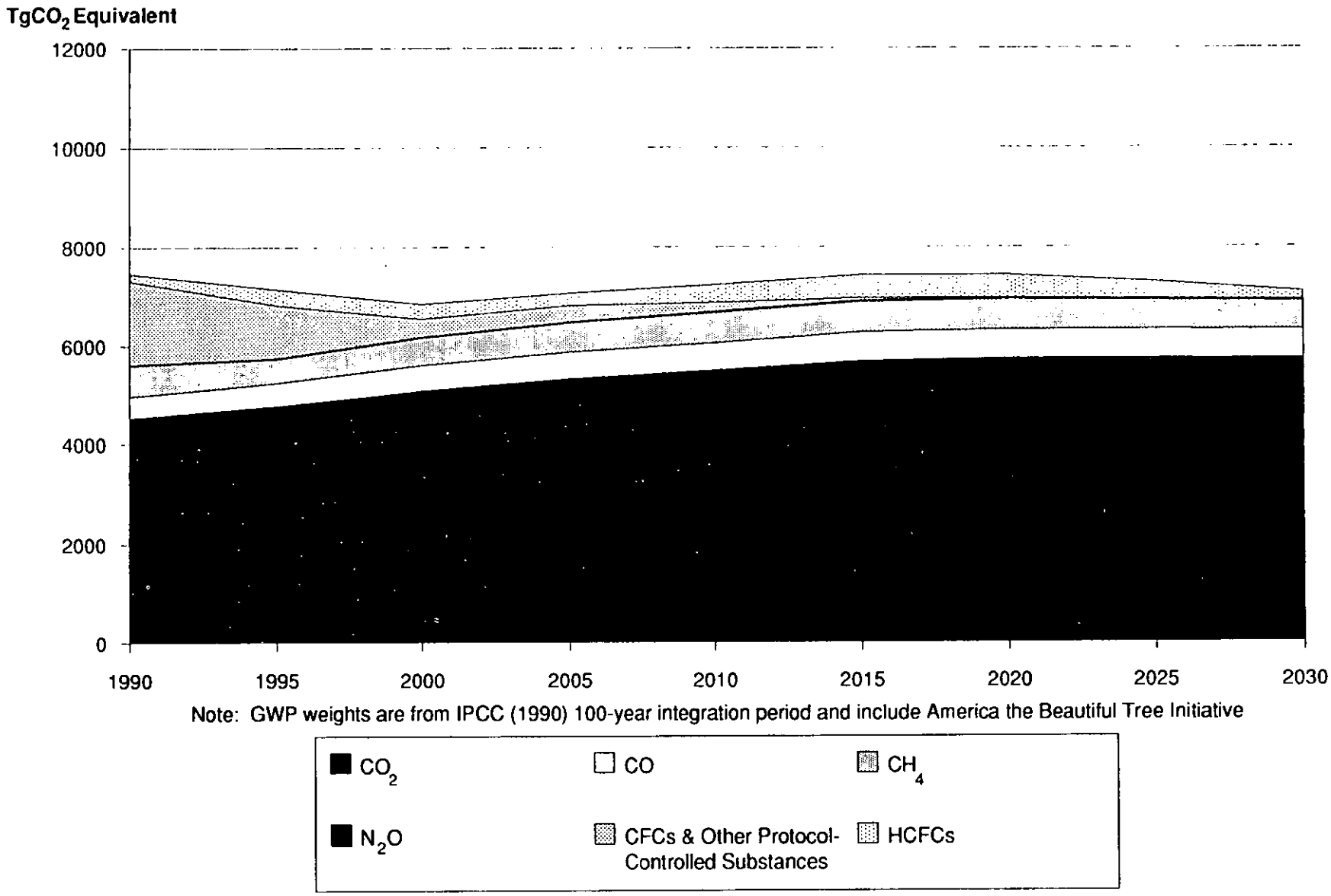

Figure 5.32. NES Actions Case: GWP-Weighted Energy-Related Emissions by Gas and by Year ($TgCO_2$ equivalent)

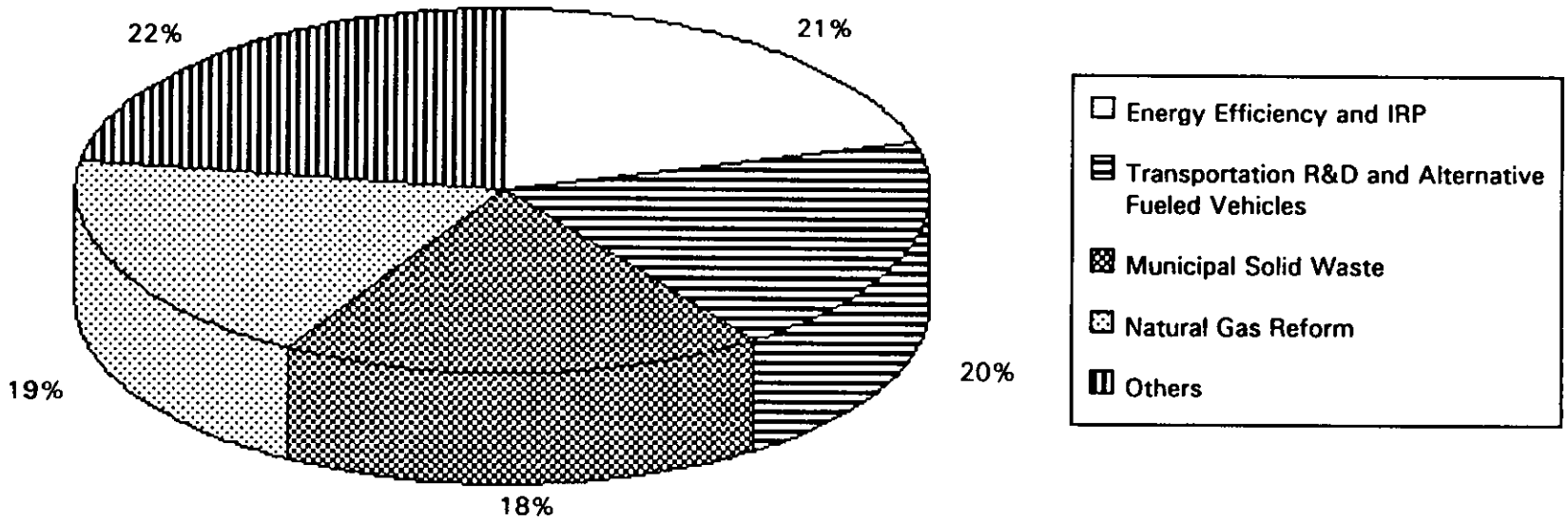

Figure 5.33. Year 2000 Contribution by NES Actions to Greenhouse Gas Emissions Reductions

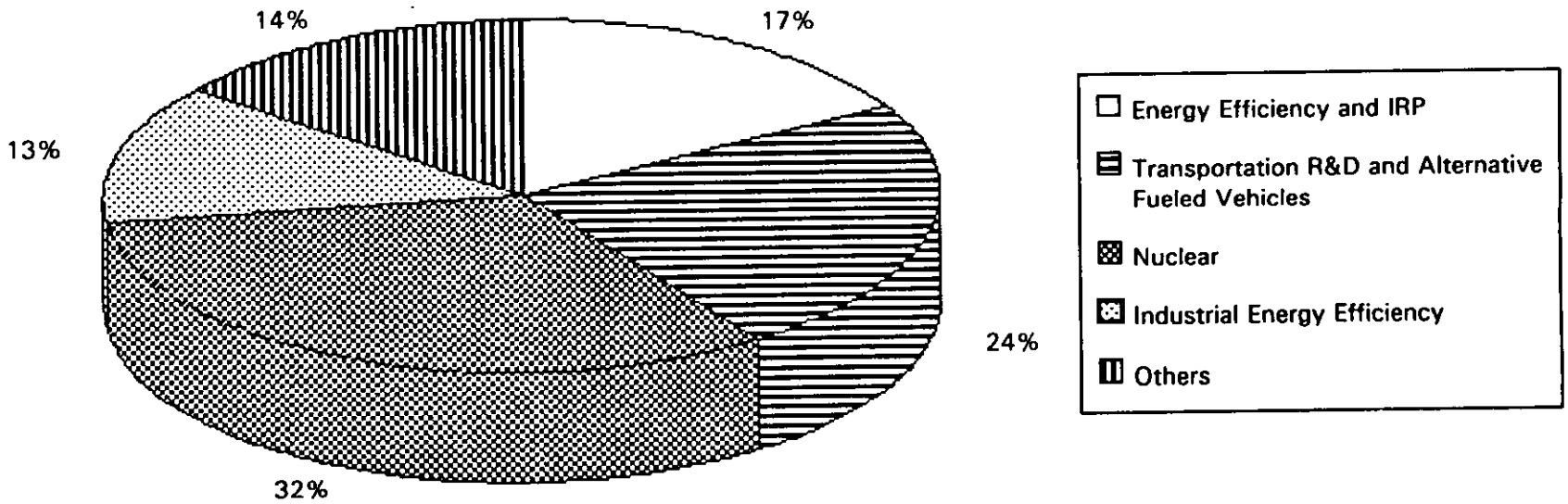

Figure 5.34. Year 2030 Contribution by NES Actions to Greenhouse Gas Emissions Reductions

6.0 FISCAL INSTRUMENTS

6.1 INTRODUCTION

In this chapter, we examine two individual policy instruments that go beyond the instruments considered as part of the NES Actions package and that take the form of financial incentives. Financial incentives are measures that effect changes in emissions through changes in the prices of various commodities and services that emitters pay. These price changes can take the form of a charge for the emission itself or a change in the cost of an activity associated with emissions. Carbon and total GWP-weighted emissions are closely associated with the consumption of fossil fuels. The examination of policy measures is restricted in this chapter to an examination of fossil fuel taxation. Other measures are also available, such as accelerated capital depreciation allowances. For an exhaustive discussion of financial incentive measures, see DOE 1989. Fuel taxes were chosen because they appeared to offer promise of substantial impact on greenhouse gas emissions. Nevertheless, the assumption that only fossil fuel carbon emissions are taxed is limiting. A more general analysis would consider taxation of carbon from other potential net sources, including, for example, cement manufacture and forest practices, as well as the effect of taxes on other activities that produce greenhouse gas emissions.

Any financial incentive, tax, or subsidy that affects the production and/or consumption of energy affects greenhouse gas emissions. Numerous financial incentives have been suggested, including taxation of gasoline, taxation of energy in general, subsidizing of renewable energy sources, and taxation of fossil fuels on the basis of their carbon content. Economic theory suggests that the most cost-effective approach to taxation is to denominate the financial incentive directly in terms of the activity that is to be either encouraged or discouraged. If emissions of fossil fuel CO_2 are the focus of emissions control strategies, the taxation of fossil fuels on the basis of their carbon content is attractive, as it directly associates a penalty for undesired emissions with the rate of emission for each level of activity. Such a tax scheme is statically efficient if CO_2 is the only greenhouse gas of concern, and if there are no acceptable carbon removal technologies and no important dynamic effects.[a] We have therefore chosen to focus on efficient financial instruments that address the problem of reducing energy-related greenhouse gas emissions and have ignored other financial instruments such as gasoline and Btu taxes, which might be efficient in a multiple-objective analysis.

The calculation of fuel-specific tax rates based on carbon emissions of fossil fuels is a technically simple procedure. Tax rates for carbon emissions, denominated in terms of energy prices, are proportioned to the carbon content of the fuel; that is, if coal has twice the carbon content of natural gas, then the tax added to the price of coal is twice the tax added to the price of natural gas. The product of the carbon-to-energy ratio and the desired tax rate on carbon yields the energy tax that must be added to the fuel price to implement the carbon tax. In subsequent chapters, we will relax the assumption that there are no acceptable carbon removal technologies and explore a deposit-refund approach

(a) The theoretical possibility of a perverse region in the carbon tax response schedule was pointed out in personal communication with H. Dowlatabadi. Consider a simple case in which there is a single fossil fuel used either directly in end-use or indirectly to make electricity. End-users consume both electricity and fossil fuels. Because the capital cost of power generation is large, relative to operating costs, the imposition of a carbon tax could result in a reduction in the price of electricity, compared to fossil fuels. The resulting substitution of electricity for direct fossil fuel use could lead to an overall increase in the use of electric power. Since the generation of electric power is significantly more carbon intensive per unit end-use energy than is direct fossil fuel use, the increased power generation could more than compensate for carbon emissions reduction, particularly if the principal price response is fuel substitution. The conditions for such an anomalous response are most likely to occur in the real world at low carbon tax rates where cost differentials are insufficient to cause fuel switching by utilities, and when excess fossil fuel generating capacity exists.

in which a carbon tax is levied, but is refunded if the carbon is captured. The capture of carbon can, in principle, be effected either prior or subsequent to combustion.

The concept of GWP is an alternative metric for the development of tax and subsidy rates. In principle, such values, if appropriately constructed, provide the correct approach to weighting emissions from multiple gases. The idea is that the "correct" weights should allow a direct comparison of damage or benefit associated with emissions of disparate gases. A set of weights, referred to as GWP coefficients, has been constructed by several researchers.[a] In our analysis, we have constructed a set of GWP-weighted energy taxes as an alternative to the much-discussed carbon tax.

In Chapter 11, we discuss how the carbon tax and GWP tax results compare with the results of recent similar studies of fiscal incentives.

6.2 THE CARBON TAX

6.2.1 Assumptions

Six different carbon tax rates were examined. These rates and the implied fuel tax per unit of energy for oil, gas and coal are given in Table 6.1 below. Implied fuel tax rates in terms of common energy units are given in Table 6.2.

6.2.2 GWP-Weighted Emissions Reductions Relative to the NES Actions Case

The overall impact of a fuel carbon tax on energy-related, GWP-weighted emissions is shown in Table 6.3 and Figure 6.1 in terms of teragrams of CO_2 equivalent ($TgCO_2e$).[b] The percent reduction from the 1990 emission level in 2030 is shown for each case. Under the NES Actions Case, GWP-weighted emissions decrease from 7458 $TgCO_2e$ to 7082 $TgCO_2e$ between 1995 and 2030, with an

(a) See Chapter 3 for discussion. In our analysis, we adopt the 100-year integration period GWP weights as reported in IPCC 1990.

(b) Recall that these emissions include CO_2, CO, CH_4, N_2O, CFCs, and HCFCs.

Table 6.1. The Relationship Between Carbon Tax Rates and Fuel Tax Rates

		Implied Fuel Tax ($/mBtu)		
Tax Case	Carbon Tax Rate	Oil	Gas	Coal
Case 1	$ 25/mtC	$ 0.53	$ 0.36	$ 0.64
Case 2	$ 50/mtC	$ 1.05	$ 0.72	$ 1.27
Case 3	$100/mtC	$ 2.10	1.45	$ 2.54
Case 4	$250/mtC	$ 5.26	3.62	$ 6.36
Case 5	$500/mtC	$10.52	$ 7.25	$12.72
Case 6	$750/mtC	$15.78	$10.87	$19.08

Notes: mtC = metric tonnes of carbon = 10^6gC. Fuel tax based on carbon content coefficients of 21.04TgC/PBtu oil; 14.50 TgC/PBtu gas; and 25.45 TgC/PBtu coal. Constant 1989 dollars.

Table 6.2. Fuel Price Changes per $100 Carbon Tax

Fuel	Base Cost ($)	Added Cost ($)	Added Cost (%)
Crude Oil ($/bbl)	16.81	12.19	73
Gasoline ($/gal)	0.98	0.26	27
Heating Oil, distillate ($/gal)	0.89	0.29	33
Wellhead Natural Gas ($/tcf)	1.81	1.49	82
Residential Natural Gas ($/tcf)	5.87	1.50	25
Minemouth Coal ($/short T)	23.02	55.33	240
Utility Coal ($/short T)	33.51	55.33	165
Electricity (c/kwh)	6.5c	1.76c	27

Notes: 1989 constant dollars. Base year 1990.

Table 6.3. Total Energy-Related GWP-Weighted[a] Emissions ($TgCO_2e$)

	Carbon Tax Rate ($/mtC)						
Year	$0[b]	$25	$50	$100	$250	$500	$750
1990	7458	7458	7458	7458	7458	7458	7458
1995	7143	7052	6928	6709	6274	5780	5477
2000	6843	6674	6544	6265	5628	4993	4681
2005	7064	6894	6739	6495	5583	4962	4718
2010	7233	7042	6866	6610	5539	4877	4653
2015	7422	7183	6956	6625	5607	4830	4617
2020	7431	7130	6847	6309	5327	4598	4389
2025	7293	6858	6497	5889	4968	4299	4102
2030	7082	6524	6105	5478	4534	3938	3748
Percentage Change from 1990 Emissions Level in 2030[c]:	-5%	-13%	-18%	-27%	-39%	-47%	-50%

(a) 100-year integration period.
(b) NES Actions Case.
(c) Negative values represent reductions.

interim peak of about 7430 $TgCO_2e$ in 2020. Thus, under the NES Actions Case, GWP-weighted emissions are stabilized below the 1990 level for the entire analysis period.

The $50/mtC tax is the first carbon tax instrument to achieve significant (approaching 20%) reductions in GWP-weighted emissions, relative to 1990, in 2030. Increasingly stringent

taxes decrease these emissions further, with the decreases leveling out at the highest rates. A quadrupling of the tax rate from $25/mtC to $100/mtC causes the GWP-weighted emissions reduction, relative to the 1990 level, in 2030 to increase by a factor of three, from 13% to 39%. Nearly tripling the tax, from $100/mtC to $250/mtC, causes the emissions reduction to increase by about half, from 27% to 39%. A second tripling, from $250/mtC to $750/mtC, increases the emissions reduction by less than one-third, from 39% to 50%. For tax rates of $500/mtC and above, GWP-weighted emissions decrease steadily after 2005, while for lower tax rates and the NES Actions Case, emissions generally increase between 2000 and 2015.

In Section 6.2.8, we discuss these emissions in terms of carbon and methane emissions. (All changes in CFC and HCFC emissions occur as a result of current regulatory initiatives; emissions of these gases are not affected by carbon taxes.)

6.2.3 Carbon Tax Impacts on Energy Prices

In this section, we discuss the price results for primary fossil energy resources (oil, natural gas, and coal) and for electricity.

Oil Prices

The imposition of the carbon tax in the U.S. would cause demand for oil to drop, resulting in a small decrease in the world oil price.[a] There is a relatively low price response elasticity in Fossil2 that alters the world oil price assumption based on changes in U.S. oil demand. The results do not vary appreciably among carbon tax cases. By 2030, the world oil price is virtually identical to the NES Actions Case price for taxes up to $100/mtC, and about 7% ($0.52/mBtu or $3.00/bbl) lower than the NES Actions Case price for a $750/mtC tax (see Table 6.4). Because these are world oil prices, they reflect demand changes only.

The prices at the point of end use reflect both the tax itself and the demand changes caused by the tax. As a result, gasoline prices increase for all tax cases, and the increases vary dramatically among cases. As shown in Table 6.5, the gasoline price increase relative to the NES Actions Case in 2030 ranges from 4% ($0.48/mBtu) for the $25/mtC Case to 115% ($14.42/mBtu) for the $750/mtC tax.

(a) In Chapter 10, we explore the implications of various degrees of global participation in emissions reduction for the cost of emissions reductions.

Table 6.4. World Oil Prices Under Carbon Taxes ($/mBtu)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	2.90	2.90	2.90	2.90	2.90	2.90	2.90
1995	3.46	3.44	3.42	3.38	3.29	3.17	3.08
2000	4.56	4.52	4.50	4.45	4.32	4.16	4.03
2005	5.03	4.99	4.96	4.90	4.73	4.55	4.36
2010	5.52	5.48	5.45	5.37	5.18	4.99	4.82
2015	6.15	6.11	6.08	6.02	5.85	5.65	5.46
2020	6.56	6.54	6.52	6.46	6.33	6.15	5.95
2025	6.88	6.87	6.84	6.79	6.67	6.50	6.35
2030	7.07	7.05	7.04	7.00	6.86	6.70	6.55

(a) NES Actions Case.

Table 6.5. Gasoline Prices Under Carbon Taxes ($/mBtu)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	7.86	7.86	7.86	7.86	7.86	7.86	7.86
1995	8.49	8.96	9.44	10.40	13.30	18.17	23.07
2000	9.70	10.17	10.64	11.58	14.44	19.27	24.13
2005	10.23	10.69	11.15	12.09	14.90	19.70	24.49
2010	10.78	11.23	11.69	12.61	15.39	20.19	25.00
2015	11.47	11.93	12.39	13.34	16.15	20.92	25.71
2020	11.93	12.41	12.88	13.82	16.68	21.48	26.26
2025	12.29	12.77	13.24	14.19	17.05	21.87	26.69
2030	12.50	12.98	13.46	14.42	17.26	22.09	26.92

(a) NES Actions Case.

Natural Gas Prices

The wellhead gas price, like the world oil price, reflects the carbon tax only indirectly, via the tax's impact on demand. As indicated in Table 6.6, the prices do not vary considerably among tax cases. The wellhead gas price in 2030 ranges from $0.77/mBtu (11%) higher than the NES Actions Case for the $100/mtC Tax Case to $0.38/mBtu (5%) lower than the NES Actions Case for the $750/mtC Tax Case. The effects of the taxes differ over time. In the period before 2005, wellhead gas prices are lower than NES Actions Case prices for all tax cases. After 2005, prices fluctuate about the NES Actions Case price; by 2030, only the price associated with the $750/mtC Tax Case is lower than the NES Actions Case price. The greatest discrepancy between the NES Actions Case and the tax cases occurs in 2000; at this point, the price associated with the $750/mtC Tax Case is 30% lower than the NES Actions Case price.

These price patterns reflect gas consumption patterns that are initially suppressed, relative to the NES Actions Case, but that rebound in later periods (see Figure 6.2). Beginning in 2010, gas consumption in all tax cases is lower than in the NES Actions Case.

The effect of taxes on end-use gas prices, shown in Table 6.7, is less ambiguous. Reflecting both demand changes and the tax itself, the residential gas price in 2030 ranges from $0.58 (5%) to $9.99 (90%) per mBtu higher than the NES Actions Case for the $25/mtC and $750/mtC Tax Cases, respectively.

Coal Prices

Demand reductions in response to the imposition of fuel carbon taxes cause the minemouth price of coal to be suppressed, relative to the NES Actions Case, in all cases (see Table 6.8). In the highest tax cases, the price initially declines from the 1990 level as the tax is phased in. Otherwise, the price rises from 1990 onward in all cases, including the NES Actions Case, although before 2005, prices in the two high-tax cases ($500/mtC and $750/mtC) rise much more slowly than in the other cases. Between 2015 and 2020, the two high-tax cases result in sharply higher prices that almost reach the NES Actions Case price; however, these prices drop sharply afterward. The differences in minemouth coal prices in 2030 range from $0.04 (3%) to $0.17 (12%) below the NES Actions Case for the $25/mtC and $750/mtC Tax Cases, respectively.

Table 6.6. Wellhead Gas Prices Under Carbon Taxes ($/mBtu)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	1.78	1.78	1.78	1.78	1.78	1.78	1.78
1995	2.38	2.37	2.34	2.28	2.20	2.11	2.06
2000	3.89	3.83	3.68	3.51	3.16	2.84	2.72
2005	4.16	4.20	4.20	4.13	4.28	4.13	3.62
2010	5.12	5.18	5.24	5.33	5.33	5.25	5.14
2015	6.07	6.07	6.05	6.23	6.41	6.00	5.61
2020	6.59	6.72	6.79	6.67	6.77	6.48	6.32
2025	6.60	6.72	6.81	6.97	6.95	6.78	6.59
2030	7.33	7.59	7.82	8.10	8.01	7.37	6.95

(a) NES Actions Case.

Table 6.7. Residential Gas Prices Under Carbon Taxes ($/mBtu)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	5.69	5.69	5.69	5.69	5.69	5.69	5.69
1995	6.22	6.56	6.88	7.52	9.53	12.90	16.32
2000	7.67	7.95	8.16	8.69	10.43	13.60	16.96
2005	7.98	8.37	8.71	9.33	11.54	14.85	17.87
2010	8.89	9.29	9.69	10.46	12.53	15.90	19.25
2015	9.82	10.17	10.49	11.36	13.60	16.67	19.76
2020	10.35	10.82	11.23	11.80	13.97	17.16	20.46
2025	10.43	10.88	11.31	12.15	14.20	17.48	20.76
2030	11.13	11.71	12.27	13.22	15.19	18.06	21.12

(a) NES Actions Case.

The effect of the tax on the utility coal price, which reflects both demand changes and the tax itself, is large. As shown in Table 6.9, at the higher tax rates, prices increase sharply between 1990 and 1995; after 1995, all prices increase steadily at a rate close to that of the NES Actions Case prices. By 2030, the NES Actions Case price has risen to $2.22/mBtu. The tax boosts this price by $.56/mBtu (25%) in the $25/mtC Tax Case and by $17.95 (809%) in the $750/mtC Tax Case.

Electricity Prices

Because electricity is not a fossil fuel, it is not taxed directly under a fuel carbon tax system. However, taxes on fossil fuels affect the cost of generating electric power and therefore the cost of electricity to consumers. In 1990, fossil fuels provided approximately 70% of the energy input to generate electric power in the NES Actions Case; this fraction decreases to 60% by 2030. Fossil fuel

Table 6.8. Minemouth Coal Prices Under Carbon Taxes ($/mBtu)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	1.04	1.04	1.04	1.04	1.04	1.04	1.04
1995	1.07	1.06	1.05	1.03	1.00	0.98	0.99
2000	1.12	1.10	1.10	1.09	1.05	0.99	0.98
2005	1.15	1.14	1.13	1.13	1.06	1.00	1.00
2010	1.25	1.23	1.23	1.23	1.13	1.09	1.07
2015	1.31	1.30	1.29	1.27	1.24	1.19	1.17
2020	1.37	1.36	1.34	1.31	1.31	1.35	1.36
2025	1.42	1.39	1.36	1.32	1.29	1.29	1.29
2030	1.47	1.43	1.40	1.35	1.31	1.30	1.30

(a) NES Actions Case.

Table 6.9. Utility Coal Prices Under Carbon Taxes ($/mBtu)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	1.57	1.57	1.57	1.57	1.57	1.57	1.57
1995	1.69	2.27	2.86	4.05	7.64	13.68	19.75
2000	1.74	2.33	2.93	4.13	7.71	13.69	19.74
2005	1.78	2.38	2.97	4.19	7.72	13.71	19.76
2010	1.92	2.51	3.10	4.32	7.82	13.82	19.86
2015	2.00	2.60	3.19	4.38	7.97	13.96	19.99
2020	2.09	2.68	3.26	4.43	8.06	14.18	20.25
2025	2.15	2.72	3.29	4.45	8.04	14.10	20.16
2030	2.22	2.78	3.34	4.49	8.06	14.12	20.17

(a) NES Actions Case.

costs can therefore have a substantial effect on the overall cost of power generation.

In the NES Actions Case, the average electricity price remains relatively stable throughout the course of the analysis, rising only about 17% from the 1990 level, to $21.77/mBtu. Figure 6.3 illustrates that, in 1995 (after the tax has been phased in), the average electricity price increase is roughly proportional to the fuel carbon tax rate applied. The $25/mtC tax adds approximately 8% to the average cost of electricity in 1995, while the $50/mtC tax adds approximately 16% and the $500 tax adds about 142%. The $750/mtC tax level adds over 200% to the average electricity cost in 1995. Deviations from proportionality occur because utilities can reorder the use of their facilities for base load and peaking power.

Over the long term, utilities can adjust their capital stocks to avoid the taxes. As a result, the differences in electricity costs among the cases

decrease over time. By 2030, the electricity price in the $25/mtC Tax Case is 5% higher than in the NES Actions Case, while in the $750/mtC Tax Case, the price is 52% higher. The pronounced decline in percentage increase relative to the NES Actions Case reflects the decrease in the fraction of energy inputs to electricity generation provided by fossil fuels, as well as shifts in the composition of the fossil fuel inputs and overall increases in electricity demand. While the fraction of the energy input to electricity generation provided by fossil fuels decreases to 60% in the NES Actions Case, it decreases to about 50% in the $25/mtC Tax Case, to 36% in the $100/mtC Tax Case, and to 19% in the $750/mtC Tax Case.

6.2.4 Carbon Tax Impacts on Primary Energy Consumption

In this section, we discuss the effects of the carbon tax on total primary energy consumption and on consumption of oil, natural gas, coal, and renewable energy resources. Because all nuclear fuel is consumed in the utility sector, its consumption is discussed in Section 6.2.5, "Energy Transformation."

Total Energy Consumption

Total energy consumption grows from approximately 85 quads in 1990 to approximately 126 quads in 2030 in the NES Actions Case, an increase of about 48%. As shown in Table 6.10, total energy demand is suppressed relative to the NES Actions Case in all tax cases. After 2000, total energy consumption grows at a roughly equivalent rate for all cases, including the NES Actions Case. After 1990, the total energy consumption in the $25/mtC Case is 1% to 2% lower than in the NES Actions Case. In the $100/mtC Tax Case, total consumption is reduced by about 3% to 7%, while in the $750/mtC Case, it is reduced 20% to 25%.

None of the tax rates cause energy consumption in 2030 to be below the 1990 level. Although consumption is initially suppressed relative to the 1990 level for tax rates above $100/mtC, it regains the 1990 level by 2010 in all cases.

Oil Consumption

As Table 6.11 indicates, in 2015, total oil consumption peaks in all cases, including the NES

Table 6.10. Total Primary Energy Consumption Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	85.4	85.4	85.4	85.4	85.4	85.4	85.4
1995	91.5	90.3	88.8	86.0	80.2	74.1	70.0
2000	99.2	97.3	95.6	92.1	85.1	78.4	73.6
2005	105.3	103.6	101.9	98.3	90.9	84.4	79.3
2010	110.9	109.4	107.9	104.4	96.9	91.1	85.9
2015	115.9	114.2	112.7	110.0	102.6	94.8	90.3
2020	119.9	118.5	117.2	114.3	106.2	98.8	93.9
2025	123.7	122.4	121.4	119.2	110.3	104.2	98.8
2030	126.6	125.5	124.9	123.1	114.7	108.8	103.4

(a) NES Actions Case.

Table 6.11. Total Oil Consumption Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	34.4	34.4	34.4	34.4	34.4	34.4	34.4
1995	34.7	34.3	33.8	32.9	30.8	28.3	26.5
2000	35.9	35.3	34.8	33.9	31.8	29.4	27.4
2005	37.3	36.8	36.4	35.5	33.3	31.1	29.1
2010	38.0	37.5	37.1	36.3	34.2	32.1	30.0
2015	38.3	37.8	37.4	36.8	34.9	32.5	30.4
2020	37.8	37.4	37.1	36.2	34.2	31.8	29.8
2025	36.6	36.3	36.0	35.3	33.4	31.0	29.1
2030	35.6	35.4	35.3	34.7	32.5	30.2	28.3

(a) NES Actions Case.

Actions Case. Oil becomes a decreasingly important form of energy consumption in all of the cases. The share of total primary energy consumption decreases from about 40% in 1990 to about 30% of the total in 2030.

The domestic oil market is modeled as an essentially open market whose price is controlled by the world market. As described in Section 6.2.3, imposition of a tax causes U.S. demand to drop, which causes a small decrease in world oil demand. Oil consumption is suppressed relative to the NES Actions Case for all tax cases, and the suppression of consumption grows as the tax becomes more stringent. In all cases, the reduction (relative to the NES Actions Case) is smaller in 2030 than in 1995. The decrease in consumption in 2030 ranges from 1% to 20% of the NES Actions Case in the $25/mtC and $750/mtC Tax Cases, respectively.

In all tax cases, oil consumption decreases initially, relative to the 1990 level. A tax rate of $250/mtC is the inflection point for oil consumption. For lower tax rates, consumption regains the 1990 level by 2005, peaks in 2015, then decreases to levels that are still above the 1990 level; for higher tax rates, oil consumption is below the 1990 level for the entire analysis period. At a tax rate of $250/mtC, the peak in 2015 is slightly above the 1990 level; thereafter, consumption declines to below the 1990 level.

Gas Consumption

The effect of the carbon taxes on natural gas consumption is shown in Figure 6.2. Gas is the least penalized of fossil fuels under the carbon tax cases. The most important observation to be made is that cumulative consumption between 1990 and 2030 is within 5% of the NES Actions Case value in all cases. Gas consumption in all of the tax cases is lower than in the NES Actions Case in the period to 2000, but exceeds consumption under the NES Actions Case from 2010 onward in all cases. Taxes have the effect of shifting natural gas consumption farther into the future. In response to the taxes, cheap energy conservation measures are substituted for fossil fuel consumption in early periods, and low-carbon fossil fuels are substituted for high-carbon fossil fuels in the later periods. Gas consumption peaks in the NES Actions Case at 24.7 quads per year in the year 2000. In all of the tax cases, this peak is delayed for 15 years, and the peak is higher than the NES Actions Case peak in the $100/mtC, $250/mtC, and $500/mtC Tax Cases. These results reflect the interplay of an essentially

closed gas market with a finite resource of inexpensive domestic natural gas supply.

Coal Consumption

Coal receives the heaviest penalty of fossil fuels under the carbon taxes; as a result, coal consumption is directly and greatly affected by these taxes (see Table 6.12). In the NES Actions Case, coal consumption increases steadily after 1990; by 2030, coal consumption is 80% higher than in 1990. This pattern is changed for all tax cases.

An important shift in the effeectof the carbon taxes occurs between $100/mtC and $250/mtC. At lower tax rates, coal consumption grows steadily after 1995 to a peak in 2015, after which it decreases slightly to levels that in 2030 are still above the 1990 level. The 2030 value is about 40% and 15% above the 1990 level for the $25/mtC and $50/mtC tax rates, respectively. In the $100/mtC Tax Case, consumption peaks in 2010 slightly above the 1990 level, then decreases by 2030 to 21% below the 1990 level. At higher tax rates, coal consumption declines continuously after 1990. Coal consumption in 2030 is 62%, 81%, and 83% below the 1990 level for the $250/mtC, $500/mtC, and $750/mtC Tax Cases, respectively.

In any year, the effect of carbon taxes on coal consumption is greater, relative to the NES Actions Case, with more stringent taxes. In the $25/mtC Tax Case, coal consumption is 19% lower than in the NES Actions Case in 2030. In the $750/mtC Tax Case, consumption is 90% lower than in the NES Actions Case in 2030.

The relative importance of coal in domestic energy consumption varies dramatically among cases. In the NES Actions Case, coal use is roughly stable, growing from 22% to 26% of domestic energy consumption from 1990 to 2030. Coal use remains roughly stable for the $25/mtC Tax Case, then decreases to 18% of domestic energy consumption by 2030 in the $50/mtC Tax Case, and to 13% in the $100/mtC Case. Coal's share decreases dramatically by 2030 for higher tax rates, to only 7% of domestic energy consumption in the $250/mtC Case and 3% in the $500/mtC and $750/mtC Cases.

There is little difference between the coal consumption trajectories for the $500/mtC and $750/mtC Tax Cases. At these tax rates, there is virtually no investment in new coal capacity after 1990. Only coal capacity already under

Table 6.12. Total Coal Consumption Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	19.0	19.0	19.0	19.0	19.0	19.0	19.0
1995	20.0	19.5	18.7	17.5	15.2	12.4	11.1
2000	22.3	21.1	20.4	18.6	13.7	9.4	8.6
2005	25.0	23.6	22.3	20.8	12.5	8.2	7.5
2010	27.8	25.9	24.2	22.0	12.0	6.8	6.4
2015	28.9	26.7	24.5	20.7	11.1	5.5	5.1
2020	29.5	26.4	23.6	18.5	9.5	4.5	4.0
2025	31.0	26.4	22.5	16.5	8.2	3.9	3.5
2030	32.3	26.3	21.6	15.0	7.3	3.6	3.2

(a) NES Actions Case.

construction is continued, and all existing capacity is retired as it reaches the end of its useful lifetime.

The large decrease in coal use under high carbon taxes is compensated for by shifts to other fuels and by decreases in consumption **relative to the NES Actions Case** (recall that none of the tax rates causes consumption in 2030 to fall below the 1990 level). For example, after 1990, total energy consumption is 20% to 25% below the NES Actions Case level under a $750/mtC tax.

As indicated, the relative importance of coal in domestic energy consumption decreases with higher tax rates. In any year, coal's share of domestic energy consumption is lower with higher tax rates. The difference is made up primarily by increases in the consumption of renewable and nuclear energy sources. For example, for tax rates of $250/mtC and higher, renewable energy sources account for over one-quarter of domestic energy consumption in 2030 and nuclear sources account for about one-fifth. These changes represent a tripling of the share of each fuel relative to their 1990 shares, and smaller increases relative to their shares under the NES Actions Case in 2030.

Renewable Energy Consumption

In the NES Actions Case, renewable energy sources represent a steadily increasing fraction of domestic primary energy consumption over time. This fraction more than doubles between 1990 and 2030, from 8% to 18%. The consumption trajectory for renewable energy is roughly constant for tax rates up to $100/mtC; at the $100/mtC tax rate, the renewable share of primary energy consumption is 21%. Renewable energy use increases more rapidly under higher taxes. By 2030, the renewable energy share is one-quarter or more of total domestic consumption, more than triple the 1990 levels.

In terms of absolute energy consumption, renewable consumption more than triples in the NES Actions Case, from about 7 quads to over 22 quads (see Table 6.13). Renewable energy use increases steadily over time under carbon taxes to more than quadruple the 1990 level by 2030 in the highest tax cases. After 1995, renewable energy consumption peaks under the $500/mtC tax rate, decreasing slightly as the tax is increased to $750/mtC. The decrease results from reduced demand for electricity and transportation fuel at the highest tax rate.

6.2.5 Energy Transformation

Electric Power Generation

As shown in Table 6.14, total electricity demand is higher in all cases in 2030 than in 1990. After 1995, electricity demand grows without reversal in all of the carbon tax cases. In the three highest tax cases, demand is reduced initially (between 1990 and 1995) but grows steadily afterward, regaining 1990 levels by 2000 in the $250/mtC Tax Case and soon after 2005 in the $750/mtC Case. By 2030, electricity demand is reduced by 2% to 6% in the three lower tax cases and by 12% to 16% in the three higher tax cases. In the latter cases, electricity demand increases at a higher rate than in the NES Actions Case after 2020.

Heat rates are slightly lower in the highest tax cases than in the NES Actions Case, despite the reduced demand for electricity and therefore reduced level of needed capacity. Two factors contribute to this. First, as tax rates rise, the repowering option becomes decreasingly attractive, and older, less efficient powerplants are retired rather than repowered. Second, high-efficiency natural gas units become a relatively more attractive option.

Total utility consumption of natural gas is shown in Figure 6.4. Gas consumption rises above the NES Actions Case level for the higher tax cases between 2000 and 2005, and by 2010 consumption is higher than the NES Actions Case level for all tax cases. After 1995, demand remains strong at 4 quads to 6 quads per year, even in the lowest of the

Table 6.13. Total Renewables Consumption Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	6.8	6.8	6.8	6.8	6.8	6.8	6.8
1995	7.7	7.7	7.7	7.7	7.7	8.1	8.2
2000	9.0	9.0	8.9	8.8	9.2	10.5	10.4
2005	10.3	10.4	10.4	9.9	11.9	12.6	11.9
2010	11.9	12.1	12.2	11.9	14.0	14.8	14.1
2015	14.5	14.7	14.9	15.2	16.8	17.0	16.8
2020	17.3	17.7	17.9	18.7	20.3	20.5	20.2
2025	20.2	20.9	21.5	22.6	23.7	24.8	23.9
2030	22.4	23.4	24.2	25.3	27.3	28.4	27.4

(a) NES Actions Case.

Table 6.14. Total Electricity Demand Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	9.2	9.2	9.2	9.2	9.2	9.2	9.2
1995	10.5	10.4	10.2	9.7	9.1	8.4	8.1
2000	11.8	11.5	11.2	10.5	9.5	8.8	8.2
2005	12.8	12.5	12.2	11.5	10.4	9.6	9.0
2010	13.7	13.5	13.2	12.5	11.2	10.5	9.9
2015	14.9	14.6	14.3	13.6	12.2	11.5	10.9
2020	16.1	15.8	15.5	14.7	13.3	12.8	12.2
2025	17.3	16.9	16.6	15.9	14.7	14.3	13.6
2030	18.4	18.0	17.7	17.2	16.3	16.0	15.4

(a) NES Actions Case.

the tax cases. By 2030, gas consumption for electric power production in the $100/mtC Tax Case is 2.2 quads per year or 56% higher than in the NES Actions Case.

As Figure 6.5 indicates, oil-fired powerplants become more attractive in the higher tax cases and therefore continue to be used. However, oil consumption never exceeds 2.4 quads per year or approximately 6% of total electric power input energy.

The most striking effects of fuel carbon taxes are reflected in the use of coal to generate electric power, as shown in Figure 6.6. Coal use almost doubles between 1990 and 2030 in the NES Actions Case, and the fraction of total power generation fueled by coal decreases from 54% to 49% over the same period. Coal use is suppressed relative to the NES Actions Case in all tax cases, and in the higher tax cases, coal use in 2030 is below 1990 levels. By 2030, coal use decreases by 5.5 quads per year, or 19%, in the $25/mtC Tax Case. A tax of $100/mtC

reduces coal use by about 16 quads/yr, or 55%; the reduction due to the $500/mtC and $750/mtC tax rates is about 26 quads per year, or about 91%. At the lower tax levels, some increase in coal usage occurs until 2015, due at least in part to the new orders for coal-fired powerplants that are placed before 1990. However, in all cases and in all years, the fraction of electric power generation fueled by coal is lower than in the NES Actions Case. This fraction decreases steadily over time for each tax case. By 2030, the coal share of electricity generation is roughly 33% in the $50/mtC Tax Case, 22% in the $100/mtC Case, and 5% in the $500/mtC and $750/mtC Tax Cases.

Despite these reductions, coal use in 2030 remains above 5 quads for tax rates up to $250/mtC and never falls below 2 quads. This apparent floor on coal usage is an artifact of the Fossil2 Model structure, which assumes that existing capacity will not be retired prior to the end of its useful life. Coal therefore continues to be used despite its extremely high cost of operation. The effects of taxes are probably underestimated, particularly in the highest tax cases. It is also interesting to note that the economic characteristics of coal-fired powerplants are sufficiently attractive to result in continued increases in coal use until penalties become extremely high.

Nuclear energy is not taxed under fuel carbon taxes. As a result, the use of nuclear power is enhanced by the application of the taxes. As shown in Figure 6.7, new and advanced nuclear technologies result in a relatively steady increase in the use of nuclear power of 1.5 quads to 2 quads per year after 2015. After 1990, the fraction of electric power input energy supplied by nuclear sources first decreases from 19% to 14%, then increases to roughly 22% by 2030. All of the fuel carbon tax cases increase the use of nuclear power relative to the NES Actions Case, particularly after 2005. The production of nuclear electric power is 26% higher in the $25/mtC Tax Case than in the NES Actions Case in 2030. This production rises to 46% above the NES Actions Case in the $50/mtC Tax Case, 62% above the NES Actions Case in the $750/mtC Tax Case, and 71% to 73% above the NES Actions Case in the $100/mtC, $250/mtC, and $500/mtC Tax Cases. (The shares of input energy supplied by nuclear sources for several tax rates are shown in Table 6.15.) The reduced demand under the $750/mtC tax rate, relative to the lower rates, is driven by two factors. First, total electricity demand, and therefore productive capacity, is reduced by higher tax rates. Second, the model does not retire existing capacity before the end of its useful life, and coal-fired plants continue to be used at extremely high tax rates. For tax rates above $500/mtC, these two factors actually reduce the share of nuclear power and raise the share of oil-, gas-, and coal-fired power in total utility energy consumption in the year 2030. The failure of the model to retire existing capacity before the end of its useful life at very high tax rates may result in underestimation of the role nuclear power might play and of the overall effectiveness of these taxes, particularly at high fuel carbon tax rates.

The use of renewable energy, shown in Figure 6.8, is also enhanced generally by the application of fuel carbon taxes. The NES Actions Case anticipates that renewable energy technologies will provide an increasing source of power, with the total share of utility energy consumption supplied by renewable energy sources increasing from about 13% in 1990 to about 21% in 2030. The application of fuel carbon taxes increases the relative share of electric power production of renewable energy in all years, compared with the NES Actions Case (see Table 6.16). As was the case with nuclear power, the highest tax rate does not result in the highest absolute level of renewable energy use. After 2015, the use of renewable energy in the $750/mtC Case diminishes relative to the $500/mtC Case. Also, between 1990 and 2010, tax rates of $100/mtC and below cause the amount of renewable energy used to remain at or below the NES Actions Case level. Steeper taxes are required to cause much effect in the early years of the assessment period.

Table 6.15. Fraction of Electric Power Generation Input Energy Supplied by Nuclear Sources Under Carbon Taxes

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	19.3%	19.3%	19.3%	19.3%	19.3%	19.3%	19.3%
1995	17.4%	17.5%	17.9%	18.7%	20.2%	21.6%	22.7%
2000	16.0%	16.5%	16.9%	17.8%	20.0%	21.7%	22.9%
2005	15.7%	16.1%	16.6%	17.0%	21.5%	24.3%	23.1%
2010	15.7%	16.4%	17.2%	17.1%	24.0%	28.0%	26.3%
2015	14.4%	15.8%	17.6%	18.7%	24.3%	29.7%	27.8%
2020	16.1%	18.7%	21.4%	26.0%	29.9%	35.7%	33.3%
2025	19.2%	23.5%	27.1%	32.8%	36.3%	40.2%	38.6%
2030	21.5%	27.3%	31.5%	37.3%	41.4%	43.7%	42.9%

(a) NES Actions Case.

Table 6.16. Fraction of Electric Power Generation Input Energy Supplied by Renewable Energy Sources Under Carbon Taxes

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%	12.7%
1995	13.4%	13.5%	13.8%	14.4%	15.5%	18.6%	19.9%
2000	14.1%	14.6%	14.7%	15.3%	18.2%	24.5%	25.8%
2005	15.1%	15.6%	16.0%	15.5%	23.2%	27.1%	26.9%
2010	15.9%	16.5%	17.1%	17.3%	25.1%	28.9%	28.9%
2015	16.4%	17.3%	18.0%	19.4%	25.8%	29.6%	30.8%
2020	18.2%	19.1%	19.8%	22.4%	29.1%	32.6%	34.0%
2025	19.9%	21.4%	22.7%	25.4%	31.4%	35.9%	36.6%
2030	21.1%	22.9%	24.3%	26.7%	33.6%	38.0%	38.2%

(a) NES Actions Case.

The effects of increasingly stringent tax levels on the relative shares of utility energy consumption by fuel are shown in Figures 6.9 and 6.10 for the $25/mtC and $750/mtC Tax Cases.

Synfuels Conversion

As discussed in Chapter 5, this analysis considers two synfuels processes: the conversion of oil to synthetic gas, and the use of biomass feedstocks to produce synthetic liquid fuels. It is assumed that only small amounts, 0.1 quad per year, of synthetic gas are produced from oil, and this production rate is assumed to be independent of the cases under consideration.

In the NES Actions Case, the biomass synfuels industry projected by the Fossil2 Model is small,

producing only 3.8 quads of synfuel liquids per year in 2030 (an increase of 3.7 quads from 1990). These liquids take the form of methanol fuel for vehicles and ethanol for use in ethanol/gasoline blends. The imposition of carbon taxes would have been expected to increase the use of synfuels, or at least to accelerate their introduction. Before the year 2015, the synfuels liquid production rate remains relatively constant for all tax cases. However, beginning in 2015, synfuels liquid production from biomass **decreases** at the higher tax rates. At a tax rate of $750/mtC, annual production of synfuel liquids in 2030 is 3 quads, a decrease of about 20% from the NES Actions Case. This unexpected result appears to be due to two factors: 1) as gasoline prices increase, the vehicle miles traveled decrease (relative to the NES Actions Case), so the demand for ethanol-blend gasoline decreases; and 2) the Fossil2 Model does not have a mechanism to increase the market share of methanol-fueled vehicles as taxes increase. It should be noted that total transportation energy use in 2030 ranges from approximately 27 quads in the NES Actions Case to approximately 22 quads in the $750/mtC Tax Case, such that alternative motor fuels derived from biomass account for only about 14% of total transportation energy use.

6.2.6 Carbon Tax Impacts on End-Use Energy Consumption

Fuel carbon taxes reduce total end-use energy consumption relative to the NES Actions Case in all instances. As shown in Table 6.17, the taxes reduce demand by increasingly greater percentages as the taxes become more severe. By 2030, total end-use energy consumption is reduced by 1% to 5% as the tax rate increases from $25/mtC to $100/mtC; when the tax is increased to $750/mtC, end-use consumption is reduced by 17%, relative to the NES Actions Case. However, after 1995, total end-use energy consumption grows over time in all cases, due to population and economic growth.

The relative importance of electricity in satisfying end-use energy demands, relative to the NES Actions Case, remains approximately constant as taxes increase, although it grows over time. In 1995, the fraction of end-use demand supplied by electricity is about 16%; by 2030, this fraction rises to about 21%. Throughout the period of analysis, the relative contribution of each sector to total end-use energy consumption remains essentially unchanged, relative to the NES Actions Case. Energy consumption in each of the four end-use

Table 6.17. Total End-Use Energy Consumption Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	64.5	64.5	64.5	64.5	64.5	64.5	64.5
1995	67.4	66.5	65.5	63.7	59.6	54.9	51.7
2000	72.3	71.1	70.0	67.9	63.4	58.3	54.8
2005	76.3	75.1	74.0	71.9	67.2	62.3	58.7
2010	79.7	78.5	77.5	75.4	70.8	66.2	62.6
2015	82.1	81.0	79.9	77.9	73.2	68.4	64.8
2020	83.6	82.4	81.3	79.5	74.9	70.6	67.1
2025	85.3	84.1	83.0	81.3	77.2	72.9	69.4
2030	86.0	84.8	83.8	82.0	78.2	74.4	71.0

(a) NES Actions Case.

sectors (residential, commercial, industrial, and transportation) is shown in Table 6.18.

6.2.7 Carbon Tax Impacts on Energy Production and International Trade

Domestic energy production, like energy consumption, decreases in the tax cases, with the decreases becoming more pronounced at the higher tax levels (see Table 6.19).

Domestic Oil Production

Oil is assumed to be available from the world market. U.S. purchases from that market are assumed to have only minor impacts on the world price. Domestic oil production, shown in Figure 6.11, is affected only slightly by the various fuel carbon taxes. The most stringent tax, which (as discussed earlier) causes the world oil price to decrease slightly, results in a reduction in total

Table 6.18. Energy Consumption in End-Use Sectors Under Carbon Taxes (quads)

Tax Rate	Residential		Commercial		Industrial		Transportation	
($/mtC)	1995	2030	1995	2030	1995	2030	1995	2030
$0[a]	10.8	12.5	7.2	11.1	25.9	34.5	23.5	27.9
$25	10.7	12.5	7.1	11.0	25.5	33.9	23.3	27.5
$50	10.6	12.5	7.0	10.9	24.9	33.3	23.0	27.1
$100	10.4	12.5	6.8	10.7	23.9	32.3	22.5	26.5
$250	9.9	12.2	6.3	10.5	22.0	30.3	21.3	25.2
$500	9.3	11.7	5.8	10.1	20.3	29.1	19.6	23.6
$750	8.7	11.2	5.5	9.7	19.3	27.9	18.2	22.2

(a) NES Actions Case.

Table 6.19. Total Domestic Energy Production Under Carbon Taxes (quads)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	70.0	70.0	70.0	70.0	70.0	70.0	70.0
1995	72.4	71.7	70.7	68.7	64.9	61.2	58.6
2000	81.5	80.1	78.8	76.1	71.1	66.4	63.3
2005	89.3	88.0	86.7	83.9	78.4	73.8	70.4
2010	93.9	92.8	91.7	89.0	83.5	79.1	75.4
2015	95.5	94.2	93.2	91.0	85.6	79.5	77.0
2020	98.0	96.8	95.8	93.7	87.1	81.9	78.8
2025	100.9	99.8	99.1	97.4	90.2	86.2	82.6
2030	102.9	102.0	101.3	100.0	93.6	89.9	86.4

(a) NES Actions Case.

domestic oil production of 0.8 quads, or 8%, relative to the NES Actions Case in 2030. Other tax cases result in less change relative to the NES Actions Case; for taxes up to $250/mtC, production is virtually indistinguishable from that in the NES Actions Case.

In the NES Actions Case, oil import dependence increases from 55% to 69% of domestic consumption, from 19 quads to 25 quads, in the period from 1995 to 2030. As shown in Table 6.20, the taxation of fuel carbon reduces oil import dependence only slightly. Because oil consumption is only slightly affected by tax rates below $100/mtC, in these cases oil import dependence is virtually unchanged from the NES Actions Case. In 1995, the high tax rates decrease energy import dependence to 44% to 50% of domestic consumption, or to 12 quads to 15 quads. However, in 2030, the high tax rates decrease oil import dependence only slightly from the NES Actions Case value, to 65% of domestic productions, approximately 18 quads.

Domestic Gas Production

The gas market is treated differently than the oil market. The gas market is treated as essentially closed in the Fossil2 Model, whereas the oil market is treated as essentially open. Imports of natural gas are therefore largely unaffected by shifts in domestic demand. For example, the 3-quad increase in domestic consumption in 2030 under the $100/mtC Tax Case, relative to the NES Actions Case, results in only a 0.3 quad increase in imports in that year. Similarly, domestic consumption in 2000 under the $750/mtC Tax Case is 4.7 quads lower than in the NES Actions Case in that year, but imports decrease by only 0.2 quads relative to the NES Actions Case. For all cases, including the NES Actions Case, the import fraction is approximately 9% of domestic consumption in 1995 and 13% in 2030.

This modeling approach, combined with assumptions regarding the availability of relatively inexpensive domestic gas supplies, has some important implications. First, because the market is closed, taxes on final consumption affect gas production. As shown in Figure 6.12, production is depressed in the earlier years of the analysis and augmented in the later years. But because the availability of relatively inexpensive domestic gas supplies is fixed, cumulative production over the period from 1990 to 2030 is within 5% of the NES Action

Table 6.20. Oil Import Dependence Under Carbon Taxes

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	48%	48%	48%	48%	48%	48%	48%
1995	55%	54%	53%	52%	50%	46%	44%
2000	49%	48%	48%	47%	44%	41%	38%
2005	41%	41%	40%	39%	36%	33%	30%
2010	44%	43%	42%	41%	38%	35%	32%
2015	54%	54%	53%	52%	49%	46%	43%
2020	60%	60%	60%	59%	58%	56%	53%
2025	66%	66%	65%	65%	63%	62%	60%
2030	69%	69%	69%	69%	67%	66%	65%

(a) NES Actions Case.

Case in all fuel carbon tax cases. Gas is the least penalized fossil fuel under the carbon tax cases. For tax rates of $250/mtC and below, the cumulative production is slightly higher than in the NES Actions Case, while for higher tax rates, the cumulative production is slightly lower than in the NES Actions Case. This result is, at least in part, an artifact of the time period of the analysis. If the period of analysis had been shorter, cumulative production would have been more significantly affected by the taxes. For example, cumulative production through 2010 is 11% to 13% lower in the higher tax rate cases than in the NES Actions Case. If the time period had been longer, the resource base of more expensive natural gas would have become important.

Domestic Coal Production

The coal market is handled similarly to the gas market, although the availability of relatively inexpensive coal does not provide any meaningful constraint in the forecast of coal production. Coal exports are, for practical purposes, fixed outside the Fossil2 Model. The coal export market is assumed to be growing and to be independent of domestic consumption activities. Because there is a large supply of relatively inexpensive coal, domestic coal production (Figure 6.13) generally mirrors domestic consumption. Domestic coal production is depressed, relative to the NES Actions Case, in all carbon tax cases and is dramatically affected by the higher tax rates. As tax rates escalate, domestic production grows less rapidly than in the NES Actions Case, and in tax cases of $250/mtC and higher, coal production goes into decline after the taxes are imposed. In the $750/mtC Tax Case, coal production in 2000 is 9.7 quads or approximately 45% lower than in 1990. In Chapter 10, we explore the implications of various tax schemes for energy imports and exports in the context of a global energy economic model.

Coal exports are assumed to be unaffected by the domestic fuel carbon taxes. In all cases, including the NES Actions Case, coal exports total 2.6 quads in 1995 and 7.2 quads in 2030. In increasingly stringent tax cases, the importance of coal exports increases. In the $250/mtC Tax Case, almost half of all domestic coal production is exported. In the $500/mtC and $750/mtC Cases, two-thirds or more of domestic production is exported. These results may, in fact, be conservative. In a declining domestic coal market, there would be great incentive to find foreign markets, and coal exports might expand more rapidly than is assumed.

Nuclear and Renewables Production

Nuclear production in the NES and Fuel Carbon Tax Cases exactly matches utility consumption (Figure 6.7). Renewables production is increased relative to utility consumption (Figure 6.8) because of consumption in end-use sectors. The factors influencing these trajectories are discussed in Section 6.2.5, Energy Transformation, and Section 6.2.6, Carbon Tax Impacts on End-Use Energy Consumption.

6.2.8 Carbon Tax Impacts on Energy-Related Greenhouse Gas Emissions

We discussed the effects of fuel carbon taxes on GWP-weighted emissions in Section 6.2.2. In this section, we discuss the effects of the taxes on unweighted emissions of carbon (primarily from combustion) and methane.

Carbon Emissions

Carbon emissions from fossil fuel combustion are greatly affected by the fuel carbon taxes. In the NES Actions Case, carbon emissions increase at an average rate of less than 1% per year between 1990 and 2030; cumulative emissions during this time period are approximately 63,470 TgC. The rate of growth reaches a maximum of 1.6% per year in the year 2000, then drops off, with emissions held approximately constant after 2020. The final emissions rate is approximately 35% higher than in 1987. As shown in Table 6.21, application of increasingly stringent fuel carbon tax rates has a dramatic effect on fossil fuel carbon emissions. As expected, however, the efficacy of the tax in reducing

Table 6.21. Total Fossil Fuel Carbon Emissions Under Carbon Taxes (TgC/yr)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	1299	1299	1299	1299	1299	1299	1299
1995	1376	1353	1322	1268	1160	1038	963
2000	1487	1444	1412	1343	1184	1026	950
2005	1573	1530	1492	1431	1202	1047	986
2010	1640	1592	1548	1483	1214	1049	993
2015	1695	1635	1578	1494	1238	1045	992
2020	1710	1634	1563	1428	1180	999	947
2025	1710	1600	1509	1356	1125	959	909
2030	1707	1567	1461	1303	1067	919	871
Percentage Change from 1990 Emissions Level in 2030[b]:	+31%	+21%	+12%	0%	-18%	-29%	-33%

(a) NES Actions Case.
(b) Negative values represent reductions; positive values represent increases.

emissions exhibits diminishing returns as more severe taxes are levied.

Application of the lightest carbon tax, $25/mtC, illustrates the effectiveness of changing the price signals in an economy. Under this tax, carbon emissions in 2030 are 1567 TgC/yr, approximately 8% lower than in the NES Actions Case. A doubling of the tax to $50/mtC reduces carbon emissions to 1461 TgC/yr, a 14% decrease relative to the NES Actions Case. In some of the intervening years, however, carbon emissions approach 1600 TgC/yr. The $100/mtC tax reduces carbon emissions by 24% relative to the NES Actions Case in 2030. This reduction increases to almost 50% under the highest tax rates. Tax rates between $100/mtC and $250/mtC are important in that they begin to stabilize carbon emissions over the analysis period. The application of tax rates of $250/mtC and higher actually causes carbon emissions to decline steadily relative to 1990 levels. As noted previously, there is virtually no investment in new coal capacity after 1990 in the two highest tax rates, which contributes to the large decline in fossil fuel carbon emissions in those cases.

Table 6.22 shows the contribution of each fuel to total fossil fuel carbon emissions. The low level of utility coal use in 2030 under the highest tax rates leads to an emission share of only 10% for coal, while the shares for oil and gas increase to 54% and 33%, respectively.

Carbon emissions associated with coal consumption are dramatically affected by the fuel carbon taxes, as shown in Figure 6.14. In 2030, under the $750/mtC tax rate, the level of carbon emissions from coal is 83 TgC/yr, approximately 90% below the NES Actions Case level of 824 TgC/yr. A break occurs at tax rates between $50/mtC and $100/mtC. As tax rates rise to $100/mtC and above, carbon emissions from coal use decrease steadily from 1990 levels. At tax rates of $50/mtC and below, emissions rise steadily from

Table 6.22. Fossil Fuel Carbon Emissions by Fuel Under Carbon Taxes

Tax Rate	1995				2030			
($/mtC)	Oil	Gas	Coal	Geothermal[a]	Oil	Gas	Coal	Geothermal
$0[b]	40%	23%	37%	0%	34%	16%	48%	1%
$25	40%	23%	37%	0%	37%	19%	43%	1%
$50	40%	23%	36%	0%	40%	21%	38%	1%
$100	41%	24%	35%	0%	44%	25%	29%	2%
$250	42%	24%	33%	0%	50%	30%	18%	2%
$500	43%	26%	31%	1%	54%	32%	10%	3%
$750	44%	26%	29%	1%	54%	33%	10%	3%

(a) Although geothermal fluid is not a fossil fuel, its use results in carbon emissions.
(b) NES Actions Case.

1990 levels. This range of taxes seems to be critical in that coal technologies appear to be generally non-competitive at tax rates of $100/mtC and above.

The level of carbon emissions from oil exhibits relatively minor variation among tax cases, due to the low elasticity of demand in the transportation sector. Despite the fact that the oil market is relatively open, cumulative emissions from oil are within 10% of the NES Actions Case level in all but the two highest tax cases, for which emissions are 15% and 20% below NES Actions Case levels, respectively.

Carbon emissions from natural gas vary over time, but cumulative emissions are constrained by the same factors that constrain natural gas production. The application of fuel carbon taxes causes natural gas consumption to exceed NES Actions Case levels after 2010. Carbon emissions also increase, peaking in 2015 in all cases, including the NES Actions Case. By 2030, under the $750/mtC Tax Case, the level of carbon emissions from natural gas is approximately 5% higher than in the NES Actions Case.

In the highest tax rate cases, geothermal production is responsible for a small fraction (3%) of carbon emissions. These emissions are in the form of CO_2, which is an important trace gas in some geothermal fluids.

Carbon emissions from the residential/commercial sector follow a pattern of peaking and declining. For the lower tax rates, carbon emissions from the residential/commercial sector remain approximately constant, relative to the NES Actions Case. By 2030, the $750/mtC Tax Case reduces carbon emissions by only 15% from the NES Actions Case level. Carbon emissions from the industrial sector are reduced by 29% to 33% for each year of the analysis under the $750/mtC Tax Case. For the transportation sector, this reduction is approximately 22%. Beginning in 1995, the synfuels sector is responsible for carbon emissions of 5 TgC/yr, which account for less than 1% of total emissions. As the highest tax rates would eliminate any production of synthetic fuels, the model overstates synfuels emissions in the higher tax cases.

Carbon emissions are profoundly affected by fuel carbon taxes in the utility sector. At tax rates of $100/mtC and below, emissions continue to grow, though they begin to decrease after 2020. For higher tax rates, emissions decline steadily after 1990. In the $750/mtC Tax Case, emissions after 2020 are approximately 70% to 80% lower than in the NES Actions Case. As discussed earlier, coal plays an important role in electricity generation. At

the higher tax rates, coal use decreases relative to 1990 levels, resulting in lower emissions levels. At a tax rate between $50/mtC and $100/mtC, new coal technologies fail to penetrate the market, and existing coal technologies are phased out. Repowering ceases to be an attractive option.

Factors Affecting Carbon Emissions

In Chapter 5, we described how changes in carbon emissions can be attributed to changes in four factors: the ratio of carbon to fossil fuels (C/FF), the fossil-fuel-to-energy ratio (FF/E), the energy-to-GNP ratio (E/GNP), and the level of economic activity (GNP). Below, we discuss how changes in these factors affect carbon emissions in the fuel carbon tax cases.

In the NES Actions Case, the ratio of carbon to fossil fuel energy increases slowly over time, from 17.9 Tg/quad in 1990 to 18.6 Tg/quad in 2030 (see Table 6.23). This increase reflects a small growth (4 percentage points) in the share of domestic energy consumption supplied by coal. As taxes become increasingly severe, coal becomes a less important energy source, and natural gas is substituted for coal. As a result, for tax rates above $100/mtC, the ratio decreases steadily after 1990 and becomes roughly stable after 2010.

The fossil-fuel-to-energy ratio reflects the contribution of fossil fuel energy to total consumption relative to nuclear and renewable energy. This ratio is relatively stable in the NES Actions Case until 2005, with fossil fuels accounting for approximately 85% of all energy consumption (see Table 6.24). The fossil fuel share drops off in later years, decreasing to 72% by 2030. This share is depressed by the fuel carbon taxes in all cases, relative to the NES Actions Case; the reduction increases with time and with the tax rate until the $500/mtC level is reached. Increasing the tax from $500/mtC to $750/mtC has almost no added effect on the fossil-fuel-to-energy ratio.

Table 6.23. Carbon-to-Fossil-Fuel Ratio Under Carbon Taxes (TgC/quad)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	17.9	17.9	17.9	17.9	17.9	17.9	17.9
1995	17.7	17.7	17.6	17.5	17.4	17.3	17.3
2000	17.7	17.6	17.6	17.4	17.0	16.6	16.7
2005	17.8	17.7	17.6	17.4	16.8	16.3	16.3
2010	17.8	17.7	17.5	17.3	16.4	15.8	15.7
2015	17.9	17.8	17.6	17.3	16.3	15.7	15.6
2020	18.1	17.9	17.7	17.2	16.2	15.6	15.5
2025	18.4	18.0	17.7	17.1	16.2	15.6	15.5
2030	18.6	18.1	17.7	17.1	16.2	15.7	15.6

(a) NES Actions Case.

Table 6.24. Fossil-Fuel-to-Energy Ratio Under Carbon Taxes (percentage of energy consumption)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	85%	85%	85%	85%	85%	85%	85%
1995	85%	85%	85%	84%	83%	81%	80%
2000	85%	84%	84%	84%	82%	79%	77%
2005	84%	84%	83%	83%	79%	76%	76%
2010	83%	82%	82%	82%	76%	73%	73%
2015	82%	81%	80%	79%	74%	70%	70%
2020	79%	77%	75%	72%	69%	65%	65%
2025	75%	73%	70%	66%	63%	59%	59%
2030	72%	69%	66%	62%	58%	54%	54%

(a) NES Actions Case.

The energy-to-GNP ratio provides a rough index of energy intensity. The ratio can decrease as a result of factors such as improvements in energy efficiency, shifts in the composition of demand, and changes in material technology. As shown in Table 6.25, there is a clear tendency for the energy-to-GNP ratio to decline with time in all cases, including the NES Actions Case. Fuel carbon taxes also cause the ratio to decrease, particularly in the early years of the analysis. For the most stringent taxes, the energy-to-GNP ratio is decreased by 10% to 20%, relative to the NES Actions Case.

Table 6.25. Energy-to-GNP Ratio Under Carbon Taxes (quads/$billion)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	0.016	0.016	0.016	0.016	0.016	0.016	0.016
1995	0.015	0.015	0.014	0.014	0.013	0.012	0.012
2000	0.014	0.014	0.013	0.013	0.012	0.011	0.011
2005	0.013	0.012	0.012	0.012	0.011	0.010	0.010
2010	0.012	0.012	0.011	0.011	0.010	0.010	0.009
2015	0.011	0.011	0.011	0.011	0.010	0.009	0.009
2020	0.010	0.010	0.010	0.010	0.009	0.009	0.008
2025	0.010	0.010	0.010	0.010	0.009	0.009	0.008
2030	0.009	0.009	0.009	0.009	0.008	0.009	0.008

(a) NES Actions Case.

Under the fuel carbon taxes, there is little change in the level of economic activity when measured in terms of the percentage decrease in GNP relative to the NES Actions Case. The most stringent tax case, $750/mtC, results in a maximum reduction of 6% in 1995, with smaller reductions in other years and under other tax rates. Nevertheless, the 6% reduction under the $750/mtC Case represents a decrease of $384 billion per year. By 2030, the GNP is reduced by 2% in the $500/mtC and $750/mtC Tax Cases, which translates to reductions of $219 billion and $295 billion per year, respectively. We consider the GNP impacts of carbon taxes in more detail in Chapter 9.

The rate of fossil fuel carbon emissions can be written as the product of the four factors described above; that is,

$$C = (C/FF) \cdot (FF/E) \cdot (E/GNP) \cdot (GNP).$$

A measure of the relative contributions of these four factors to changes in fossil fuel carbon emissions can be obtained by examining the percentage changes in each of the factors relative to the percentage change in carbon emissions. (We have approximated the ratio of these percentage changes using logarithms.) The results for the lowest and highest tax rates are shown in Figures 6.15 and 6.16.

For all tax rates, the most significant contributor to carbon emissions reduction in the early years of the analysis is a decrease in the energy/GNP ratio. The importance of this factor in contributing to carbon emissions reduction relative to the NES Actions Case falls off in later years; the difference is made up primarily by increases in the importance of changes in the fossil fuel/energy ratio and also by increases in the carbon/fossil fuel ratio. Higher tax rates have a more significant impact on energy use than do lower rates; thus, the importance of changes in the energy/GNP ratio remains higher in later years for higher tax rates than for lower tax rates. In the lower tax cases, changes in the fossil fuel/energy ratio are more important in the later years of the analysis.

This pattern reflects the fact that the most important initial response to carbon taxes is to replace current technologies with energy-efficient technologies. After all low-cost conservation has been achieved, energy consumption shifts away from high-carbon fossil fuels toward low-carbon fossil fuels, and away from fossil fuels toward nuclear and renewable energy sources. These results are consistent with the relatively short lead times required to deploy energy efficiency technology and the long time lags associated with bringing non-fossil energy resources on line.

The GNP is lower in all tax cases and in all years than in the NES Actions Case. However, these decreases are small; as a result, GNP changes contribute only a small fraction of the overall decrease in carbon emissions. Changes in GNP decrease in importance with respect to reducing carbon emissions from NES Actions Case levels in later years.

Methane

Methane emissions considered in this analysis arise from three sources: coal mining, oil and natural gas production, and natural gas transmission and distribution. As shown in Table 6.26, total methane emissions from fossil fuel use grow from approximately 11.8 $TgCH_4/yr$ to approximately 15.5 $TgCH_4/yr$ in the NES Actions Case, an increase of about 31%, roughly equal to the increase in carbon emissions in the NES Actions Case.

The contribution from coal mining grows steadily in the NES Actions Case and in the $25/mtC Tax Case from about one-third in 1995 to 44% in 2030 for the $25/mtC Tax Case and 48% in 2030 for the NES Actions Case. Beginning at $50/mtC, the absolute level of coal mining methane emissions levels off in later years; for tax rates of $250/mtC and higher, coal mining methane emissions are lower in 2030 than in 1990 (see Table 6.27).

Table 6.26. Total Fossil Fuel Methane Emissions Under Carbon Taxes ($TgCH_4/yr$)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	11.8	11.8	11.8	11.8	11.8	11.8	11.8
1995	13.2	13.0	12.8	12.3	11.3	10.3	9.6
2000	14.7	14.4	14.1	13.5	12.4	11.1	10.2
2005	15.1	14.9	14.6	14.1	12.7	11.5	11.0
2010	15.4	15.2	15.0	14.7	13.1	11.9	11.4
2015	16.2	15.9	15.5	15.2	13.8	12.2	11.8
2020	16.2	15.8	15.5	14.6	13.3	11.8	11.4
2025	16.0	15.4	14.9	14.0	12.6	11.2	10.9
2030	15.5	14.7	14.2	13.4	11.7	10.5	10.2

(a) NES Actions Case.

Table 6.27. Fossil Fuel Methane Emissions from Coal Mining Under Carbon Taxes ($TgCH_4/yr$)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	4.1	4.1	4.1	4.1	4.1	4.1	4.1
1995	4.3	4.2	4.1	3.8	3.4	2.9	2.6
2000	4.9	4.7	4.5	4.2	3.2	2.4	2.3
2005	5.6	5.3	5.1	4.8	3.2	2.4	2.3
2010	6.4	6.0	5.7	5.3	3.4	2.3	2.3
2015	6.7	6.3	5.9	5.2	3.3	2.1	2.0
2020	6.9	6.3	5.8	4.8	3.1	2.1	2.0
2025	7.3	6.4	5.6	4.5	2.9	2.1	2.0
2030	7.5	6.4	5.5	4.2	2.8	2.1	2.0

(a) NES Actions Case.

As Table 6.28 indicates, total methane emissions from natural gas production, transmission, and distribution follow the characteristic natural gas production and consumption patterns of growth, stabilization, and decline. Transmission and distribution activities are the most important sources of methane emissions, accounting for roughly half of all fossil fuel methane emissions in 1995 in all tax cases. This fraction declines over time for the lower tax cases, but increases for tax rates over $100/mtC, not because of absolute growth, but because of a decline in methane emissions associated with coal mining. The total emissions contribution from production, transmission, and distribution declines from approximately 67% in 1995 to approximately 52% in 2030. When tax rates reach $100/mtC, this contribution stabilizes at approximately 69% and grows over time in the higher tax cases, although it levels out somewhat in the later years of the analysis period.

Table 6.28. Fossil Fuel Methane Emissions from Natural Gas Production and Transmission/Distribution Under Carbon Taxes ($TgCH_4/yr$)

Tax Rate	Production			Transmission and Distribution		
($/mtC)	1995	2015	2030	1995	2015	2030
$0[a]	2.4	2.5	2.1	6.5	7.0	5.9
$25	2.4	2.5	2.2	6.4	7.0	6.2
$50	2.3	2.5	2.3	6.4	7.1	6.4
$100	2.3	2.7	2.4	6.2	7.4	6.8
$250	2.1	2.8	2.3	5.8	7.7	6.6
$500	2.0	2.6	2.2	5.4	7.4	6.2
$750	1.9	2.6	2.2	5.1	7.2	6.1

(a) NES Actions Case.

6.2.9 The Cost of Reducing Fossil Fuel Carbon Emissions Using Carbon Taxes

Marginal Cost

The marginal cost schedule of carbon emissions reductions realized under a carbon tax is constructed by mapping the change in emissions from the NES Actions Case against the fuel carbon tax for each year; that is, there is a relationship between the tax rate and the carbon emissions reduction relative to the NES Actions Case for each year of the analysis: 1995, 2000, 2005, etc., through 2030. The marginal cost curve, shown in Figure 6.17, tends to drift upward in successive analysis years. In other words, the longer any tax remains in place, the greater the emission reduction associated with that tax becomes. There are two primary reasons for this phenomenon: the scale effect and the time-to-adjust effect. The scale effect occurs because the scale of economic activity tends to increase with time in the NES Actions Case. This results in a tendency for emissions to rise over time. Because the model allocates market shares to fuels in response to cost, a fixed change in share (as the consequence of a tax) yields a larger absolute change in quantity over time in a growing system. The time-to-adjust effect occurs because total emissions tend to decline over time as existing capital stocks are retired and replaced by capital stocks that reflect the new costs associated with the fuel carbon taxes.

The maximum reduction achieved increases from 413 TgC/yr in 1995 under the $750 carbon tax rate to 836 TgC/yr in 2030 at that same rate. In terms of GWP-weighted emissions, these reductions are 1666 $TgCO_2e/yr$ and 3334 $TgCO_2e/yr$, respectively. The marginal cost curve has the expected shape; that is, larger emissions reductions are associated with higher tax rates. Furthermore, smaller emissions reductions are achieved for each additional dollar of tax in any year.

Figure 6.18 shows the percentage reduction of U.S. fossil fuel carbon emissions relative to the NES Actions Case for each level of fuel carbon tax. The same general shape and relative positioning of the cost curves are apparent, as with the total quantity fossil fuel carbon emissions reduction shown in Figure 6.17. Since Figure 6.18 shows emissions reductions as percentage deviations from the NES Actions Case, the scale effect is removed, and the upward drift in the cost curves can be explained as being predominantly the result of the time-to-adjust effect.

Figure 6.19 shows carbon emissions reductions as a percentage reduction relative to 1990 emissions

plotted against the marginal cost or carbon tax rate necessary to achieve the reductions. An interpretation of the figure is given as follows. For example, it can be ascertained from the figure that a 29% reduction in carbon emissions by the year 2030 is achieved with a $500/mtC carbon tax in effect through that year. This 29% reduction means that the tax reduced emissions from the 31% increase relative to 1990 achieved in the NES Actions Case, plus an additional 29%. For tax rates below $100/mtC, carbon emissions tend to grow over time. At tax rates above the $250/mtC Tax Case studied, carbon emissions tend to decline, in absolute terms, after the year 2010. This decline is due to the fact that fossil fuels are no longer an attractive choice in many applications. Fossil fuels are driven out of new markets almost entirely and leave service from existing markets through retirement and attrition. We note that a tax rate of $500/mtC just surpasses the stated goal of a 20% reduction in carbon emissions by the year 2000. We also note that none of the carbon tax rates studied were able to meet the goal of a 50% reduction in emissions by 2010.

Total Cost

Recall that we use the term total cost to refer to the integral of marginal cost over emissions reduction. The total cost of carbon emissions reduction for individual years is plotted against the associated annual emissions reduction relative to the NES Actions Case for a given future year in Figure 6.20. Each cost curve is associated with a given future year and shows that year's total cost of emissions reduction for a given level of reduction. Each of the points--that is, total cost plotted against emissions reduction--is associated with a fuel carbon tax that was put in place after 1990.

Because the emission reduction is stated in absolute terms, TgC/yr, the cost curves tend to shift to the right with time. In other words, any given emissions reduction relative to the NES Actions Case can be achieved at a lower total cost in a given year the longer a tax has been in place. It must be emphasized that the total cost is defined as the total cost in 1989 constant dollars experienced in future years. No attempt has been made to convert these future value estimates into present values. The general tendency for the emissions reduction supply schedule to shift to the right again is the result of both the scale factor and the time-to-adjust effect operating on the marginal cost schedule.

The total costs rise sharply at tax rates above $200/mtC to $300/mtC. Total cost always increases with quantity if marginal cost is positive, and it increases more steeply with larger quantities when marginal cost rises with greater emissions reductions. The marginal cost schedule constructed from the information generated by the tax cases not only rises with quantity, but turns sharply upward at the higher tax rates. This results in the sharp corner in the total cost schedule displayed in Figure 6.20.

Figure 6.21 plots total cost against the percentage emissions reduction relative to the NES Actions Case. As was observed in the marginal cost figure, the supply schedule of emissions reductions shifts to the right with time. Specifically, after removing the scale effect by plotting carbon emissions reductions in percentage terms, the time-to-adjust effect continues to provide larger percentage reductions in carbon emissions the longer any tax has been in place.

Figure 6.22 plots total cost of fossil fuel carbon emissions reductions against the percentage reduction in emissions relative to 1990 emissions. Each curve plots total cost, as experienced in the associated year, against the percentage reduction relative to 1990 emissions. Note that negative values reflect emissions growth relative to 1990. Thus, for the year 2030, the year 2030 value for zero cost is a negative 30%, which means that at no cost, emissions will grow by approximately 30% relative to 1990 levels. The point on the 2030 curve that shows zero percent emissions reductions relative to 1990 at $16 billion per year total cost is the fourth point. Each point on each curve is associated with a different fuel carbon tax rate, shown in Table 6.29, which went into effect after 1990 and remained at that rate through the period of analysis. Thus, at a carbon tax rate of $100/mtC and a total cost of

$16 billion/yr, carbon emissions rates in 2030 are lowered to 1990 levels.

Table 6.29. Fuel Carbon Tax Rates Associated with Points (Counted Left to Right) on Each Year's Total Cost Schedule in Figure 6.22

Point	Fuel Carbon Tax Rate ($/mtC)
1	0
2	25
3	50
4	100
5	250
6	500
7	750

Note that the total cost schedule for carbon emissions reductions lies furthest to the right for the earliest years of the analysis, 1995 and 2000. This indicates that it is possible to hold emissions constant, relative to 1990, or reduce them with total costs of approximately $12 billion per year. The cost of a 10% emission reduction relative to 1990 levels is approximately $24 billion per year in 1995, but increases to $34 billion per year in 2000. Both costs are associated with a fuel carbon tax rate of $250/mtC. Costs rise sharply to achieve a 20% carbon emissions reduction relative to 1990 levels in 1995 and 2000. A fuel carbon tax of $500/mtC is required, and total costs are approximately $69 billion per year in 1995 and $95 billion per year in 2000.

The scale effect causes costs to rise initially with time, so the total cost schedules for years after 2000 lie almost entirely above those for the years 1995 and 2000. The drift ends in the period between 2010 and 2015. At this time, new nuclear powerplants are allowed to begin contributing to emissions reductions. Holding emissions constant costs approximately $31 billion per year in 2010 and $39 billion per year in 2015 and requires the implementation of a fuel carbon tax of less than $250/mtC that is put in place after 1990. A 20% emissions reduction is achieved in these years with a $500/mtC tax put in place after 1990. Costs associated with the 20% reduction approach $130 and $140 billion per year in 2010 and 2015, respectively.

After 2015, the time-to-adjust effect begins to lower the total cost of achieving any emissions reduction level. Holding emissions constant costs approximately $16 billion per year in 2030, and approximately $37 billion per year in 2020 and is achieved with fuel carbon taxes of approximately $100/mtC and less than $250/mtC, respectively, put in place after 1990. Greater emissions reductions cost less per year in 2030 than in 2020. A 20% emissions reduction costs approximately $96 billion per year in 2030 and approximately $135 billion in 2020 and requires a fuel carbon tax of between $250/mtC and $500/mtC put in place after 1990 in each case.

To provide some perspective on the magnitude of these costs, Table 6.30 displays the total cost of emissions reduction relative to GNP by year and by fuel carbon tax rate. (Note that these costs are not part of the GNP; this ratio is for comparison purposes only.) Costs never exceed 2%, relative to GNP. They rise, relative to GNP, with time. As would be expected, the greater the tax, the greater the carbon emissions reduction and also the greater the cost, relative to GNP.

Average Cost

Many studies report the cost of emissions reduction in terms of average costs. This value is calculated as the total cost of an emissions reduction relative to the NES Actions Case divided by the total emissions reduction relative to the NES Actions Case. The value varies both with the year in which it is calculated and with the fuel carbon tax rate (marginal cost) imposed on the system. The relationship between marginal cost and average cost is reported in Table 6.31.

The average cost is considerably lower than the carbon fuel tax; that is, marginal cost. This is as it should be if marginal cost rises with carbon emissions reductions; that is, if the last tonne of carbon

Table 6.30. Total Cost of Carbon Emissions Reduction as a Percentage of GNP Under Carbon Taxes

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1995	0%	0%	0%	0.1%	0.4%	1.1%	1.6%
2000	0%	0%	0%	0.1%	0.5%	1.4%	1.8%
2005	0%	0%	0%	0.1%	0.5%	1.4%	1.7%
2010	0%	0%	0%	0.1%	0.5%	1.4%	1.7%
2015	0%	0%	0%	0.1%	0.5%	1.4%	1.7%
2020	0%	0%	0%	0.1%	0.5%	1.4%	1.7%
2025	0%	0%	0%	0.1%	0.6%	1.4%	1.6%
2030	0%	0%	0%	0.1%	0.6%	1.3%	1.5%

(a) NES Actions Case.

Table 6.31. Ratio of Average to Marginal Cost Under Carbon Taxes

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1995	100%	50%	36%	37%	45%	41%	30%
2000	100%	50%	39%	38%	44%	41%	31%
2005	100%	50%	38%	39%	42%	43%	32%
2010	100%	50%	38%	40%	41%	43%	32%
2015	100%	50%	38%	40%	43%	43%	32%
2020	100%	50%	38%	38%	46%	44%	32%
2025	100%	50%	39%	39%	48%	44%	32%
2030	100%	50%	39%	40%	49%	45%	32%

(a) NES Actions Case.

saved more costs than the previous tonne saved, then the average cost should be lower than the marginal cost. Since marginal costs are always higher than average costs, average costs rise with emissions reductions and therefore with marginal costs.

Figure 6.23 plots the average cost of carbon emissions reduction against carbon emissions reduction percentage relative to 1990 levels. This figure shows that carbon emissions can be stabilized at an average cost of approximately $40 per tonne of carbon in 2030. A 10% reduction in the year 2030 has an average cost of approximately $86 per tonne, and a 20% emissions reduction in the year 2030 has an average cost of approximately $141 per tonne.

Tax Revenue Generated by Carbon Taxes

Considerable tax revenue is generated by carbon taxes. Table 6.32 shows the tax revenue per year by year for each of the tax rates. As would be expected, the higher the tax rate, the greater the revenue. For any tax rate, the revenue generated is directly proportional to the level of fossil fuel carbon emissions.

Table 6.32. Total Tax Revenues per Year Under Carbon Taxes (billions of $1989)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1995	$0	$34	$66	$127	$290	$519	$722
2000	$0	$36	$71	$134	$296	$513	$712
2005	$0	$38	$75	$143	$301	$524	$740
2010	$0	$40	$77	$148	$303	$524	$745
2015	$0	$41	$79	$149	$309	$523	$744
2020	$0	$41	$78	$143	$295	$500	$710
2025	$0	$40	$75	$136	$281	$480	$682
2030	$0	$39	$73	$130	$267	$460	$653

(a) NES Actions Case.

At low tax rates, revenues tend to rise over time. For the $25/mtC fuel carbon tax, revenues rise from approximately $34 billion per year in 1995 to approximately $39 billion per year in 2030. At a higher tax rate of $100/mtC, annual revenues rise only slightly, from $127 billion to $130 billion, between 1995 and 2030, though they reach a maximum in the year 2015 of approximately $149 billion per year. At the higher tax rates, revenues rise for some period, then decline and are lower in the year 2030 than they are in the year 1995. The $250/mtC tax rate generates almost $300 billion per year. The $500/mtC tax rate generates roughly one-half trillion dollars per year, and the $750/mtC tax rate generates almost three-quarter trillion dollars per year. As we will discuss in some detail in Chapter 9, revenues of this magnitude can have non-trivial implications for government budgets, personal consumption, and rates of national savings and investment.

To provide some perspective, Table 6.33 displays the ratio of tax revenue to GNP. The level of the tax revenue remains below 5% of GNP for tax rates of up to $250/mtC. When tax rates reach $750/mtC, these values approach 10% of GNP, though they decline with time to approximately 5% of GNP by 2030. This decline is due both to growth in GNP and to emissions reductions.

6.2.10 Summary of Carbon Tax Results

A carbon tax policy assigns fuel-specific tax rates based on carbon emissions from the combustion (only) of fossil fuels. Per unit of energy, coal is taxed most heavily under this policy, followed by oil and natural gas. Nuclear and renewable fuels are not taxed. We examined tax rates between $25/mtC and $750/mtC; all were assumed to go into effect immediately.

The Fossil2 Model was used to estimate the effect of imposing these tax rates in addition to the NES Actions. Due to the particular structure of the Fossil2 Model, the responsiveness of the U.S. economy to these taxes may be underestimated when tax rates of $100/mtC and above are imposed. This can occur because the model never prematurely retires capital stocks before their useful lives are over. Thus, existing carbon-emitting technologies continue to be employed for their entire design lifetimes, even at high tax rates that make them economically unprofitable. The implication of this observation is that, where tax rates of $100/mtC or higher are required to achieve an emissions reduction objective, total costs may be overestimated.

Table 6.33. Tax Revenues as a Percentage of GNP Under Carbon Taxes

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1995	0%	0.6%	1.1%	2.1%	4.8%	8.7%	12.4%
2000	0%	0.5%	1.0%	1.9%	4.2%	7.4%	10.4%
2005	0%	0.5%	0.9%	1.7%	3.7%	6.5%	9.3%
2010	0%	0.4%	0.8%	1.6%	3.3%	5.7%	8.2%
2015	0%	0.4%	0.8%	1.4%	3.0%	5.1%	7.4%
2020	0%	0.4%	0.7%	1.3%	2.6%	4.5%	6.4%
2025	0%	0.3%	0.6%	1.1%	2.3%	3.9%	5.6%
2030	0%	0.3%	0.5%	1.0%	2.0%	3.5%	4.9%

(a) NES Actions Case.

None of the taxes cause total energy consumption in 2030 to be lower than the 1990 level, although consumption is lower than in the NES Actions Case for all tax levels. This is due to the fact that a carbon tax induces reductions in carbon through multiple mechanisms, only one of which is the reduction of total energy consumption. Other mechanisms include shifts from fuels with high carbon-to-energy ratios, such as coal, to fuels with low carbon-to-energy ratios, such as natural gas, and the substitution of nuclear and renewable energy forms for fossil fuels. The reduction in total energy usage is accomplished primarily by substituting more energy-efficient technologies for existing technologies; as a result, there is relatively little loss in the provision of energy services.

Energy conservation is the single most important response to carbon taxes in early periods. In later periods, low-carbon content fossil fuels and nuclear and renewable energy sources substitute for high-carbon content fossil fuels, most notably coal.

Because the NES Actions reduce expected GWP-weighted energy-related greenhouse gas emissions below 1990 levels throughout the period of analysis, no carbon tax is needed to hold emissions constant. A tax of $100/mtC is the lowest tax that achieves a 20% reduction in these emissions from the 1990 level. However, this reduction is not achieved until after 2020. A $250/mtC tax achieves this reduction by 2000; higher taxes achieve a 20% reduction by 1995. Only the $750/mtC tax succeeds in reducing total energy-related, GWP-weighted emissions by 50% relative to the 1990 level. This reduction is not achieved until 2030.

The most important impact of a carbon tax is on coal use. For tax rates above $100/mtC, total coal consumption declines continuously from the 1990 level and is replaced by consumption of natural gas and nuclear and renewable energy sources. The most significant reduction in coal use is in the utility sector.

One clear general observation of this analysis is that it takes time for the full response to any tax to be observed. All measures of cost associated with the attainment of any emissions reduction objective are higher in the year 2015 than in the year 2030. This is the direct result of time delays for new technologies, particularly nuclear and renewable technologies, to come on line.

The total cost of reducing carbon emissions from levels acheived by NES Actions to those levels observed in 1990 is $12 billion per year in the year 2030. Holding emissions to 1990 levels in the year

1995 is cheaper than in any other year. Costs rise steadily until the year 2015, at which time they reach approximately $40 billion per year.

Its costs substantially less to reduce GWP-weighted emissions by 20% relative to 1990 levels than to reduce total carbon emissions by 20%. In 2000, the cost of a 20% reduction in GWP-weighted emissions relative to 1990 levels is approximately $20 billion per year. The corresponding cost to reduce carbon emissions by 20%, relative to 1990 levels, costs approximately $40 billion per year, compared with a cost of $140 billion per year in that same weighted emissions relative to 1990 levels decline steadily after 2015 to approximately $10 billion per year in 2030, while the total cost of achieving the same reduction in carbon emissions declines to approximately $100 billion per year in 2030.

While no carbon tax examined in this study reduced carbon emissions by 50% relative to 1990 levels in any year, GWP-weighted emissions were reduced by 50% relative to 1990 levels in 2030 by the $750/mtC tax rate. This reduction was achieved at a total cost of approximately $220 billion per year in 2030.

The average cost of carbon emissions reduction is obtained by dividing the total cost by the total carbon emissions reduction. Because the model always chooses the least-cost carbon emissions reductions option first, the tax rate reflects the last, and therefore the most expensive, carbon emission reduction opportunity. The average cost of achieving any level of carbon emission reduction is therefore always less than the tax rate required to achieve it.

The average cost of holding emissions at 1990 levels rises from approximately $60/mtC in 2000 to approximately $80/mtC in 2015 and declines thereafter to approximately $80/mtC in 2030.

The average cost of reducing GWP-weighted energy-related emissions by 20%, relative to 1990 levels, in 2000 was approximately $15/mtC, while the average cost of the same reduction in carbon emissions was $200/mtC. Achieving these reductions in the year 2015 costs approximately $150/mtC for a 20% reduction from 1990 levels in carbon emissions, and approximately $25/mtC for the same reduction in GWP-weighted emissions.

A great deal of revenue is raised by carbon taxes. A $25/mtC tax raises more than $30 billion to $40 billion per year. A $50/mtC tax raises $70 billion to $80 billion per year, and a $100/mtC tax raises $130 billion to $140 billion. These revenue streams are so large that they would have fiscal policy implications that cannot be ignored. They are, in fact, so great that they would likely precipitate a major re-examination of the tax policy in the United States. This issue is addressed in greater detail in Chapter 9.

6.3 THE GWP TAX

6.3.1 Assumptions

We have constructed a set of weighted energy tax rates based on IPCC GWP coefficients as an alternative to energy taxes based on carbon content of fossil fuels. If this tax were adopted as a national policy, all greenhouse gas sources and sinks, including non-energy sources, would be considered in developing the tax rates. The results described here are approximate in that they address energy-related sources only. Most importantly, they do not address CFCs and HCFCs, which are significant greenhouse gases. However, these gases are being reduced separately under the aegis of the Montreal Protocol (see Chapter 5).

Several variants of the GWP have been developed.[a] In general, GWP coefficients provide a measure of the effect on radiative forcing over a specified period of time of the instantaneous release of one kilogram of gas into the atmosphere, relative to the effect on cumulative radiative forcing over the same period of time of the release of one

(a) See Chapter 3.

kilogram of CO_2 into the atmosphere. The calculation of the GWP coefficient incorporates information about radiative forcing for different gases, the length of time a fixed quantity of each emitted gas remains resident in the atmosphere, and the disposition of each gas after its atmospheric residency and associated lifetimes of its reactive by-products. An efficient greenhouse warming tax would, in principle, take into account not only the lower carbon content per unit of energy of natural gas relative to oil, but also the associated direct emissions of methane to the atmosphere from its production, transmission and distribution, the higher greenhouse warming potential of a molecule of methane relative to CO_2, the lifetime of both CO_2 and CH_4 in the atmosphere, and the disposition of CH_4, principally into water vapor and CO_2.

As was the case for the calculation of GWP-weighted energy-related emissions, we have adopted the IPCC 100-year coefficients for our analysis. We have used these coefficients as weights to construct a set of energy taxes based on the total GWP consequences of the use of each energy form.[a]

Energy tax rates were developed as follows. A direct emission rate for CO_2, CO, CH_4, and N_2O was assigned to the production, transformation, transportation, and end use of oil, gas, and coal. All emissions associated with one unit of each fuel were then attributed to the end-use energy available in that unit of fuel.[b] Values are given in Table 6.34.

Values assume that 5% of carbon emissions take the form of CO. All fuel usage is treated as if the fuels were produced domestically; that is, CH_4 is charged with emissions associated with production, transport and distribution of all coal and gas used domestically. Combustion emissions of CH_4 are assumed to be negligible. Finally, the energy tax to be added to the fuel price is computed as the product of the emission rate (gCO_2e/Btu) and a tax rate ($/$gCO_2e$). GWP tax rates are given in Table 6.35.

Table 6.34. Energy-Related Emissions Rate Assumptions (Tg/PBtu)

	Fuel		
Gas	Oil	Nat. Gas	Coal
CO_2	73.28	50.49	88.64
CO	2.45	1.69	2.97
CH_4	0.00	0.4092	0.1908
N_2O	0.00053	0.000136	0.002072

Note: Units = Tg(molecular weight)/PBtu
$= 10^{12}g/10^{15}Btu$

Table 6.35. The Relationship Between GWP Tax Rates and Fuel Tax Rates

		Implied Fuel Tax ($/mBtu)		
Tax Case	GWP Tax Rate	Oil	Gas	Coal
Case 1	$25/mtC$_e$	0.55	0.44	0.70
Case 2	$50/mtC$_e$	1.10	0.88	1.40
Case 3	$100/mtC$_e$	2.20	1.75	2.79
Case 4	$250/mtC$_e$	5.50	4.38	6.98
Case 5	$500/mtC$_e$	11.00	8.75	13.95
Case 6	$750/mtC$_e$	16.50	13.13	20.93

Note: mtC_e = metric tonne of carbon equivalent, which is a metric tonne of CO_2 equivalent (CO_2e) converted to carbon weight. Emission rates are given in Table 6.1. Note that the conversion rate from carbon weight to CO_2 weight is 44/12.

A comparison with Table 6.1 shows that, in terms of the implied fuel tax in $/mBtu, the GWP taxes on oil do not differ appreciably from the carbon taxes for oil, for which the GWP-weighted fuel tax is 5% higher than the carbon-weighted tax. For coal, this difference is about 10%, and for natural gas it is about 21%. As noted earlier, the larger increase for natural gas reflects factors such as methane releases from gas production, transport, and

(a) See Chapter 3 for a table of GWP coefficients by gas.
(b) This implicitly assumes that coal and natural gas are produced domestically at the margin.

distribution, and the higher GWP of a molecule of methane relative to CO_2. The relatively higher increase for coal (compared with the increase for oil) reflects methane emissions from coal mining. Implied fuel tax rates in terms of common energy units are given in Table 6.36.

6.3.2 GWP-Weighted Emissions Reductions Relative to the NES Actions Case

GWP-weighted emissions under the GWP tax cases in terms of $TgCO_2e$ are shown in Table 6.37 and Figure 6.24. A comparison with Table 6.3 and Figure 6.1 shows that the GWP tax is virtually identical in impact to the carbon tax, regardless of tax level. In each tax case and year, GWP-weighted emissions under the GWP tax are on the order of 1% lower than emissions under the carbon tax case. The composition of these emissions is similar as well.

Carbon emissions are lower in the GWP tax cases than in the carbon tax cases, but only by about 1% (or less) in the lower tax cases and 1% to 2% for GWP tax rates of $250/mtC$_e$ and higher. The fractions of these emissions attributable to coal, oil, and gas use under GWP taxes are virtually indistinguishable from those for the carbon tax cases. The primary difference is that, for higher tax cases, the contributions from gas use are about one percentage point lower in the GWP tax cases than in the carbon tax cases, due primarily to the decreased use of gas under the GWP tax scenario. The difference is made up by oil, to which a slightly higher fraction of carbon emissions is attributed.

Methane emissions are also lower in the GWP tax cases than in the carbon tax cases, and the differences are slightly more significant than was the case for carbon emissions. At the higher tax levels, depression of natural gas use relative to the carbon tax cases results in methane emissions that are 3% to 4% lower than in the carbon tax cases.

6.3.3 Energy Impacts Associated With a GWP-Weighted Tax

The energy impacts of GWP-weighted taxes vary little from the impacts associated with the fuel carbon taxes. End-use fossil fuel prices increase only slightly, relative to the carbon tax case; the largest increase is in the price of residential gas, which in 2030 is about 9% higher than in the carbon tax case for the most stringent tax level. Overall demand for

Table 6.36. Fuel Price Changes per $100 GWP Tax

Fuel	Base Cost ($)	Added Cost ($)	Added Cost (%)
Crude Oil ($/bbl)	16.81	12.74	76
Gasoline ($/gal)	0.98	0.27	28
Heating Oil, Distillate ($/gal)	0.89	0.30	34
Wellhead Natural Gas ($/tcf)	1.81	1.80	99
Residential Natural Gas ($/tcf)	5.87	1.80	31
Minemouth Coal ($/short T)	23.02	60.65	263
Utility Coal ($/short T)	33.51	60.65	181
Electricity (c/kwh)	6.5c	1.94c	30

Notes: 1989 constant dollars. Base year 1990.

Table 6.37. Total Energy-Related GWP-Weighted Emissions Under Carbon Taxes ($TgCO_2e/yr$)

	Carbon Tax Rate ($/mtC)						
Year	$0[a]	$25	$50	$100	$250	$500	$750
1990	7458	7458	7458	7458	7458	7458	7458
1995	7143	7039	6902	6666	6211	5708	5403
2000	6843	6661	6515	6209	5565	4924	4598
2005	7064	6878	6712	6440	5537	4921	4634
2010	7233	7023	6834	6548	5516	4832	4599
2015	7422	7158	6917	6552	5564	4785	4559
2020	7431	7100	6795	6232	5257	4554	4332
2025	7293	6817	6431	5818	4896	4253	4044
2030	7082	6475	6033	5406	4472	3893	3693
Percentage Change from 1990 Emissions Level in 2030[b]:	-5%	-13%	-19%	-28%	-40%	-48%	-50%

(a) NES Actions Case
(b) Negative values represent reductions.

energy and for electricity changes only slightly. Consumption of natural gas, which is most significantly penalized under a GWP tax, decreases slightly (1% or less) in the lower tax cases. For taxes of $250/mtC$_e$, natural gas consumption decreases 3% to 5%.

Changes in the fraction of energy input to electric power generation associated with each fuel were also small. For example, at the $100 tax level, the fractions associated with each fuel in the GWP-based tax cases are within 4% of the fractions in the carbon tax cases for all years and fuels. The shares of nuclear and renewables are slightly higher in the GWP tax case than in the carbon tax case, while the shares of coal and natural gas are slightly lower. The share of oil is the same as in the carbon tax case, or slightly lower. Both oil and gas shares are slightly higher than in the carbon tax case after 2025.

6.3.4 The Cost of Reducing GWP-Weighted Greenhouse Gas Emissions Using GWP Taxes

The cost computations for the GWP tax cases are performed using the same methodology as that described in the previous section for the carbon taxes. The primary difference here is that the tax rates, and therefore the marginal cost schedule, are stated in terms of GWP-weighted emissions reductions in $TgCO_2e$ rather than in terms of carbon emissions reductions.

As has been discussed, the GWP taxes were explored in order to test the possibility of further lowering energy-related GWP-weighted emissions with tax rates at the same levels used in the carbon tax cases. The GWP taxes involve a slightly different distribution of cost penalties on the fossil fuels than under the straight carbon taxes to achieve the desired effect of equal marginal costs per unit of

GWP-weighted emissions across all fuels and uses. From basic economic principles, the GWP tax will achieve a given level of GWP-weighted emissions reduction at a lower total cost than any carbon tax because the marginal costs of reducing GWP-weighted emissions will not be set equal across all endeavors in the carbon tax formulation. The same logic applies in the converse, comparing carbon emissions reductions resulting from a GWP tax and from a carbon tax. Here, the carbon tax will reduce a given level of carbon emissions for a lower cost.

Brief summaries of the cost results of the GWP taxes are provided below. In all cases, the results vary only slightly from the carbon taxes at the same levels. For comparison purposes, some of the graphs shown for the carbon taxes have been constructed for the GWP taxes as well. Results and phenomena such as the shape of the marginal and total cost curves described in the carbon tax section also apply here unless otherwise noted.

Marginal Cost

The marginal cost of GWP-weighted emissions reductions with a GWP tax is calculated by mapping the change in emissions between the Tax Case and the NES Actions Case versus the level of tax per $mtCO_2e$. Figure 6.25 shows the marginal cost curve for the GWP tax, while Figure 6.26 gives the percent reduction relative to the NES Actions Case. To be consistent with the terminology of the carbon taxes of this study, the figures show the tax rates in terms of metric tonnes of CO_2 equivalent by weight of carbon. The maximum GWP-weighted emissions reduction increases from 740 $TgCO_2e$ in 1995 to 3389 $TgCO_2e$ in 2030 under a $750 tax.

Figure 6.27 shows GWP-weighted emissions reductions as a percentage relative to 1990 emissions plotted against the marginal cost or GWP tax rate necessary to achieve the associated level of emissions. Note that GWP-weighted emissions are already stabilized by the NES Actions Case ($0/mtC$_e$ Case on the figure). Therefore, each GWP tax rate studied achieves a positive reduction relative to 1990 in all years. We note that a 20% reduction in GWP-weighted emissions is achieved by 2030 with a GWP tax rate between $100/mtC$_e$ and $250/mtC$_e$. The $750/mtC$_e$ GWP tax results in a 50% reduction in GWP-weighted emissions by the year 2030.

Total Cost

The total cost of GWP-weighted emissions reduction for individual years is plotted against the associated annual reduction relative to the NES Actions Case in Figure 6.28. The total cost schedule for GWP-weighted emissions reduction is the integral of the marginal cost schedule over the reductions. Figure 6.29 is the counterpart of Figure 6.22, but in this case refers to GWP-weighted emissions reduction with respect to 1990. Despite a slight growth in the earlier years of the study period, the NES Actions Case without any tax is successful in stabilizing GWP-weighted emissions at the 1990 level by the year 2030. A $50/mtC$_e$ GWP tax achieves a 10% reduction in GWP-weighted emissions by 2000 at a total cost per year of approximately $2 billion. A $250/mtC$_e$ tax results in a 25% reduction in GWP-weighted emissions by 2000 at a total cost of about $39 billion per year and a 40% reduction in 2030 at a cost of $88 billion per year.

Average Cost and the Revenue

The average cost and tax revenue behavior do not differ significantly from the carbon tax cases. Figure 6.30 shows the average cost of GWP-weighted emissions reduction under the GWP tax. Because the GWP taxes exact a slightly higher penalty on fossil fuels than do the carbon taxes, tax revenues and GNP reduction tend to be somewhat higher in the GWP tax cases. However, all of these results are on the same order of magnitude and follow similar patterns for the two types of taxes.

6.3.5 Limitations of GWP Taxes

Several considerations are relevant to the question of whether, in the face of a decision to impose a tax on emissions, the GWP tax should be

preferred to the carbon tax. These include the differences in results, the ease of setting the tax rate, and the ease of monitoring implementation.

As described above, GWP-based taxes should, in theory, be more efficient than carbon taxes in reducing the potential for global warming from energy-related emissions of greenhouse gases because they address multiple gases and multiple emissions-causing activities. In this analysis, although GWP taxes reduce GWP-weighted emissions further than do carbon taxes, the difference is small.

Setting carbon tax rates based on carbon content is a straightforward exercise that would not engender much scientific disagreement. In contrast, significant uncertainty exists regarding the overall global warming potential of methane and nitrous oxide. This uncertainty would make reaching a consensus on the translation of GWP tax rates into fuel tax rates ($/mBtu, $/bbl, etc.) difficult and time-consuming. Another, perhaps more fundamental problem is the fact that a GWP-weighted tax offers no incentive to reduce specific secondary activities that generate emissions, by, for example, recapturing methane from coal mines or reducing nitrogen emissions. The GWP tax implicitly assumes that these activities are inseparable, which is clearly not the case. In principle, each of these activities would be more appropriately taxed separately on the basis of GWP-weighted emissions. Finally, the GWP coefficients themselves are not known precisely. Uncertainty ranges are potentially as great as 100% (see Chapter 3).

It is important to remember that the GWP tax discussed here is an energy tax only. If a GWP-based greenhouse gas reduction program were implemented throughout the economy, all greenhouse gas sources and sinks would be addressed, including non-energy sources.

6.3.6 Summary of GWP Tax Results

A GWP-based energy tax policy assigns taxes to fuels on the basis of their relative GWP consequences. The taxes are weighted to account for the full-fuel-cycle impacts of using each fuel. Under this tax scheme, the added energy tax, relative to the carbon tax cases, is highest for natural gas and coal as a result of methane emissions during fuel extraction and (for gas) distribution. A carbon tax addresses only combustion-related emissions.

In principle, the GWP-based tax should be more efficient than the carbon tax in achieving GWP-weighted emissions reduction. While this expectation is borne out by the analysis, the difference is small. In each tax case and year, GWP-weighted emissions under GWP taxes are on the order of 1% lower than under carbon taxes. The energy and price results are similar in the two cases, although there is a small reduction in the use of natural gas and coal, relative to the carbon tax cases. As a result, methane emissions are about 3% to 4% lower under GWP taxes than under carbon taxes.

A tax of $250/mtC$_e$ is required to reduce GWP-weighted emissions by 20%, relative to the 1990 level, by 2000. Only the $750/mtC$_e$ tax succeeds in reducing total energy-related, GWP-weighted emissions by 50%, relative to the 1990 level, by 2030.

6.4 SENSITIVITY ANALYSIS: CARBON AND GWP TAXES, NES ACTIONS WITHOUT NUCLEAR

In this section, we examine the effect of employing the NES Actions Case without nuclear power, discussed in Chapter 5 as an alternative reference scenario for the carbon and GWP tax cases. The carbon and GWP-weighted greenhouse gas emissions for the NES Actions Without Nuclear Case are provided in Chapter 5. Using this alternative scenario as the starting point means that the tax policies have farther to go in meeting reductions targets. This has implications both for the ability of the taxes to meet reductions targets and for the costs of meeting the targets. The results of the sensitivity analysis are provided in the following section.

6.4.1 Sensitivity Analysis with Carbon Taxes

Figure 6.31 shows the marginal costs or carbon tax rates required to achieve a given percentage of emissions reduction relative to 1990. In the earlier years, there is little difference between the tax rate needed to achieve emissions targets in the NES Without Nuclear Case and that required in the NES Actions Case. This result reflects the fact that the growth in nuclear energy in the NES Actions has its greatest impact in the last twenty years of the study period. From Figure 6.31, a tax of almost $500/mtC is required to achieve a 20% reduction in carbon emissions, relative to 1990, by the year 2000. A 20% reduction through 2030 requires a tax rate of approximately $30/mtC, compared to a tax of $250/mtC required to meet this target in the NES Actions Case.

The total costs of achieving reductions in carbon emissions relative to 1990 are given in Figure 6.32. Under the NES Actions assumptions, the total cost for a 20% reduction, relative to 1990, in the year 2000 is about $95 billion. In the case without nuclear, this total cost is roughly the same. In the later years, however, the cost differences under the two scenarios become more pronounced. For example, the total cost in 2030 for a 20% reduction relative to 1990 with the NES Actions Case is about $20 billion. Without nuclear, the total cost for reaching this goal is much higher at $175 billion in 2030.

6.4.2 Sensitivity Analysis with GWP Taxes

Figures 6.33 and 6.34 show, respectively, the marginal costs and the total costs versus percentage reductions in GWP-weighted emissions relative to 1990 levels. The same general pattern seen in the carbon tax sensitivity analysis occurs here. Until the year 2010, there is little difference in the marginal and total costs of the NES Actions Case with and without nuclear power. It is in the later years that the growth in nuclear energy has an impact. In the year 2030, for example, a tax rate of $50/mtC$_e$ results in a 20% reduction in GWP-weighted emissions relative to 1990 at a total cost of $2 billion under the NES Actions assumptions. Without nuclear, however, a 20% reduction requires a tax of almost $150/mtC$_e$ and has a total cost in 2030 of $36 billion.

6.5 CONCLUSIONS

Taxes are a powerful single-policy instrument. The fuel carbon taxes are particularly effective in reducing future fossil fuel carbon emissions because the incentive to reduce emissions is equal for all reduction strategies; that is, an incentive to reduce emissions through either energy conservation or fuel switching exists as long as the cost of reducing emissions is lower than the carbon tax.

In Section 6.2.9, we discussed the marginal costs of emissions reductions from 1990 levels that were achieved with the fuel carbon taxes. The lower marginal tax rates do not achieve the stated goals of a 20% reduction from 1990 levels in fossil fuel carbon emissions by 2000 and a 50% reduction by 2020. Not until the tax rate reaches $500 is a 20% reduction achieved at all; in this case, it is achieved by 2000. In no case are fuel carbon taxes alone able to reduce fossil fuel carbon emissions by 50%, even in 2030.

In terms of GWP-weighted emissions, a reduction of 20% from 1990 levels is achieved by 2000 for all fuel carbon tax rates above $100/mtC. A 50% reduction, relative to 1990, is achieved in 2030 under a $750/mtC tax.

The GWP taxes are slightly more effective than the carbon taxes in reducing GWP-weighted emissions. These emissions are on the order of 1% lower under GWP taxes than under carbon taxes. As noted earlier, disagreement exists on the appropriate weights to employ for different fuels in constructing the tax, and it is possible that non-combustion emissions such as methane emissions from coal mines could be addressed in a more economically efficient way with emission-specific taxes or controls.

Stabilization of fossil fuel carbon emissions is achievable under fuel carbon taxes. Carbon emissions are stabilized at 1990 levels by 2030 under a $100/mtC tax, although they rise above 1990 levels in intervening years. Emissions decrease steadily after 1990 with taxes of $250/mtC and higher. When expressed in terms of GWP-weighted emissions, emissions are lower in all years than in 1990 for all cases, including the NES Actions Case. The same is true under the GWP taxes.

In Chapter 8, we assess the effects on energy-related emissions of carbon and GWP taxes combined with a policy to enhance carbon sinks by providing incentives for reforestation (tree planting).

Despite the reduction in the use of fossil fuels, caused by the fuel carbon taxes, energy consumption and production are higher in 2030 than in 1990. The tax system has little impact on the total consumption of natural gas over the period of analysis, although the time profiles of production and consumption are affected. Higher tax rates push gas consumption and production further into the future. Oil imports are a significant source of carbon. Oil consumption remains relatively high even in the most stringent tax cases, due primarily to the relatively weak response to higher prices in the transportation sector. The fraction of oil imported in 2030 under the $750/mtC tax is 65%.

Coal is the swing fuel and the electric utility sector is the swing sector in this analysis. Carbon emissions rise and fall with coal use. In the absence of any mechanism for carbon removal, either pre- or post-combustion, carbon emissions cannot be reduced in the face of growing coal use. Because of its relatively high carbon-to-energy ratio, a fuel carbon tax places the highest fuel cost penalty on coal. Under the highest tax cases, two-thirds or more of domestic coal production is exported. If high fuel carbon taxes were implemented, there would be great incentives to expand export markets. Coal export is a significant source of carbon export; the carbon emissions would occur outside the United States.

The energy-related release of methane to the atmosphere varies directly with the release of carbon. For natural gas, a somewhat larger share of CH_4 emissions than of carbon emissions is associated with production and consumption. As a result, methane emissions are reduced somewhat lower than carbon emissions in the highest fuel carbon tax cases.

It should be noted that the results presented for this analysis are based on factors such as the assumptions inherent in the NES Actions Case, the models used to derive energy scenarios for the United States, and the emissions coefficients used to translate energy cases into emissions cases. The purpose of this chapter is not to forecast the future, but to provide a first analysis of the potential for fuel carbon taxes and GWP taxes to reduce greenhouse gas emissions and of the costs associated with those reductions.

Key assumptions that determine the starting point for both the NES Actions Case and the tax cases include the economic character and geologic distribution of the resource and reserve base of fossil fuels, particularly natural gas. More important are the assumptions about the cost and availability of conservation, renewable, and nuclear technologies. The results of both the NES Actions Case and the tax cases would be different if different assumptions were employed.

Modeling is also important. Critical assumptions regarding economic and non-economic behavior include the propensity to repower existing fossil powerplants, the rate of retirement of existing energy-using facilities, and the rate at which purchasers of energy-using equipment are willing to adopt new technologies.

The assumption that only fossil fuel carbon emissions are taxed is limiting. A more general analysis would consider taxation of carbon from other potential net sources, including, for example, cement manufacture and forest practices, as well as the effect of taxes on other activities that produce greenhouse gas emissions.

Finally, emissions coefficients for methane are very uncertain. Methane emissions scenarios are based on the best current knowledge. However, they are subject to change as new information emerges and do not represent a forecast.

6.6 REFERENCES

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U.S. Department of Energy (DOE). 1989. *A Compendium of Options for Government Policy to Encourage Private Sector Responses to Potential Climate Change.* DOE/EH-0102 and DOE/EH-0103, National Technical Information Service, Springfield, Virginia.

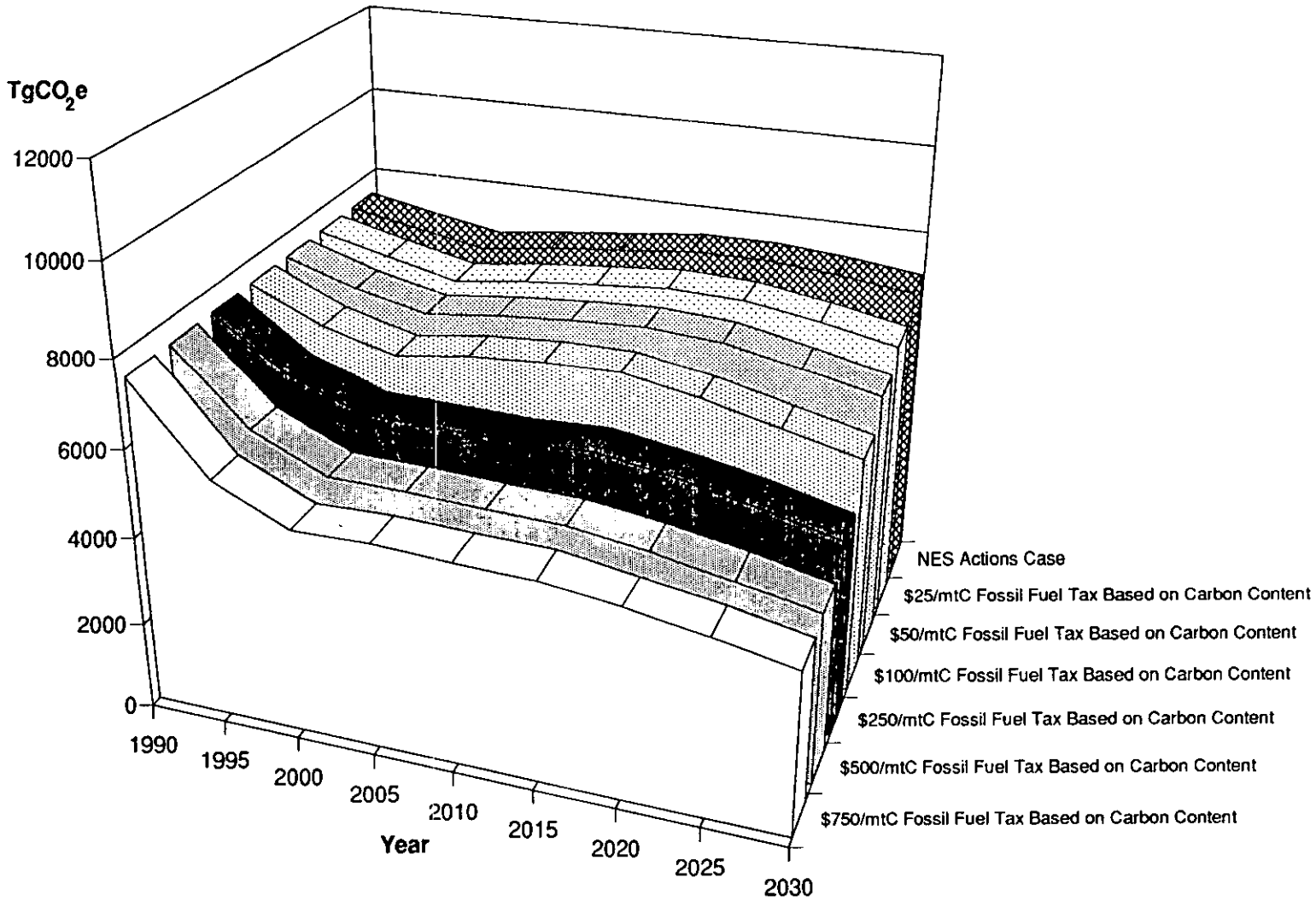

Figure 6.1. Fossil Fuel Taxes Based on Carbon Content: GWP-Weighted Energy-Related Emissions by Year ($TgCO_2e$)

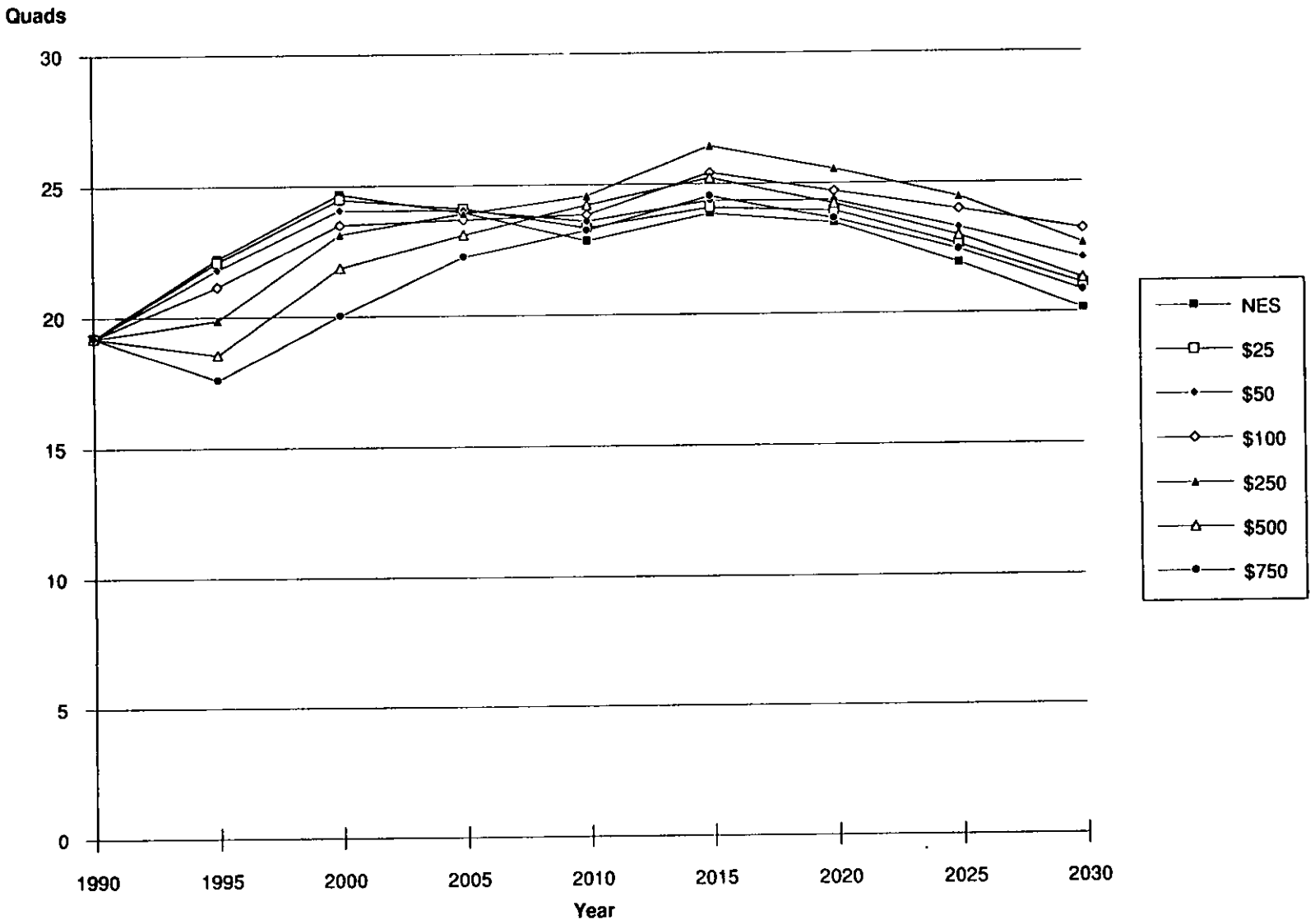

Figure 6.2. Fossil Fuel Taxes Based on Carbon Content: Total Gas Consumption by Year (quads)

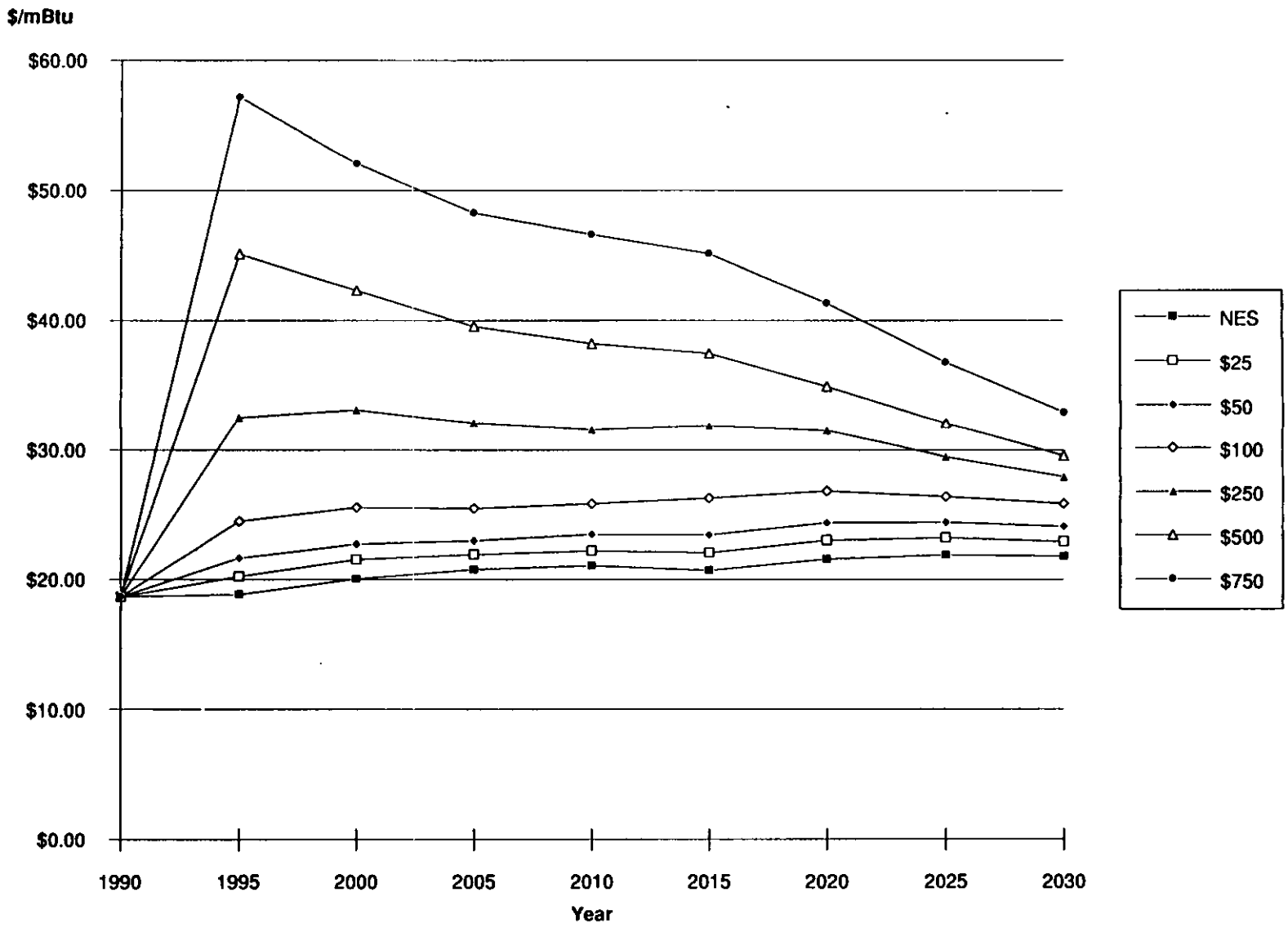

Figure 6.3. Fossil Fuel Taxes Based on Carbon Content: Average Electricity Price by Year ($/mBtu)

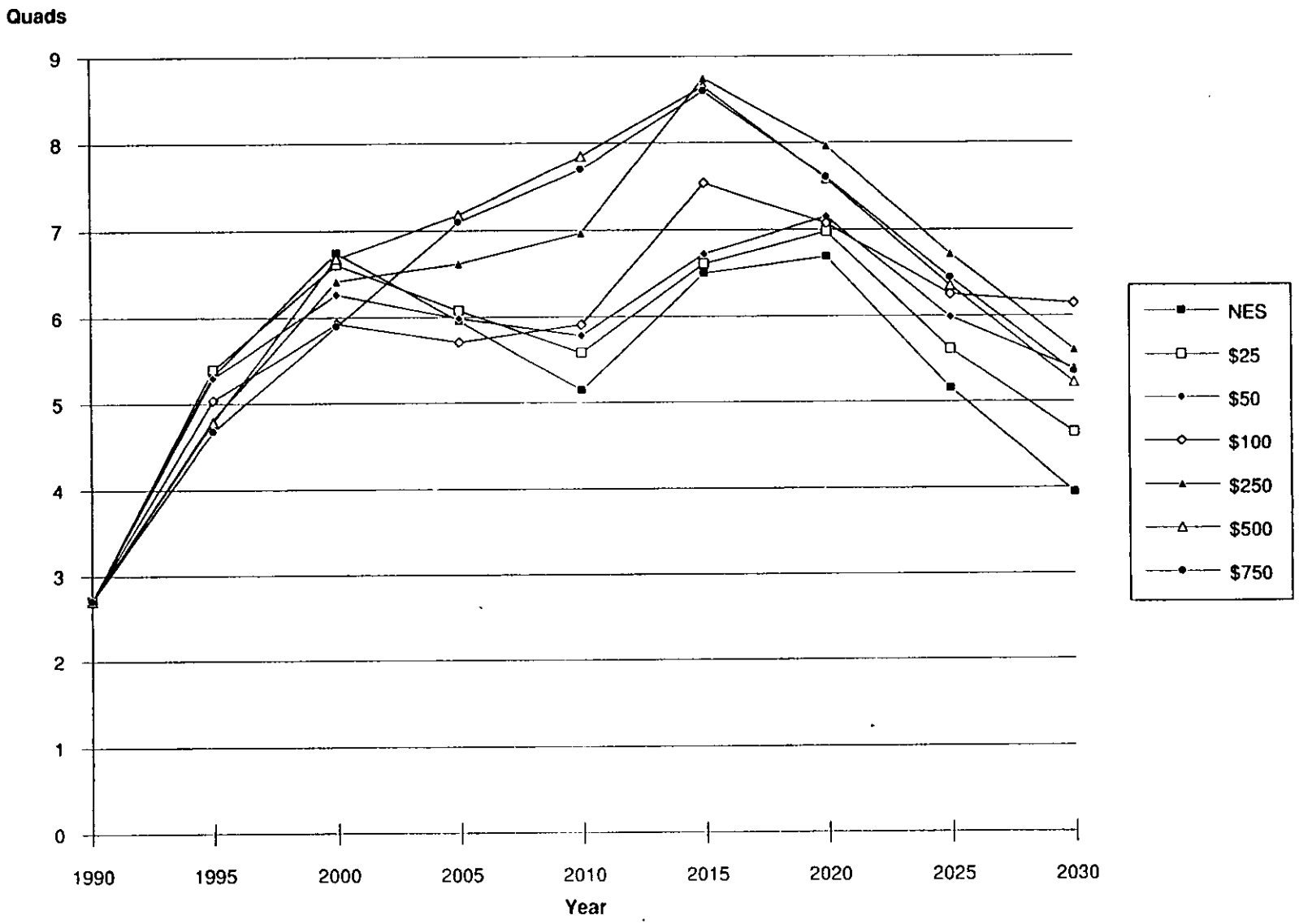

Figure 6.4. Fossil Fuel Taxes Based on Carbon Content: Total Utility Gas Consumption (quads)

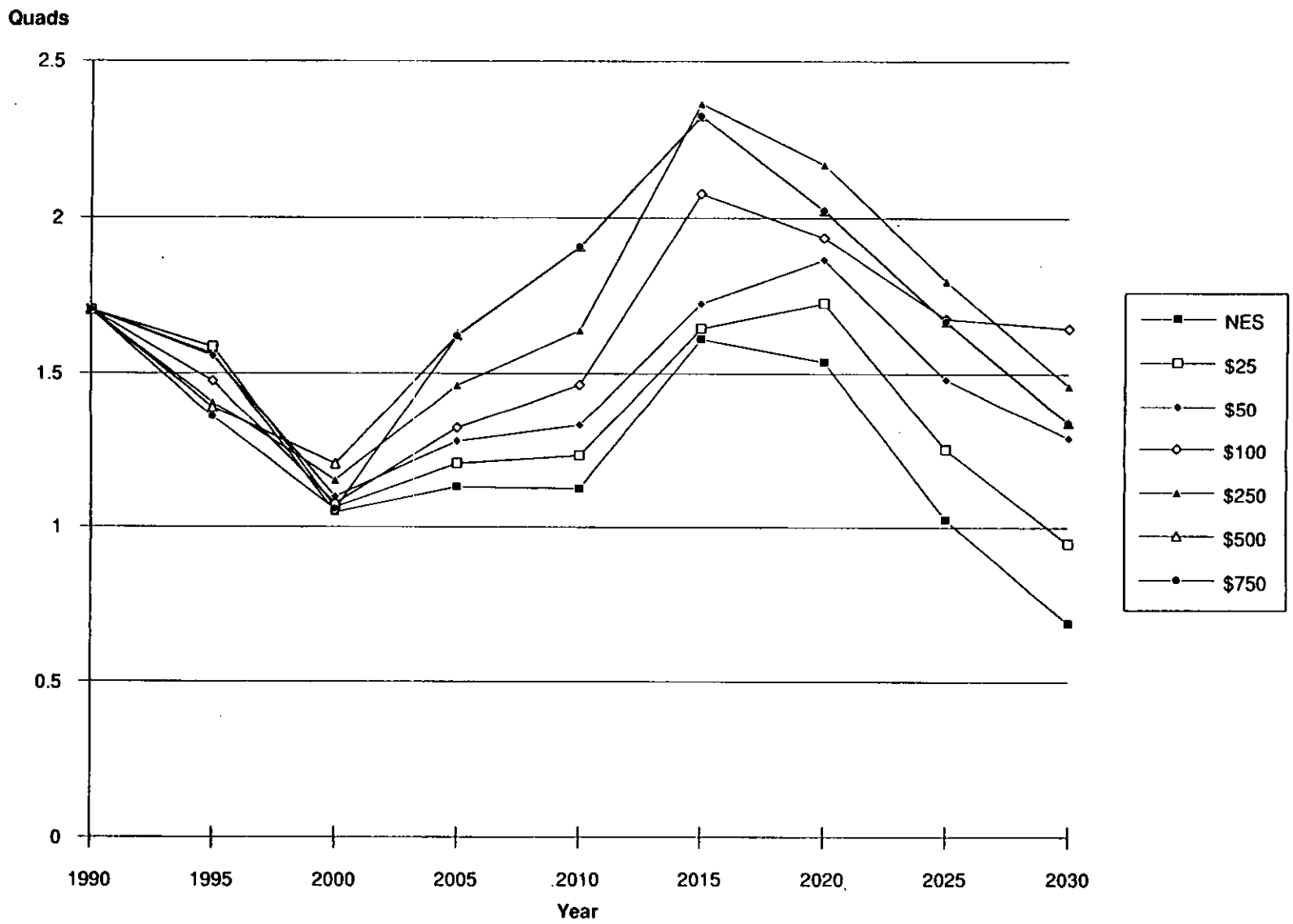

Figure 6.5. Fossil Fuel Taxes Based on Carbon Content: Total Utility Oil Consumption (quads)

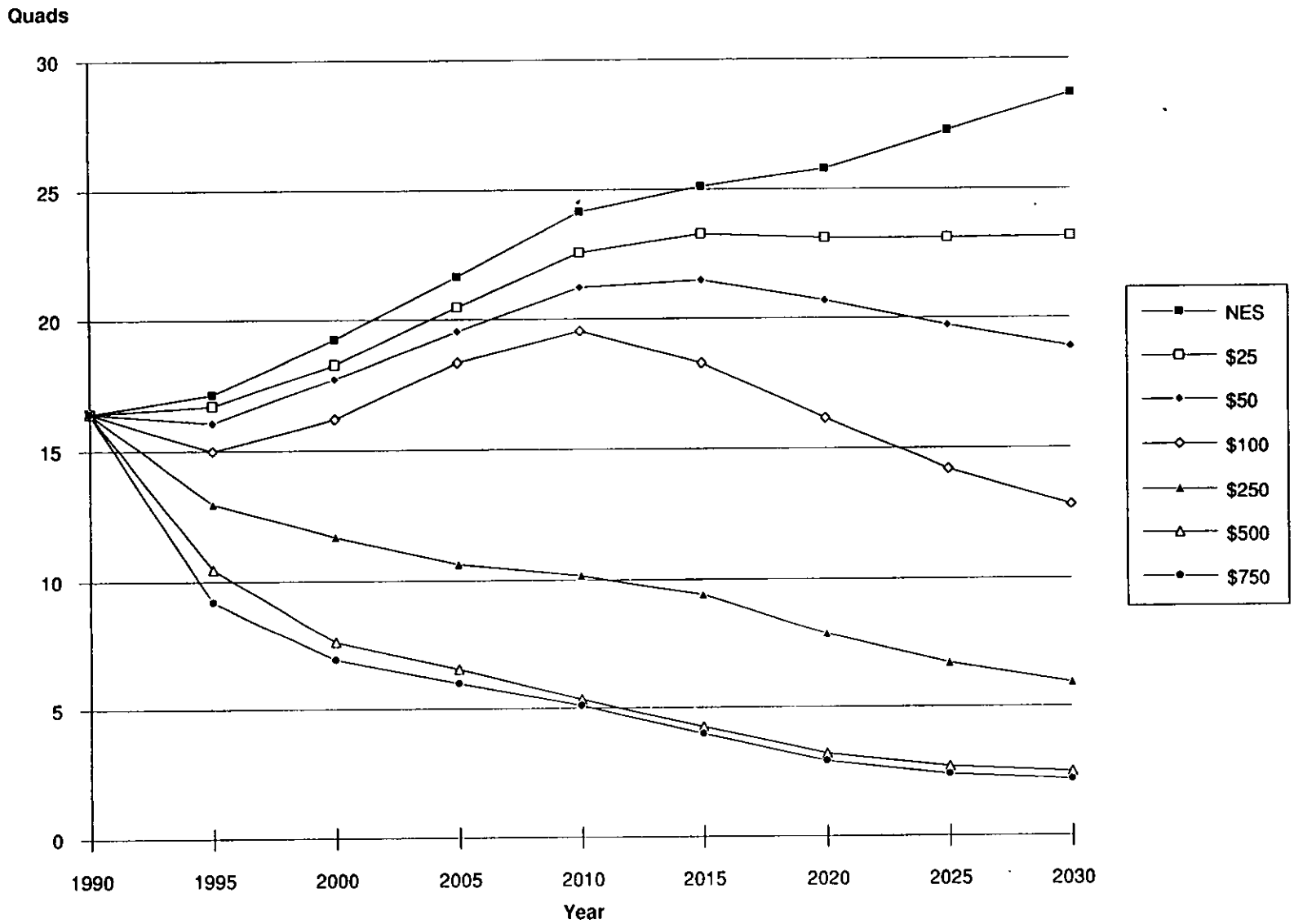

Figure 6.6. Fossil Fuel Taxes Based on Carbon Content: Total Utility Coal Consumption (quads)

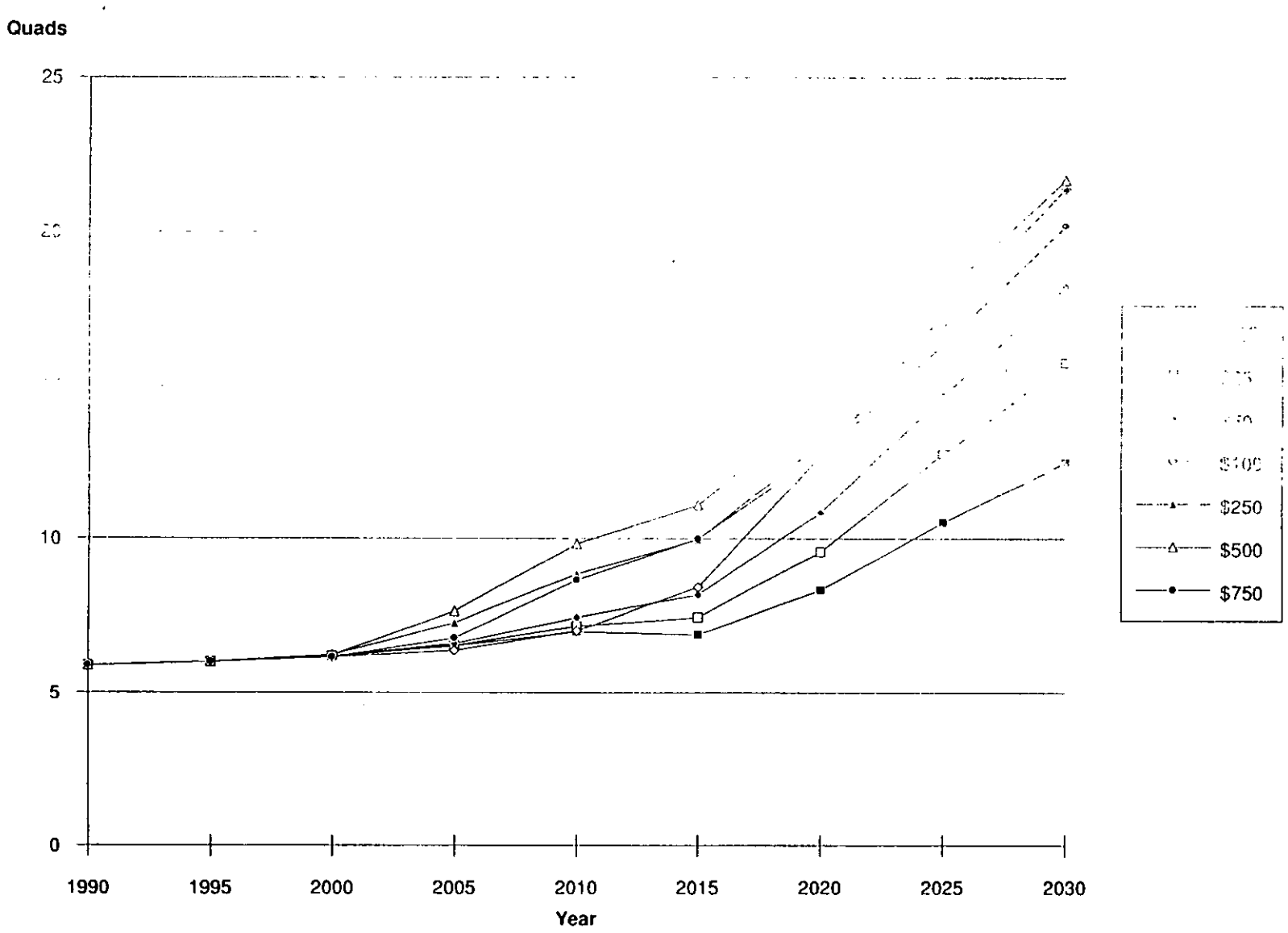

Figure 6.7. Fossil Fuel Taxes Based on Carbon Content: Total Utility Nuclear Consumption (quads)

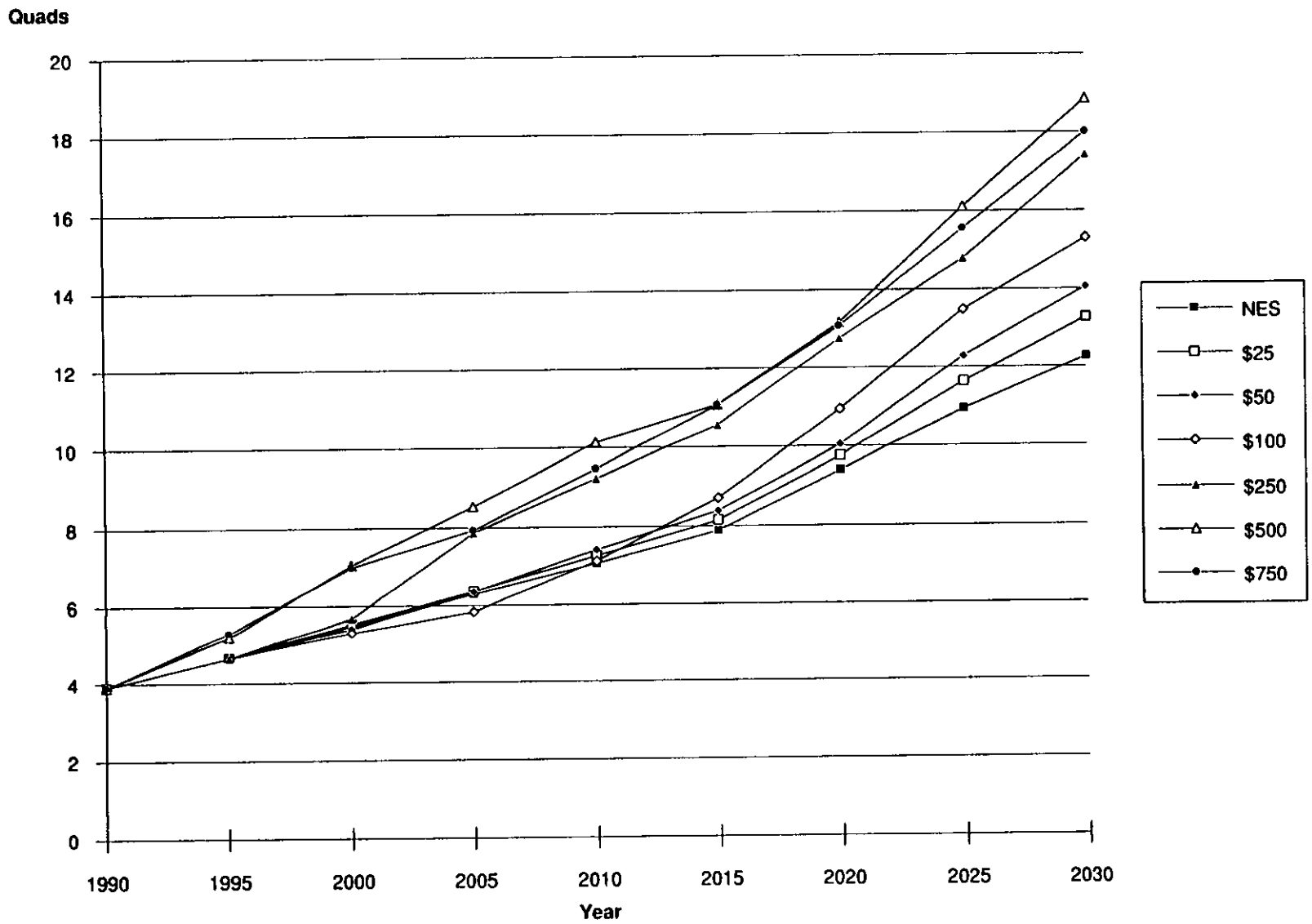

Figure 6.8. Fossil Fuel Taxes Based on Carbon Content: Total Utility Renewable Energy Consumption (quads)

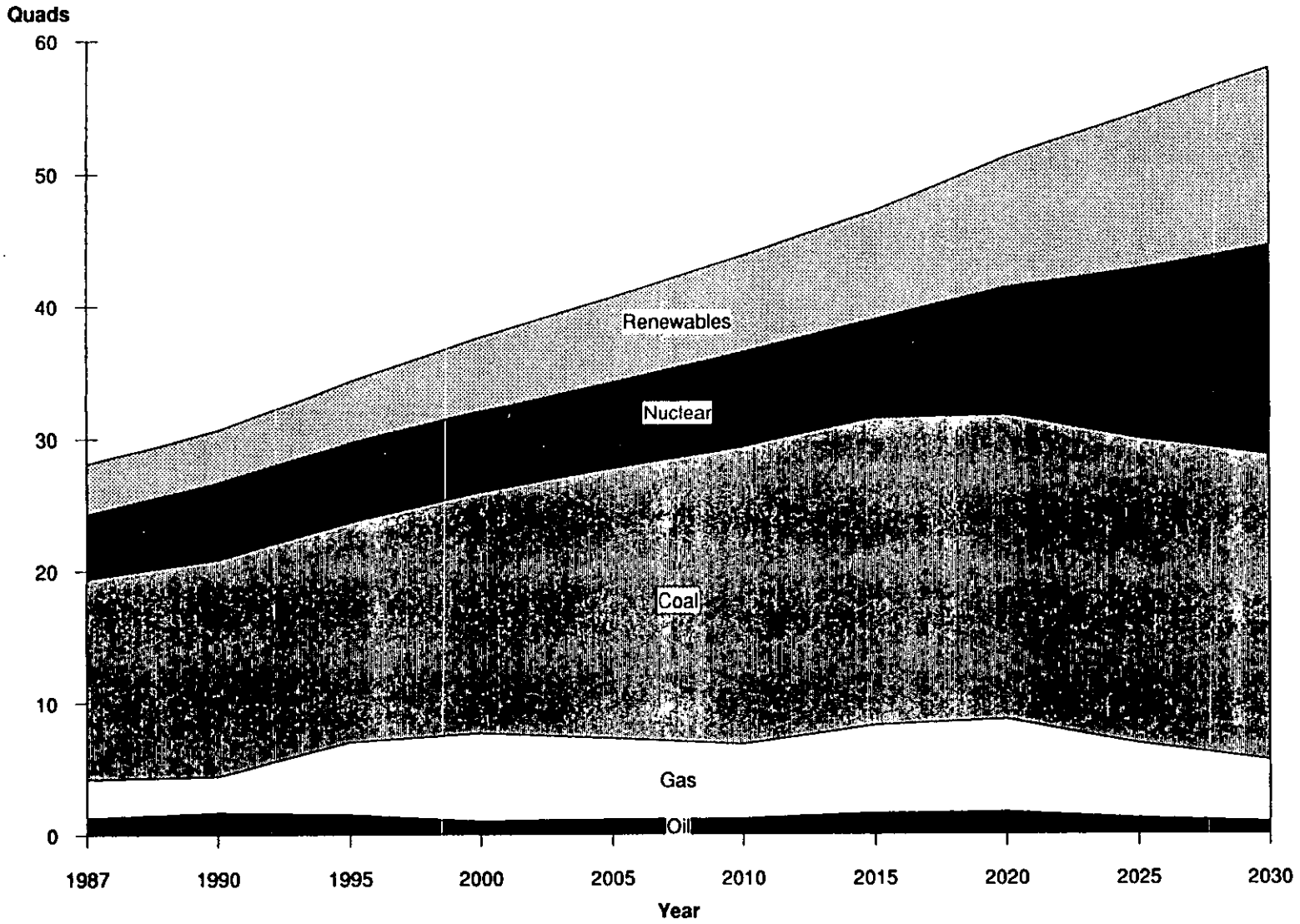

Figure 6.9. $25/mtC Fossil Fuel Tax Based on Carbon Content: Electric Utility Energy Consumption, by Fuel, 1987-2030 (quads)

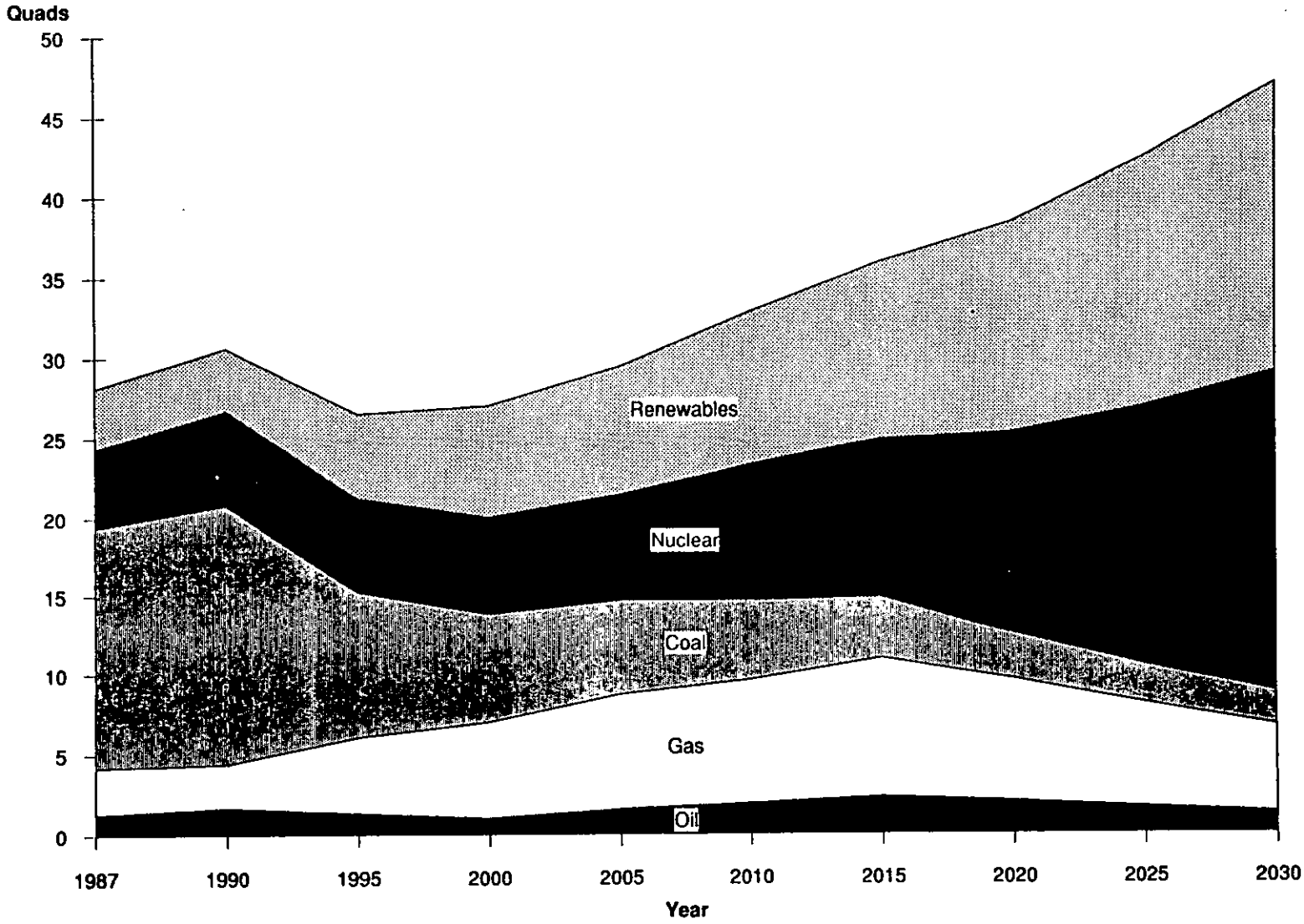

Figure 6.10. $750/mtC Fossil Fuel Tax Based on Carbon Content: Electric Utility Energy Consumption, by Fuel, 1987-2030 (quads)

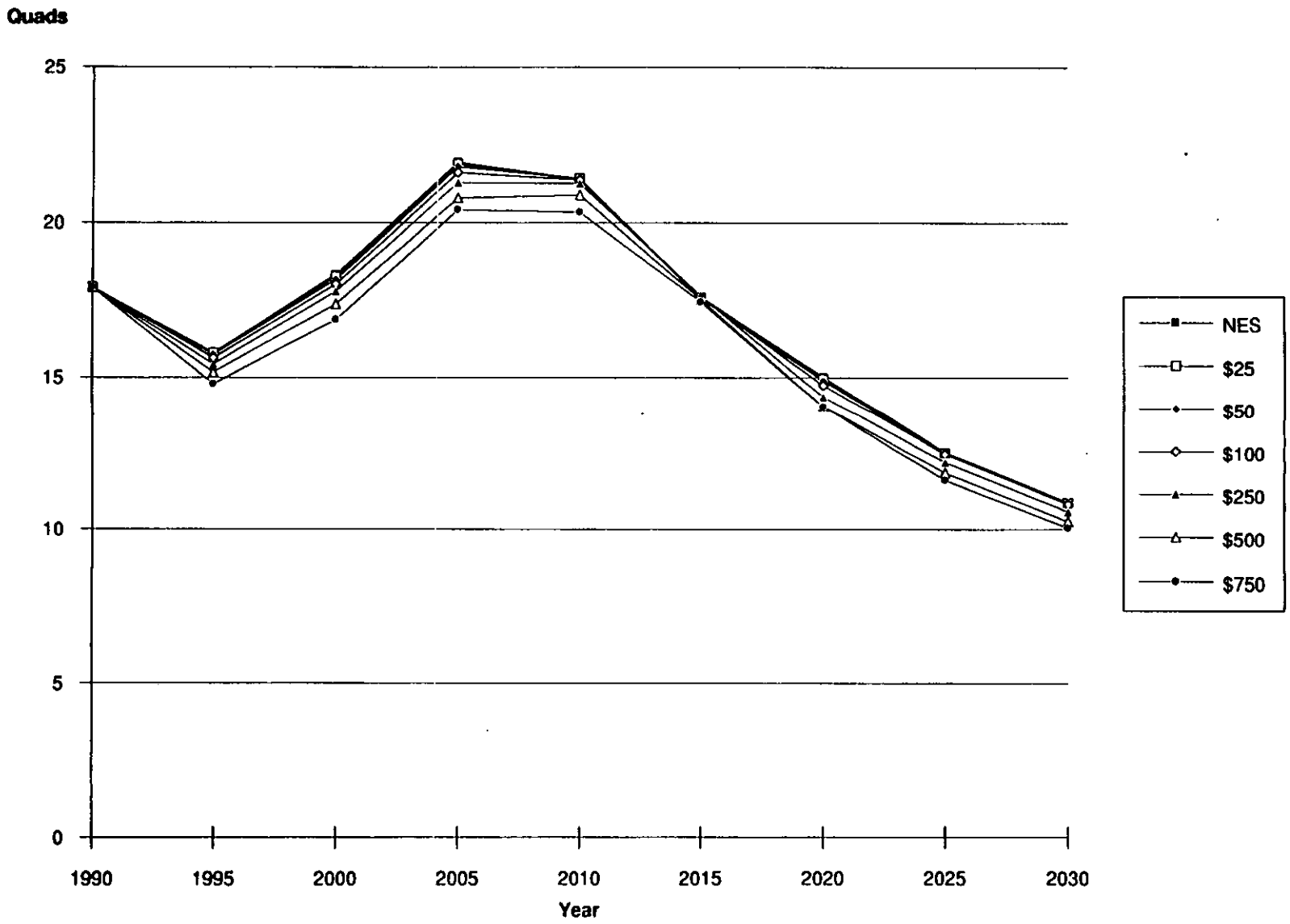

Figure 6.11. Fossil Fuel Taxes Based on Carbon Content: Total Domestic Oil Production by Year (quads)

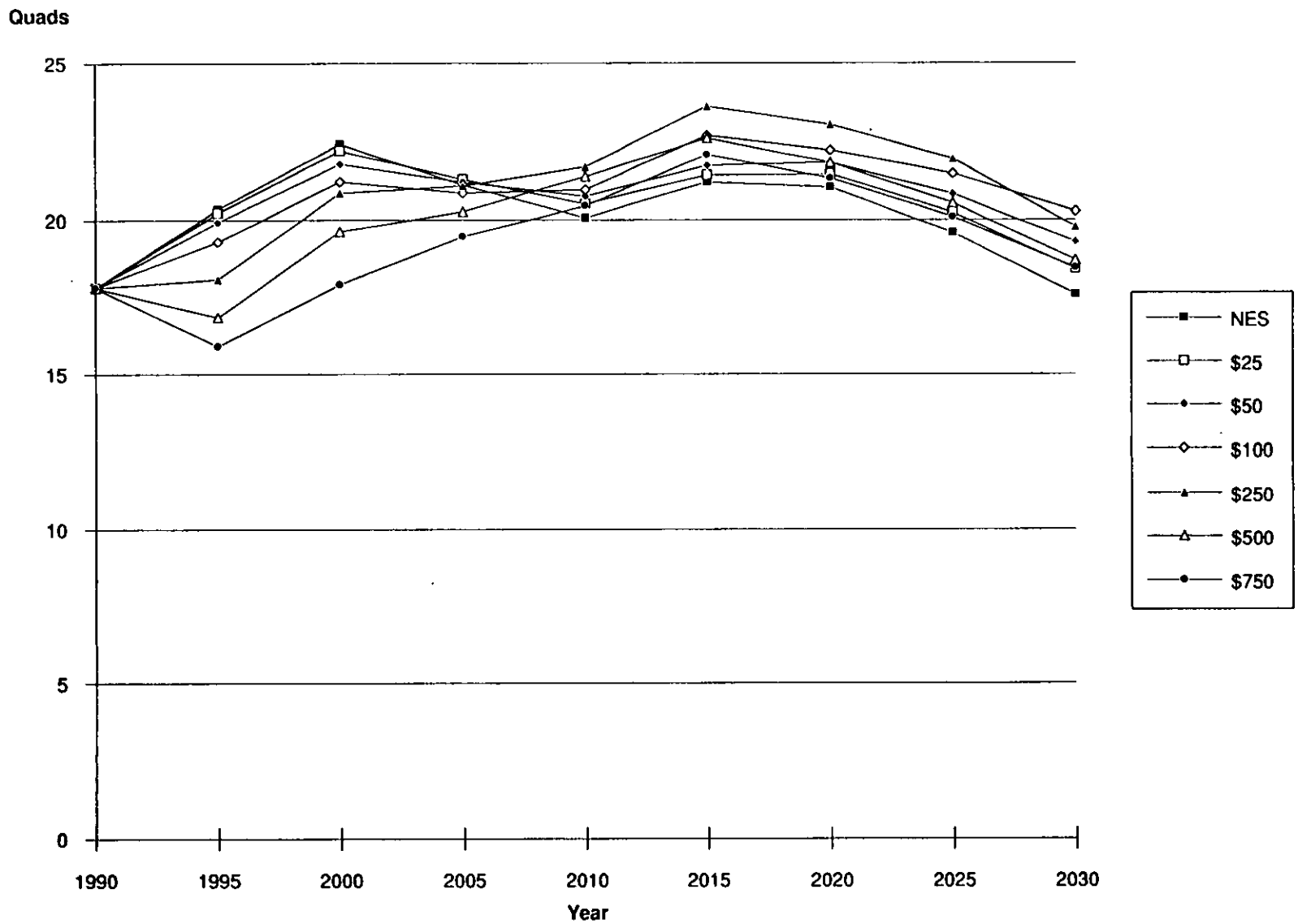

Figure 6.12. Fossil Fuel Taxes Based on Carbon Content: Total Domestic Gas Production by Year (quads)

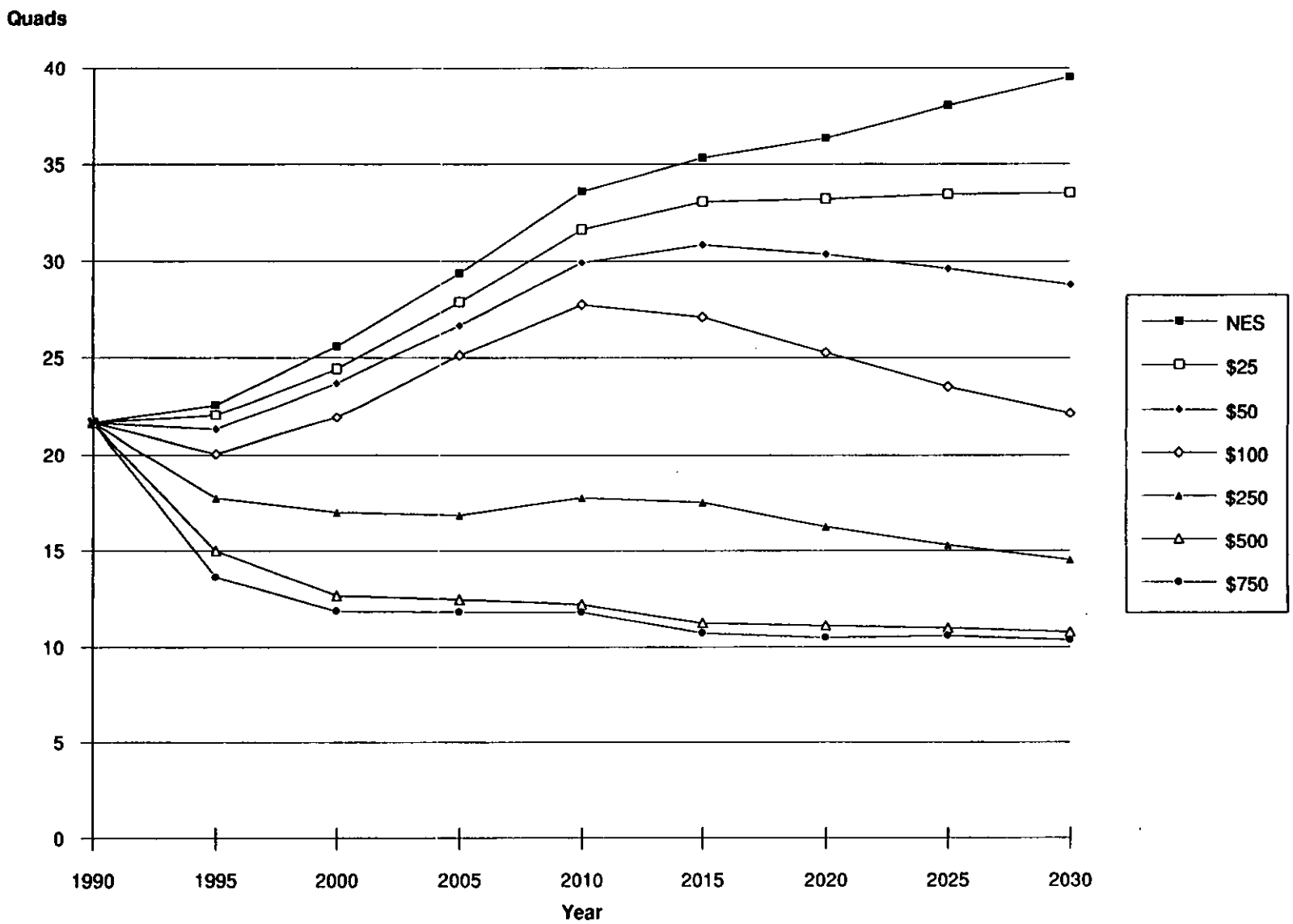

Figure 6.13. Fossil Fuel Taxes Based on Carbon Content: Total Domestic Coal Production by Year (quads)

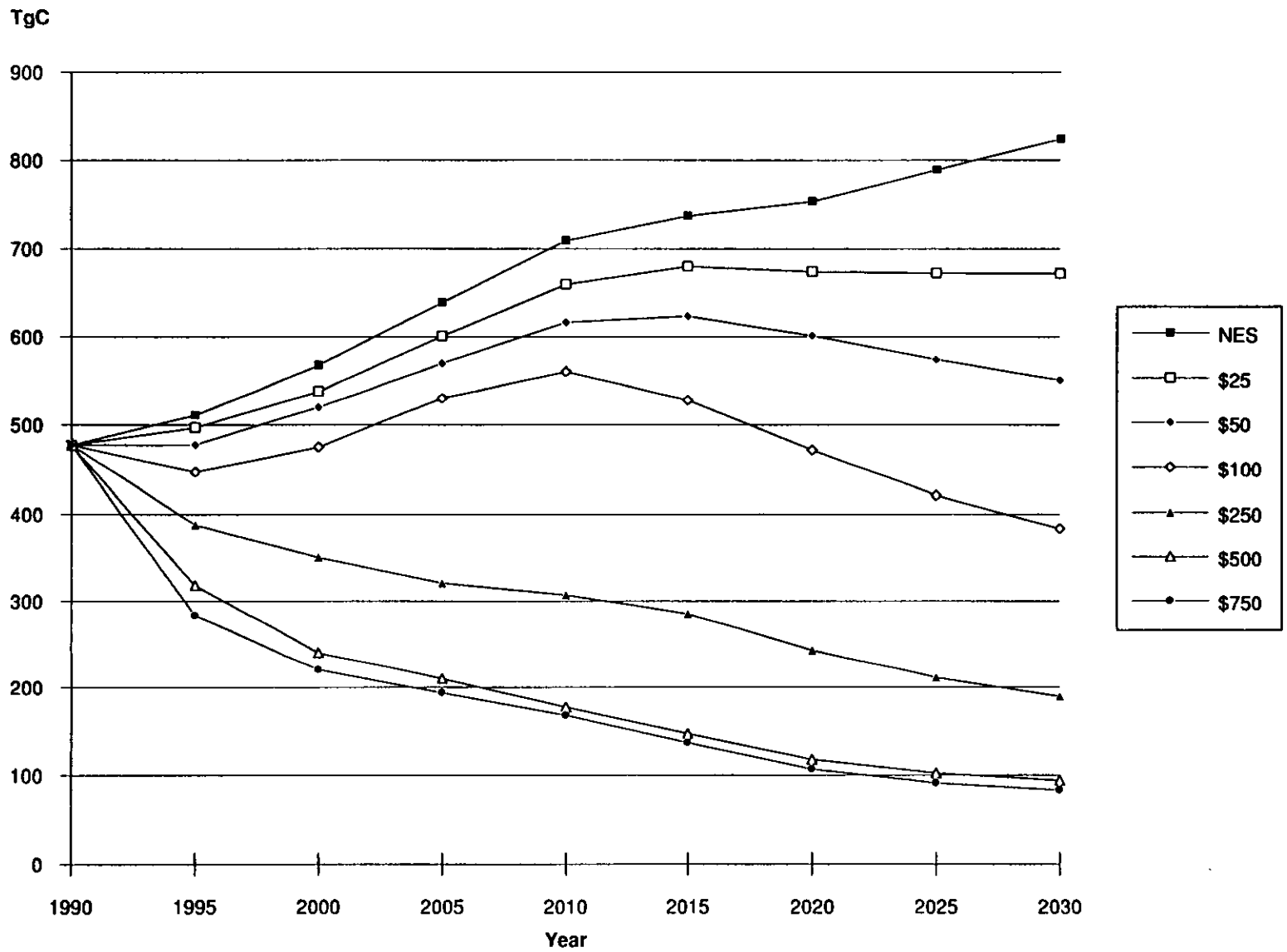

Figure 6.14. Fossil Fuel Taxes Based on Carbon Content: U.S. Fossil Fuel Carbon Emissions from Coal (TgC)

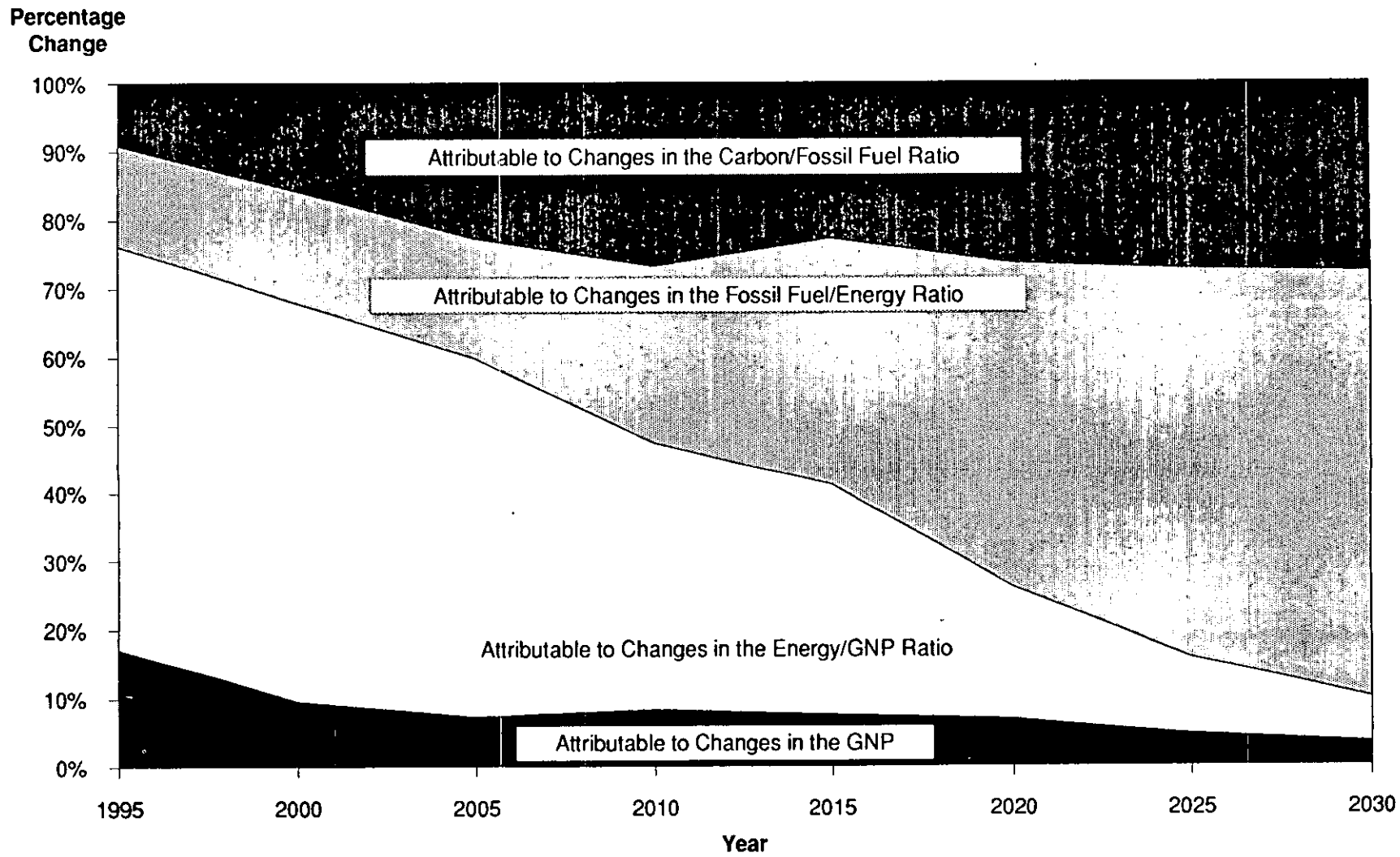

Figure 6.15. $25/mtC Carbon Tax: Attribution of Carbon Emissions Reductions to Changes in Critical Ratios

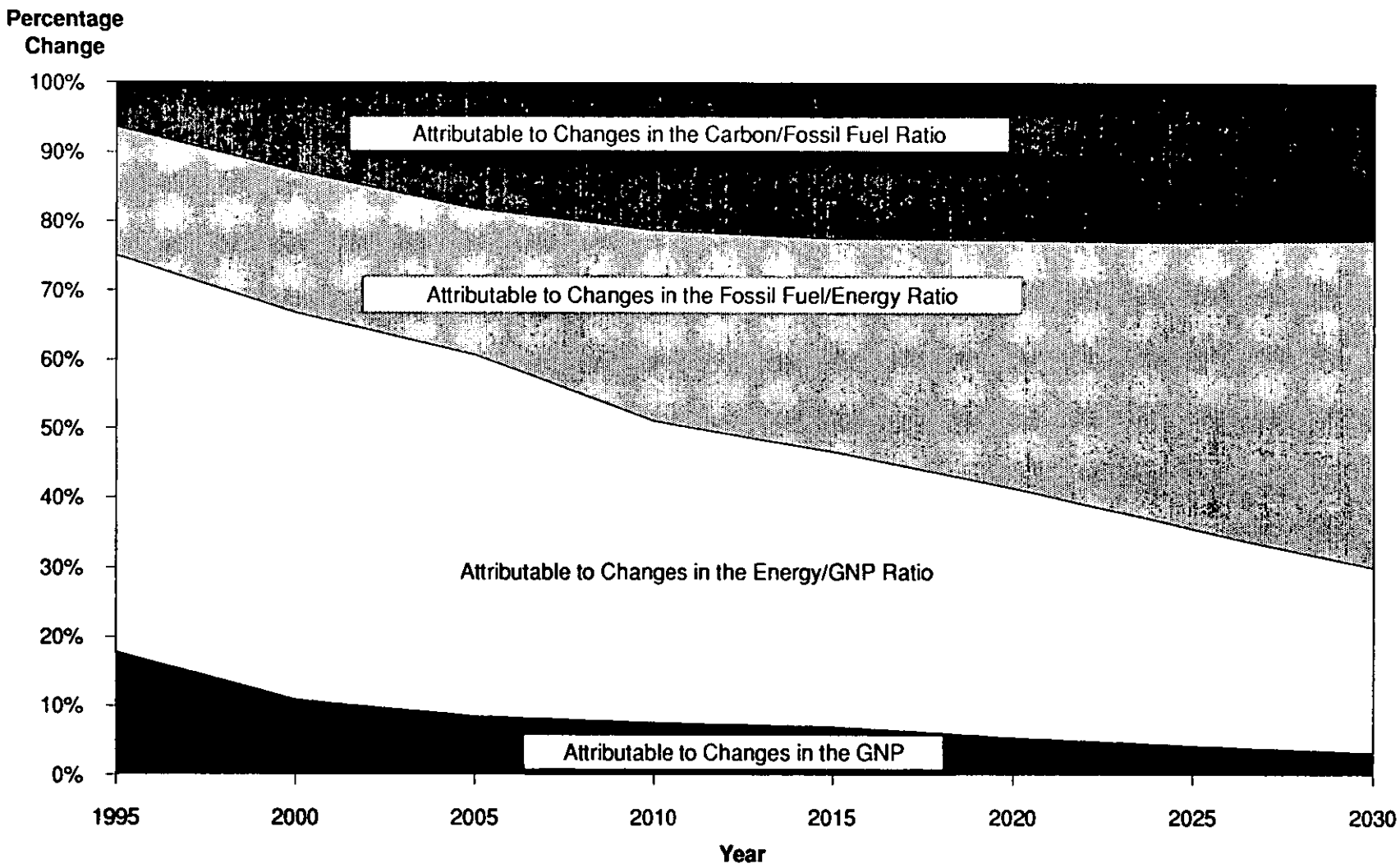

Figure 6.16. $750/mtC Carbon Tax: Attribution of Carbon Emissions Reductions to Changes in Critical Ratios

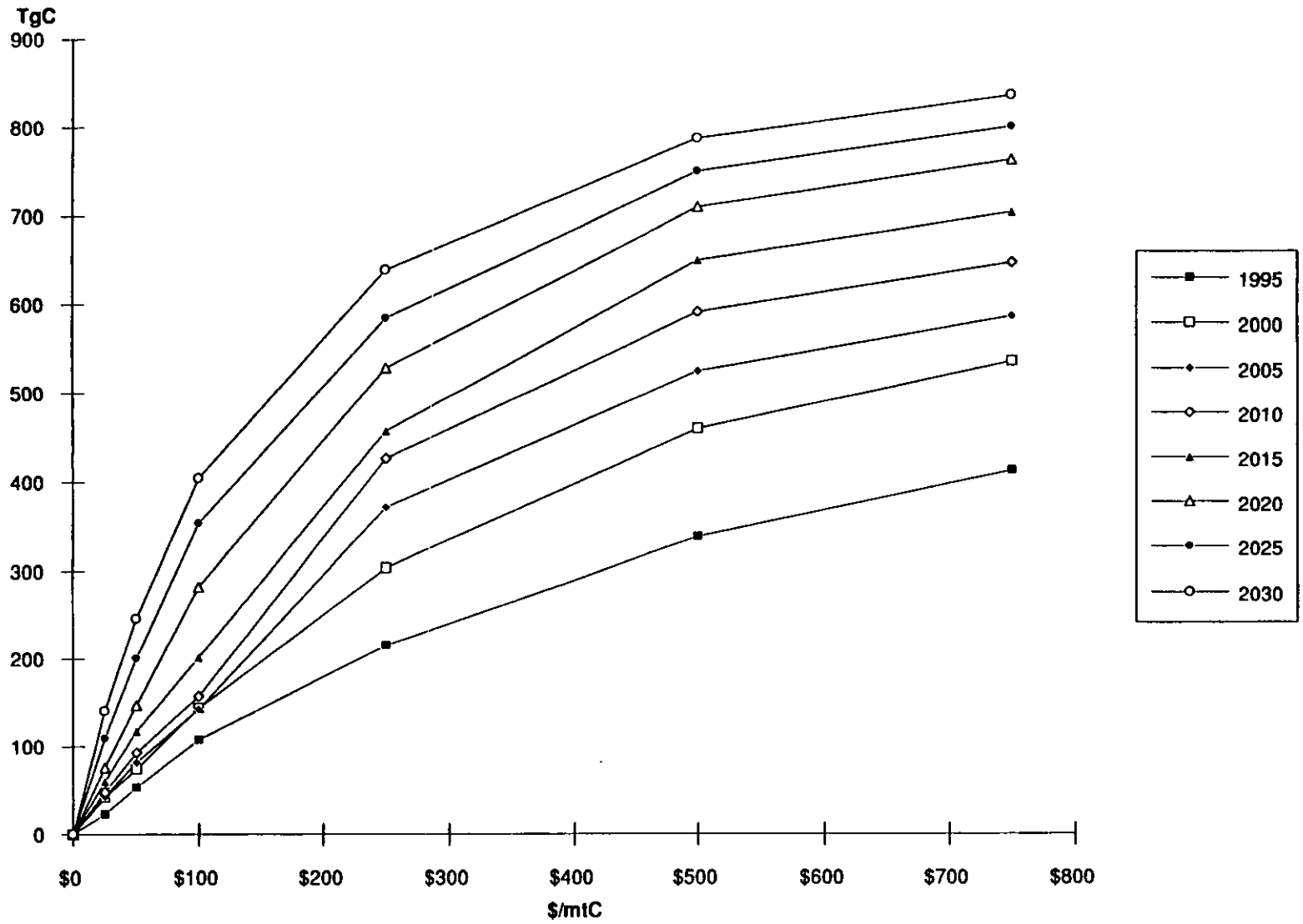

Figure 6.17. Fossil Fuel Carbon Taxes: Carbon Emissions Reductions Relative to the NES Actions Case (TgC) vs. Marginal Cost ($/mtC)

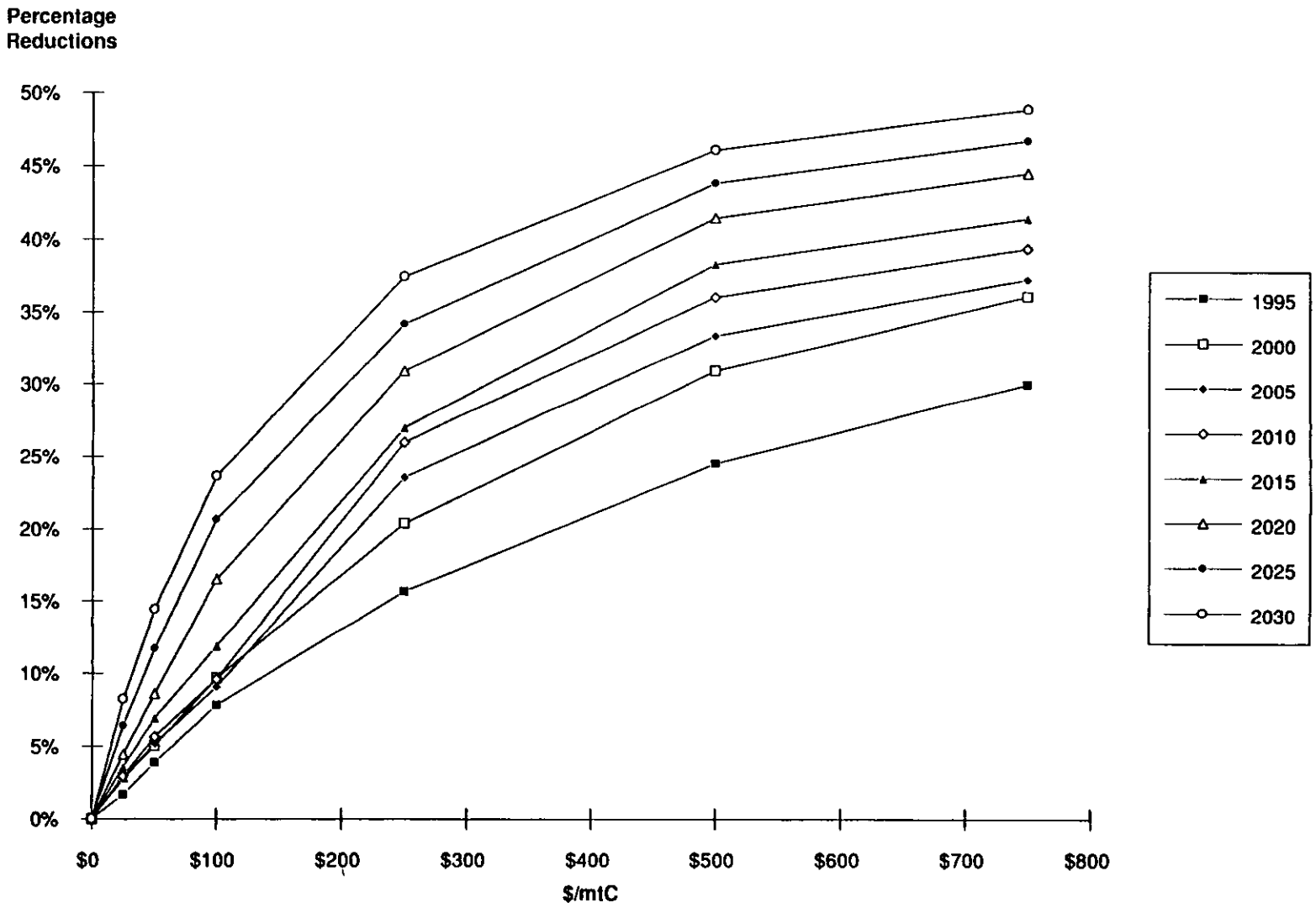

Figure 6.18. Fossil Fuel Carbon Taxes: % Carbon Emissions Reductions Relative to the NES Actions Case vs. Marginal Cost ($/mtC)

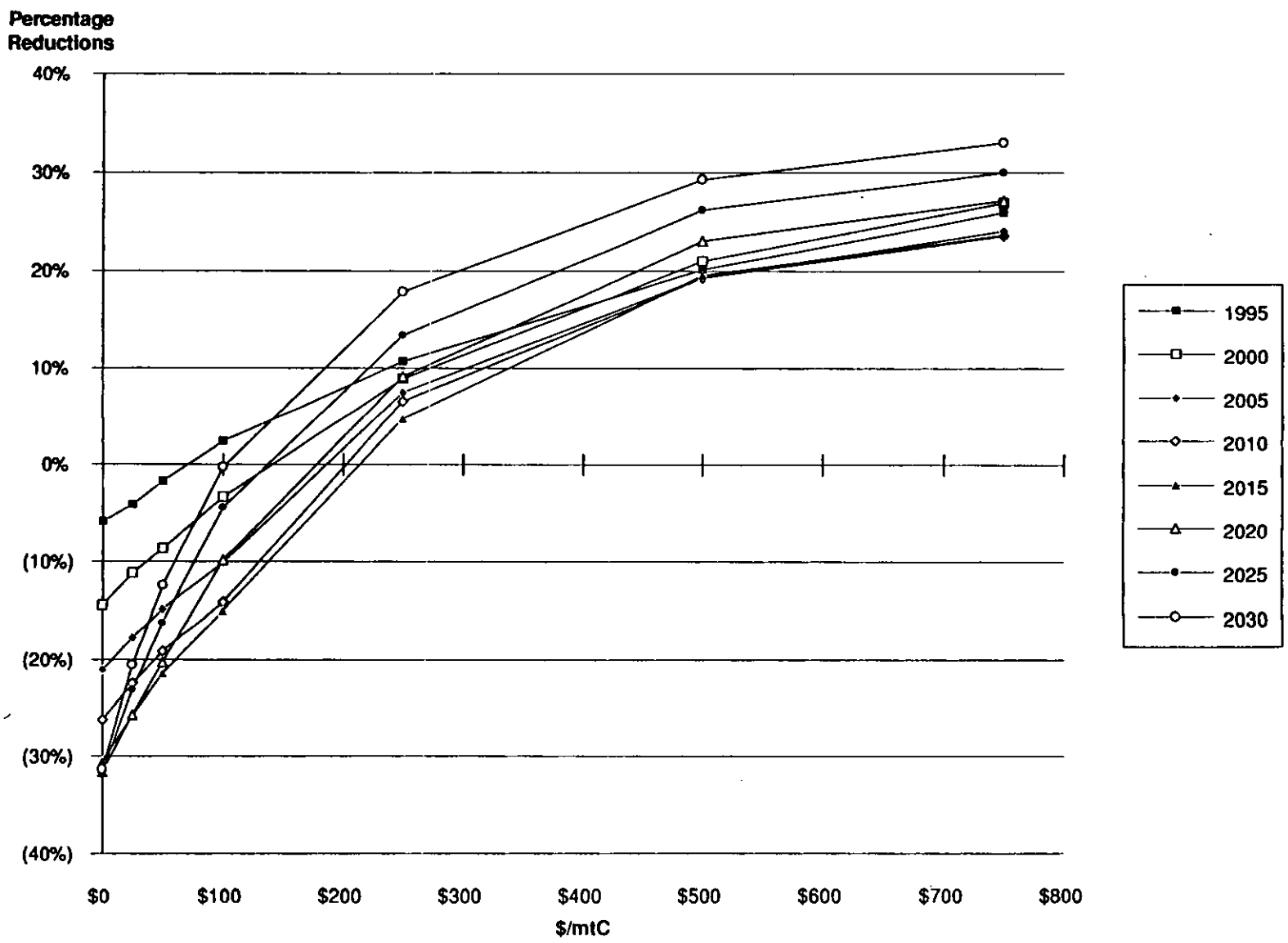

Figure 6.19. Fossil Fuel Carbon Taxes: % Carbon Emissions Reductions Relative to 1990 vs. Marginal Cost ($/mtC)

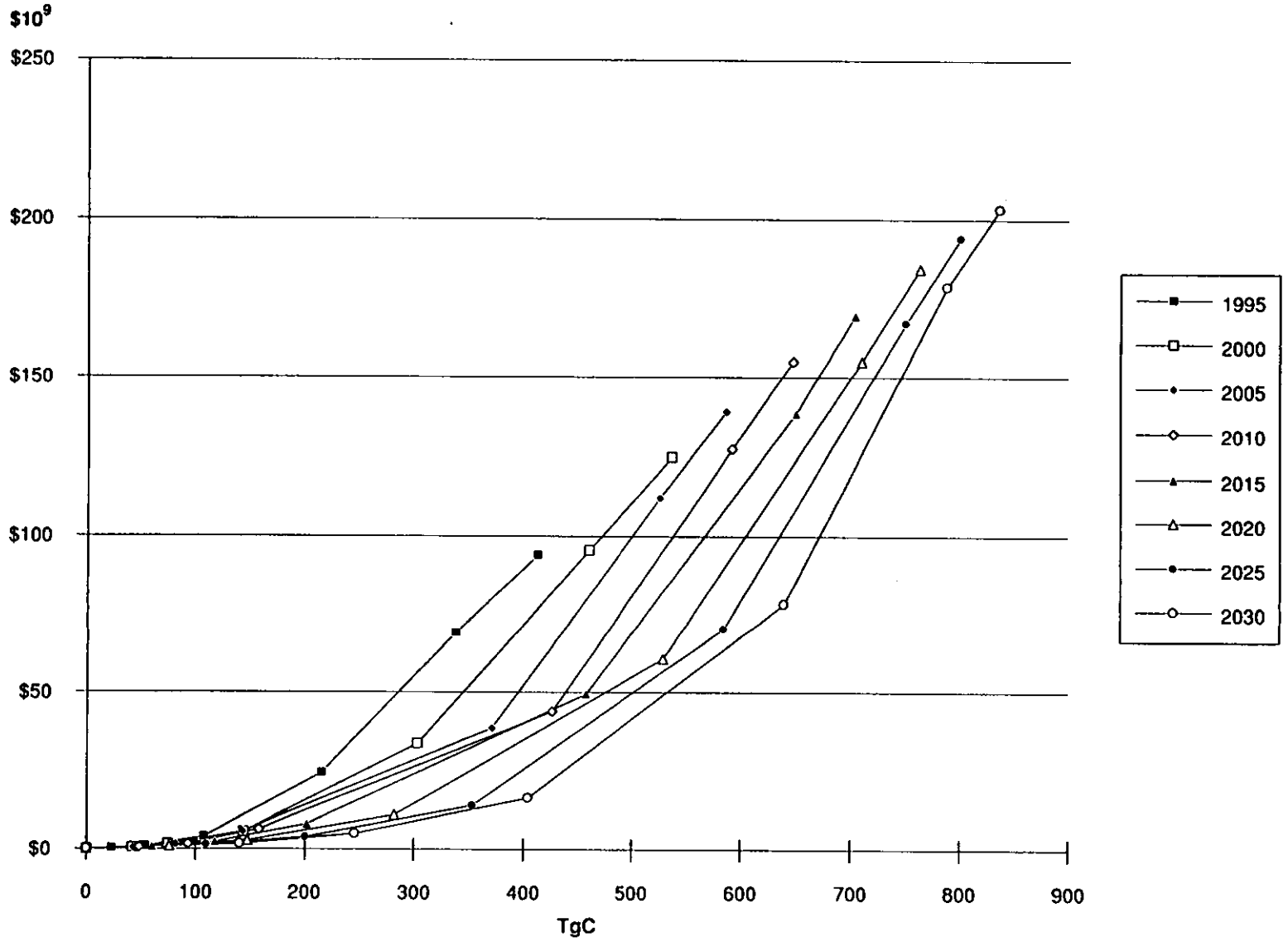

Figure 6.20. Fossil Fuel Carbon Taxes: Total Cost ($\$10^9$) vs. % Carbon Emissions Reductions (TgC) Relative to NES Actions Case

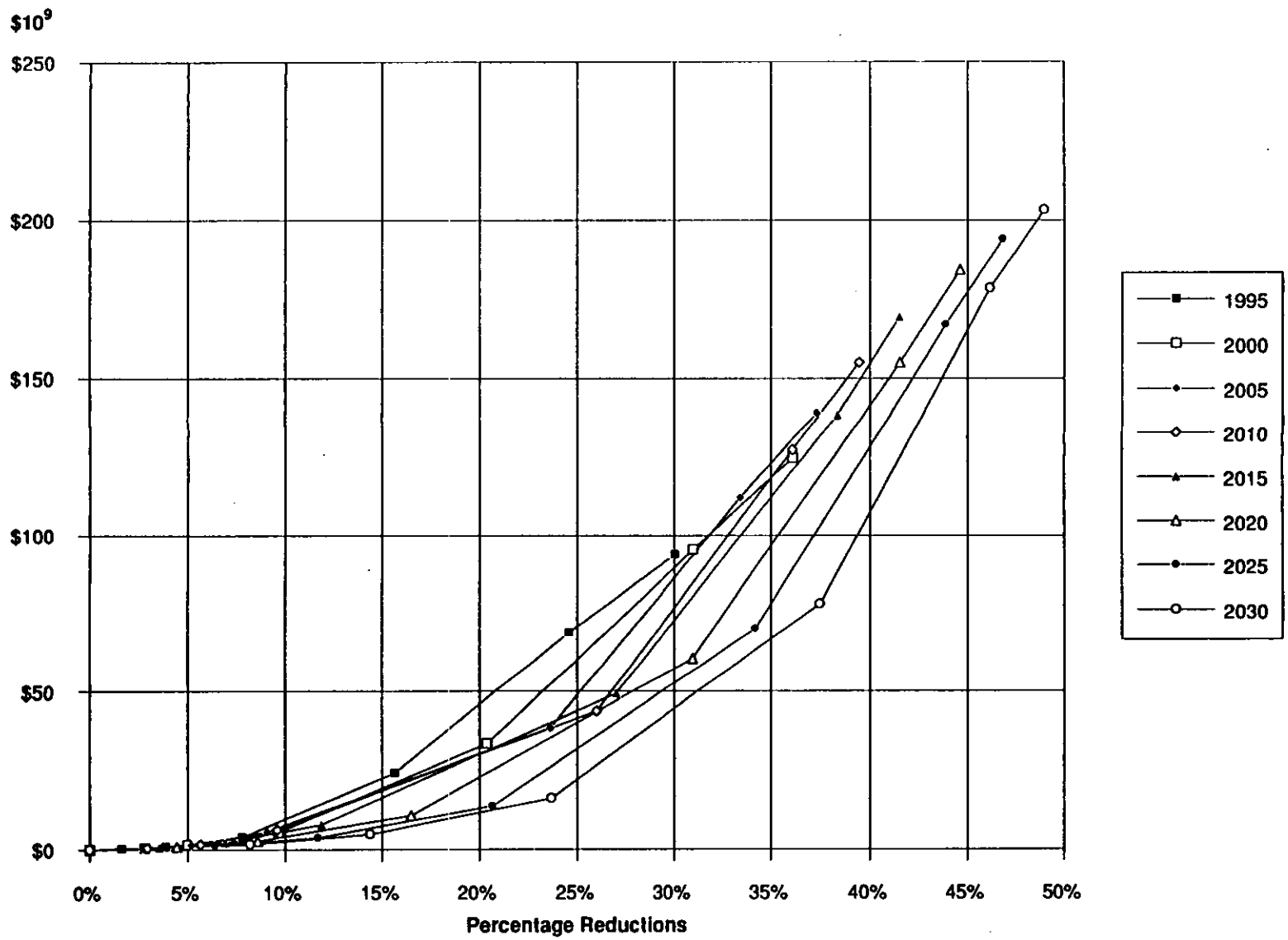

Figure 6.21. Fossil Fuel Carbon Taxes: Total Cost ($\$10^9$) vs. % Carbon Emissions Reductions Relative to NES Actions Case

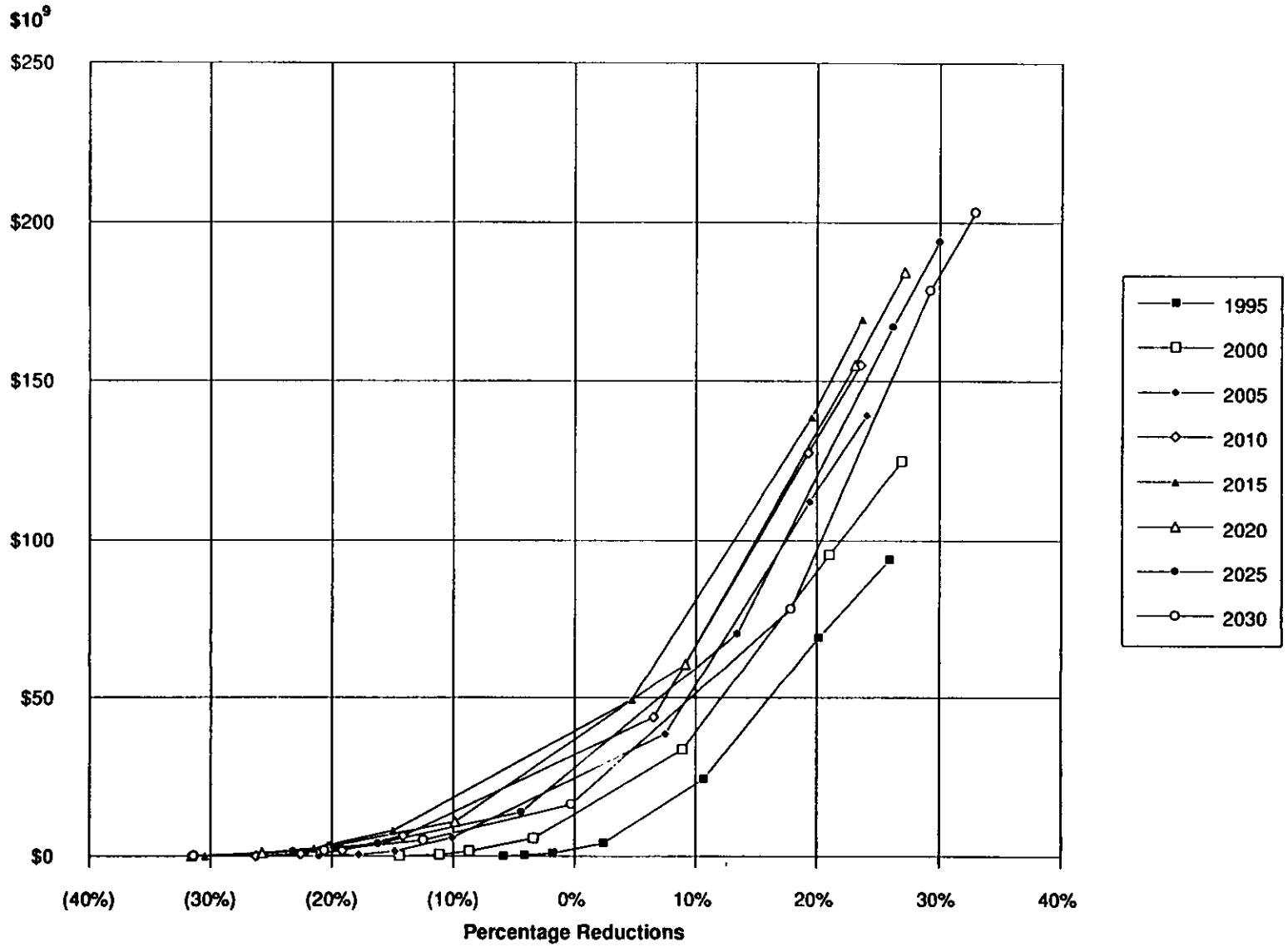

Figure 6.22. Fossil Fuel Carbon Taxes: Total Cost (10^9) vs. % Carbon Emissions Reductions Relative to 1990

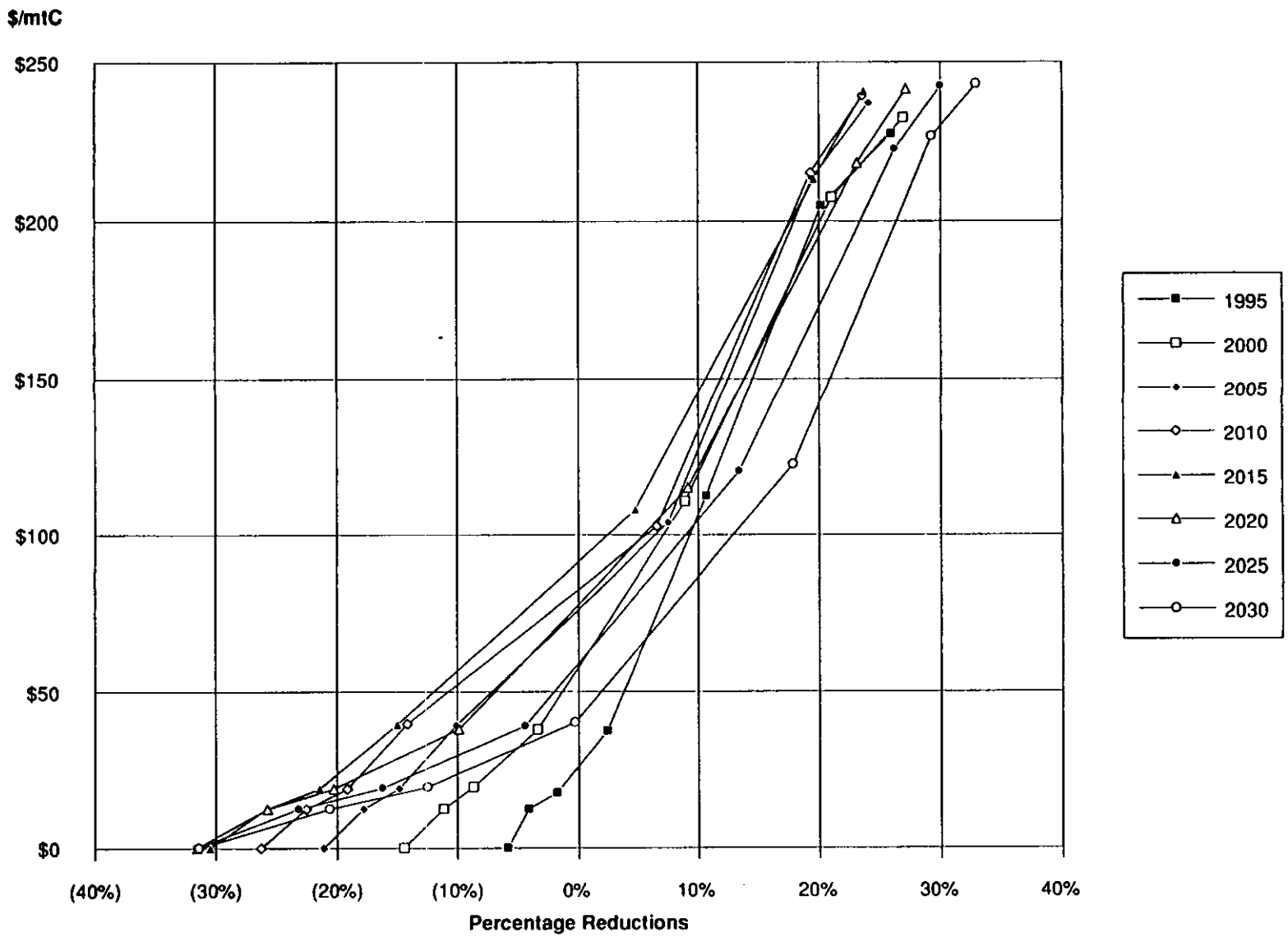

Figure 6.23. Fossil Fuel Carbon Taxes: Average Cost ($/mtC) vs. % Carbon Emissions Reductions Relative to 1990

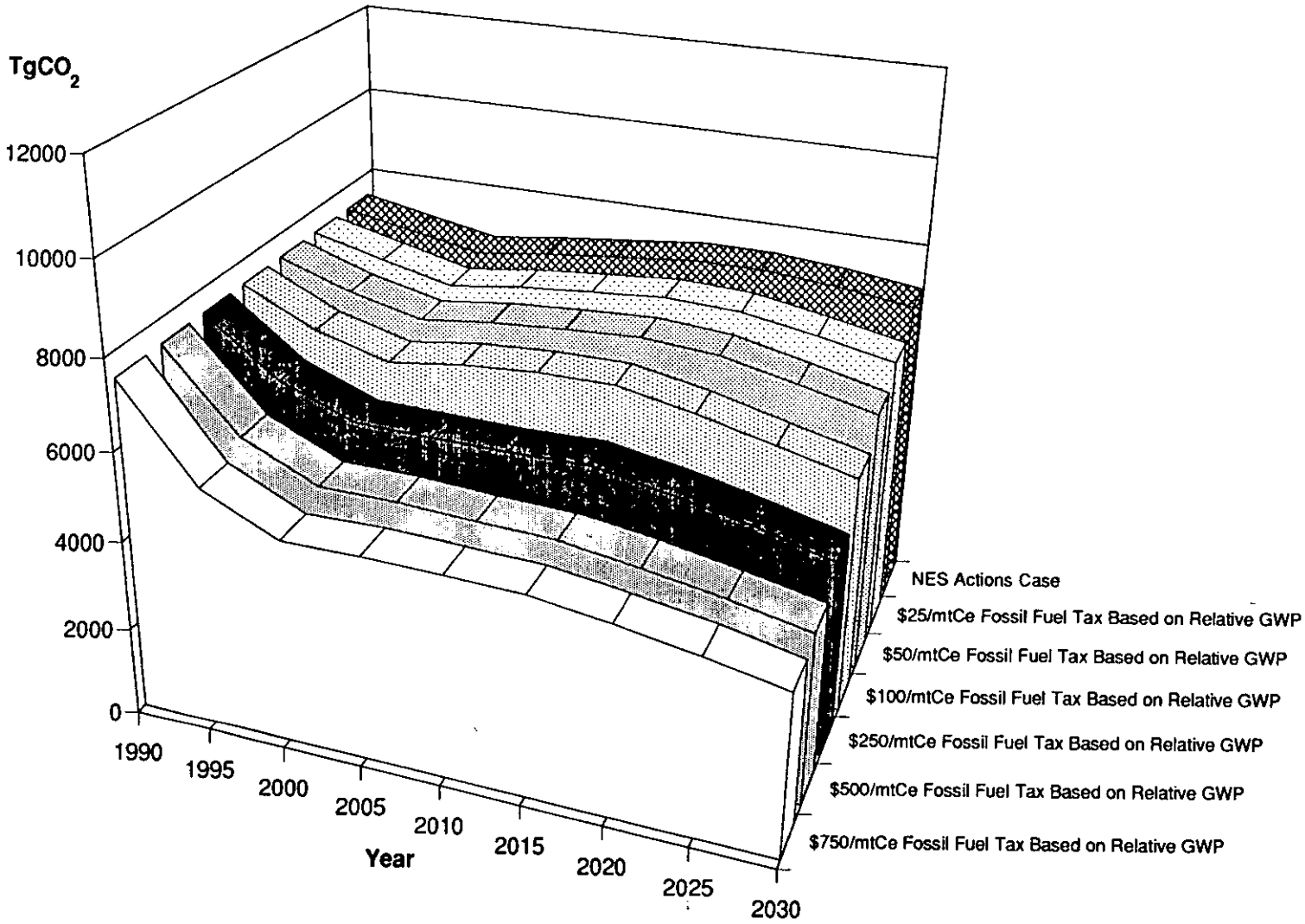

Figure 6.24. Fossil Fuel Taxes Based on Relative GWP: GWP-Weighted Energy-Related Emissions by Year ($TgCO_2e$)

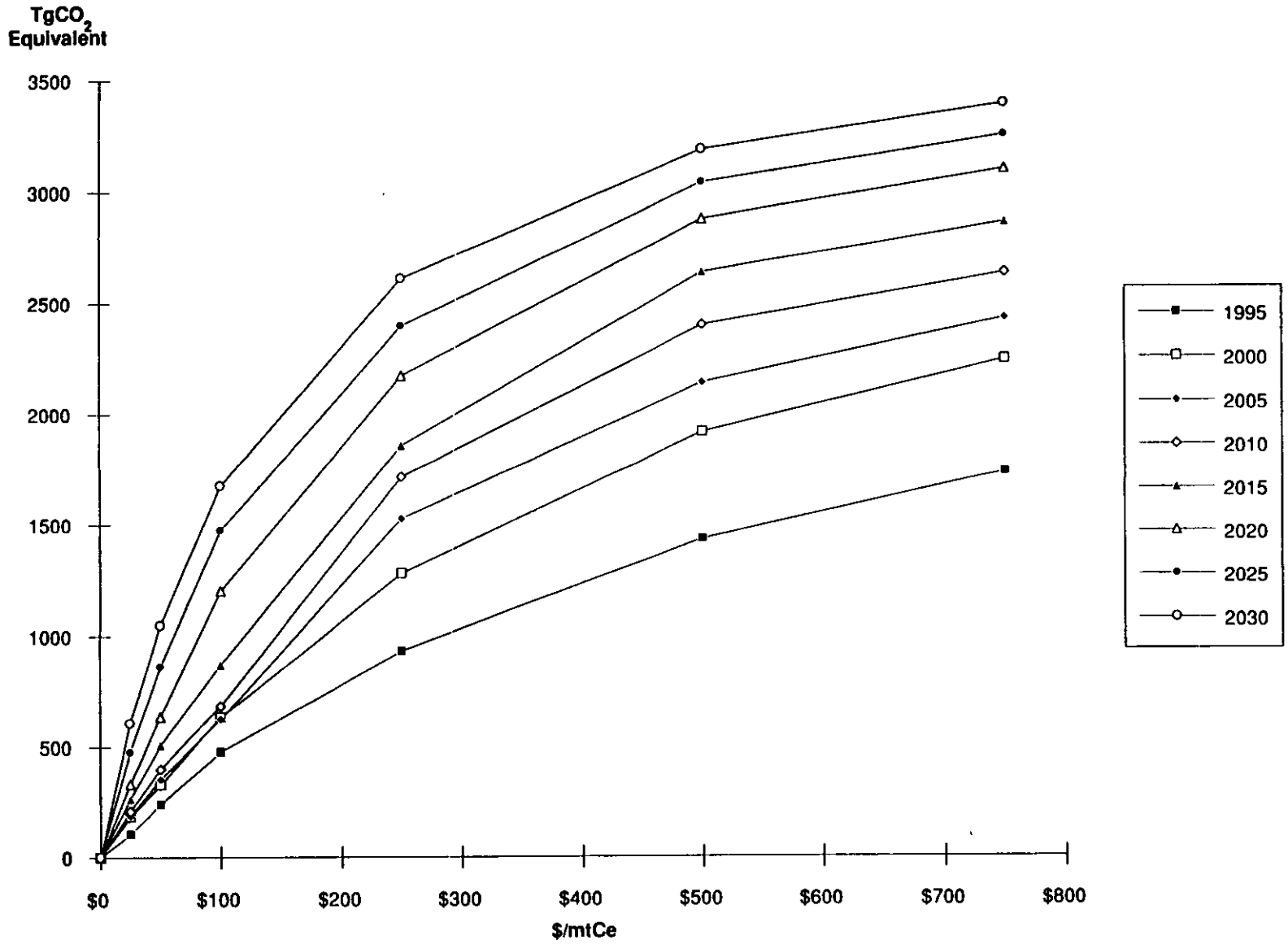

Figure 6.25. Fossil Fuel Taxes Based on Relative GWP: GWP-Weighted Emissions Reductions Relative to the NES Actions Case vs. Marginal Cost

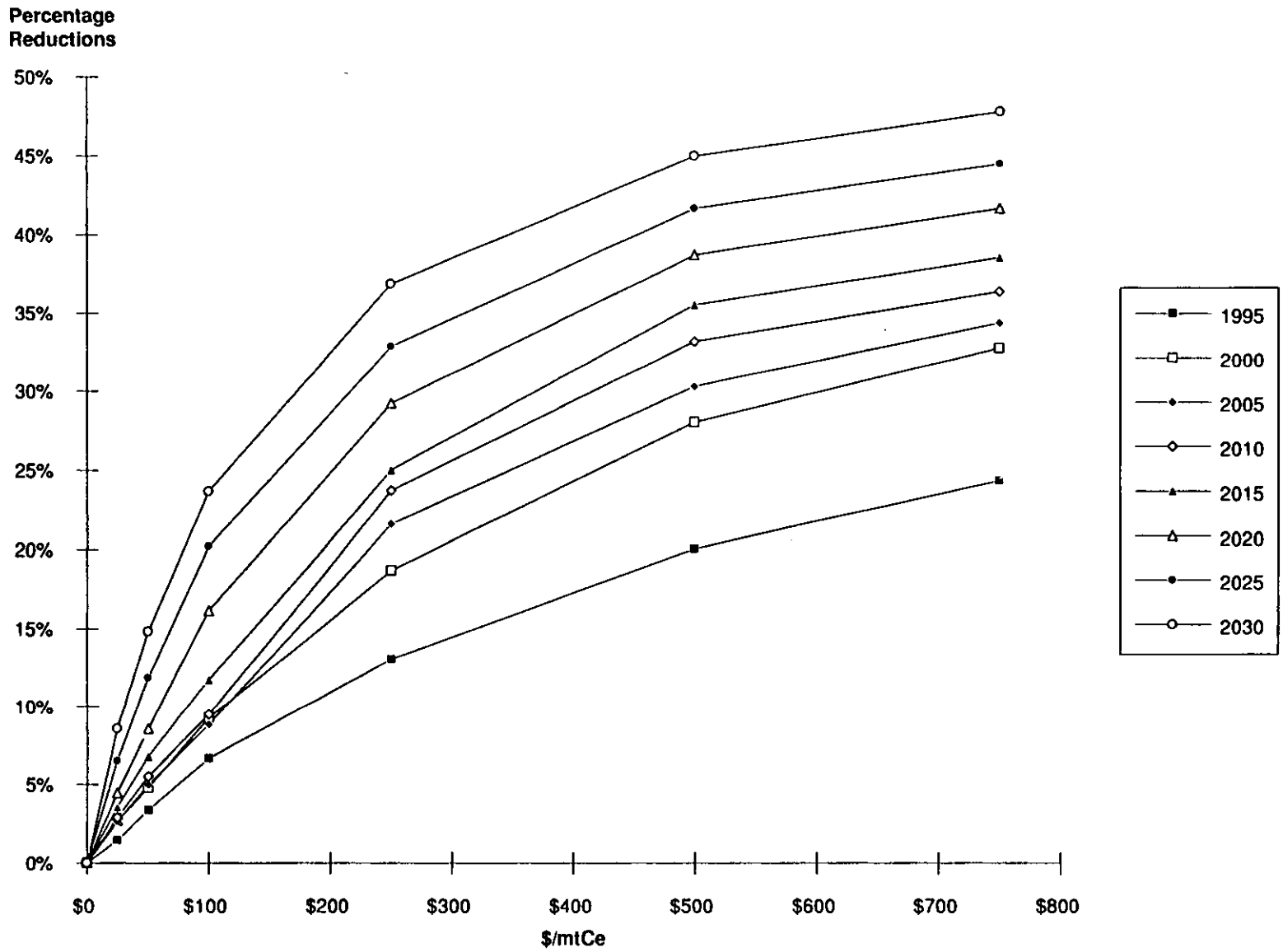

Figure 6.26. Fossil Fuel Taxes Based on Relative GWP: % GWP-Weighted Emissions Reductions Relative to the NES Actions Case vs. Marginal Cost

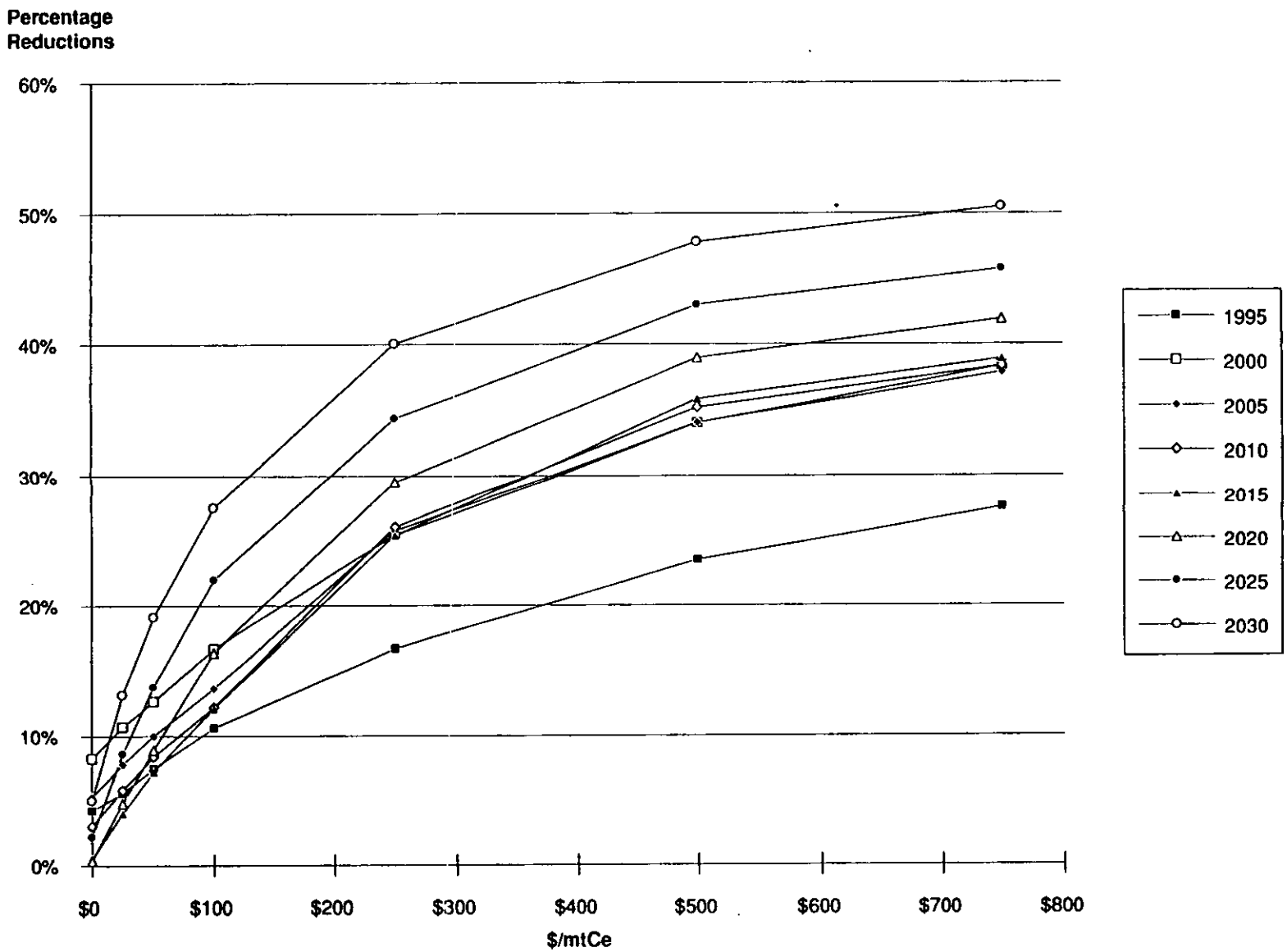

Figure 6.27. Fossil Fuel Taxes Based on Relative GWP: % GWP-Weighted Emissions Reductions Relative to 1990 vs. Marginal Cost

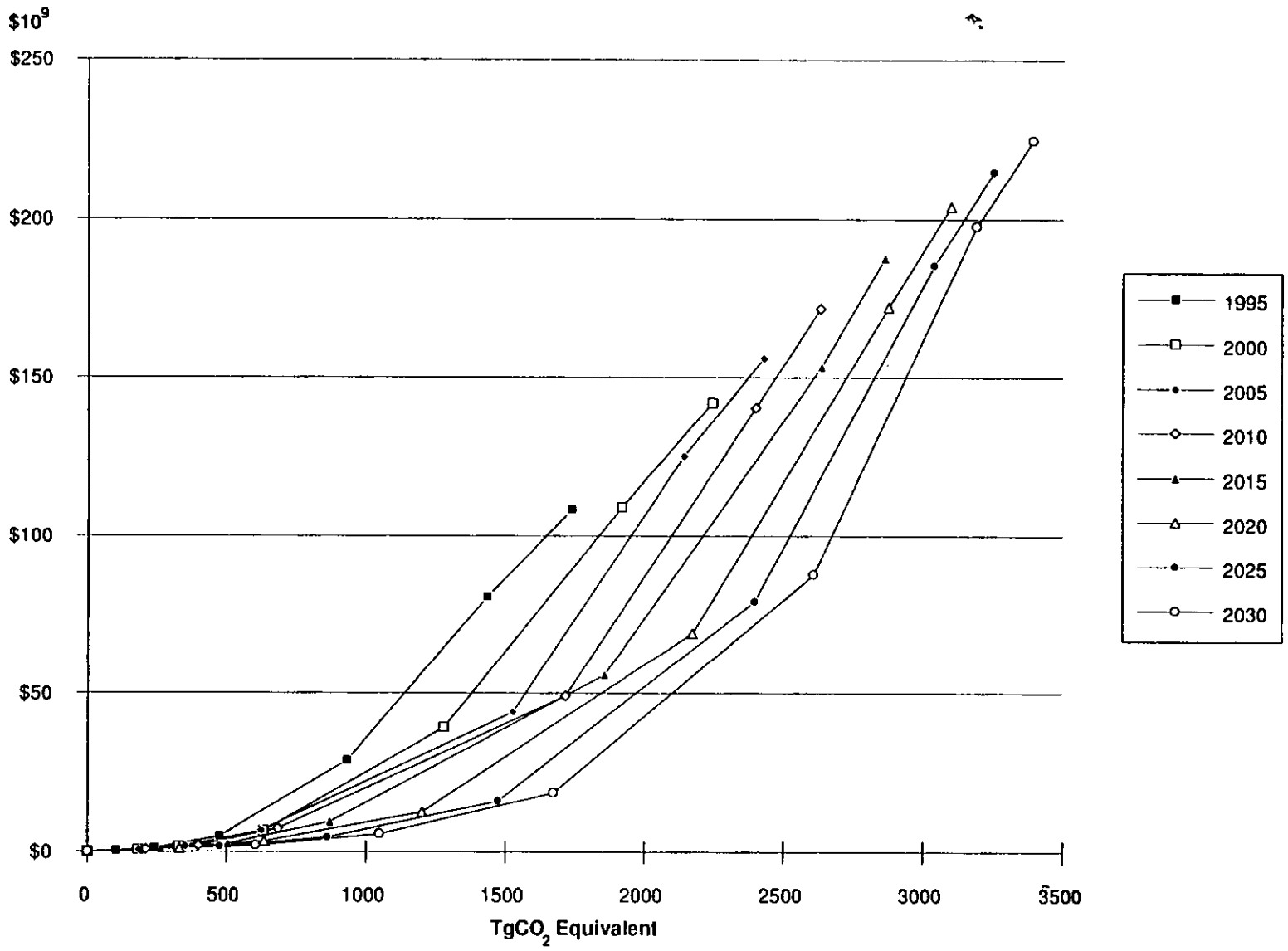

Figure 6.28. Fossil Fuel Taxes Based on Relative GWP: Total Cost vs. GWP-Weighted Emissions Reductions Relative to NES Actions Case

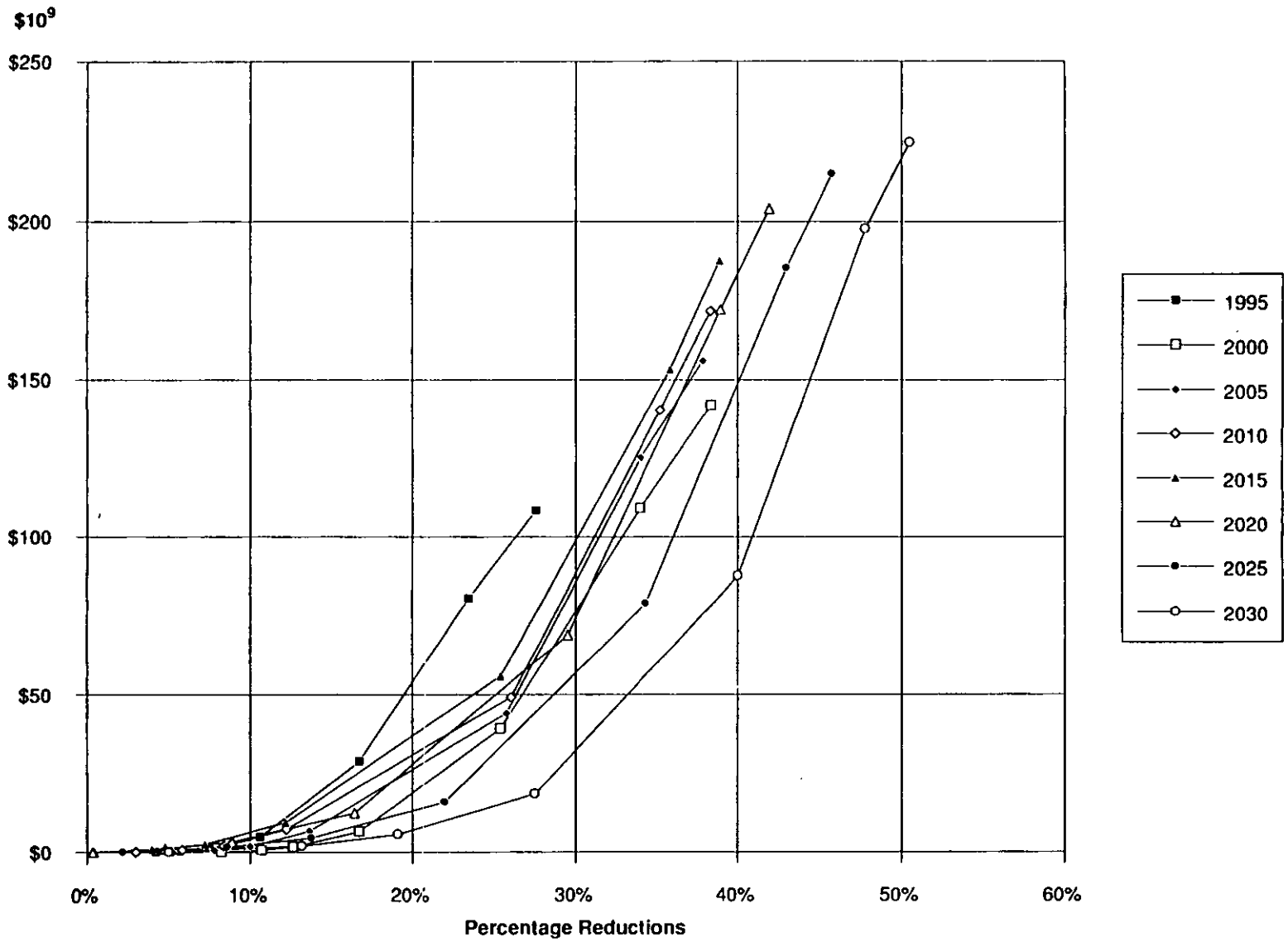

Figure 6.29. Fossil Fuel Taxes Based on Relative GWP: Total Cost vs. % GWP-Weighted Emissions Reductions Relative to 1990

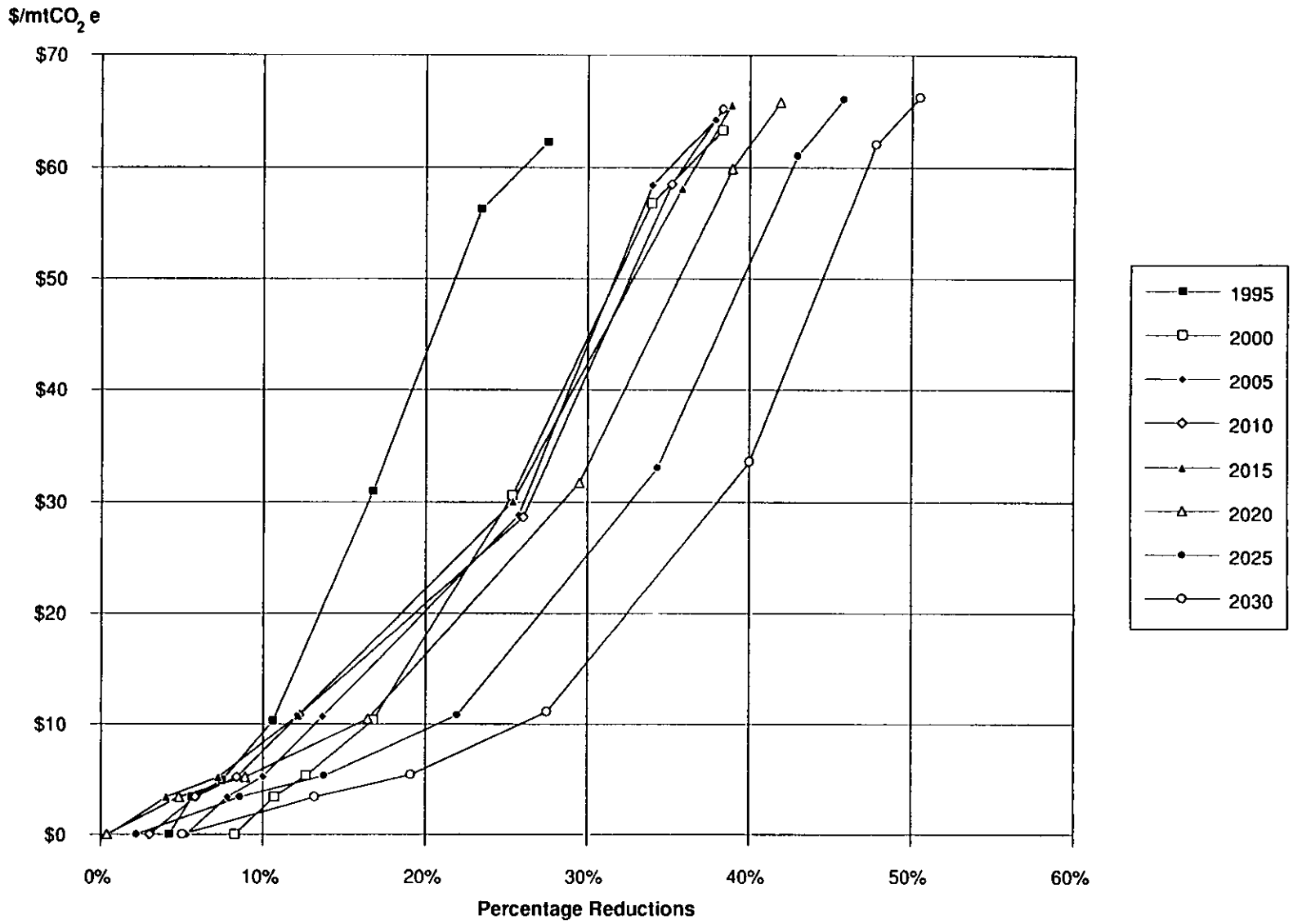

Figure 6.30. Fossil Fuel Taxes Based on Relative GWP: Average Cost vs. % GWP-Weighted Emissions Reductions Relative to 1990

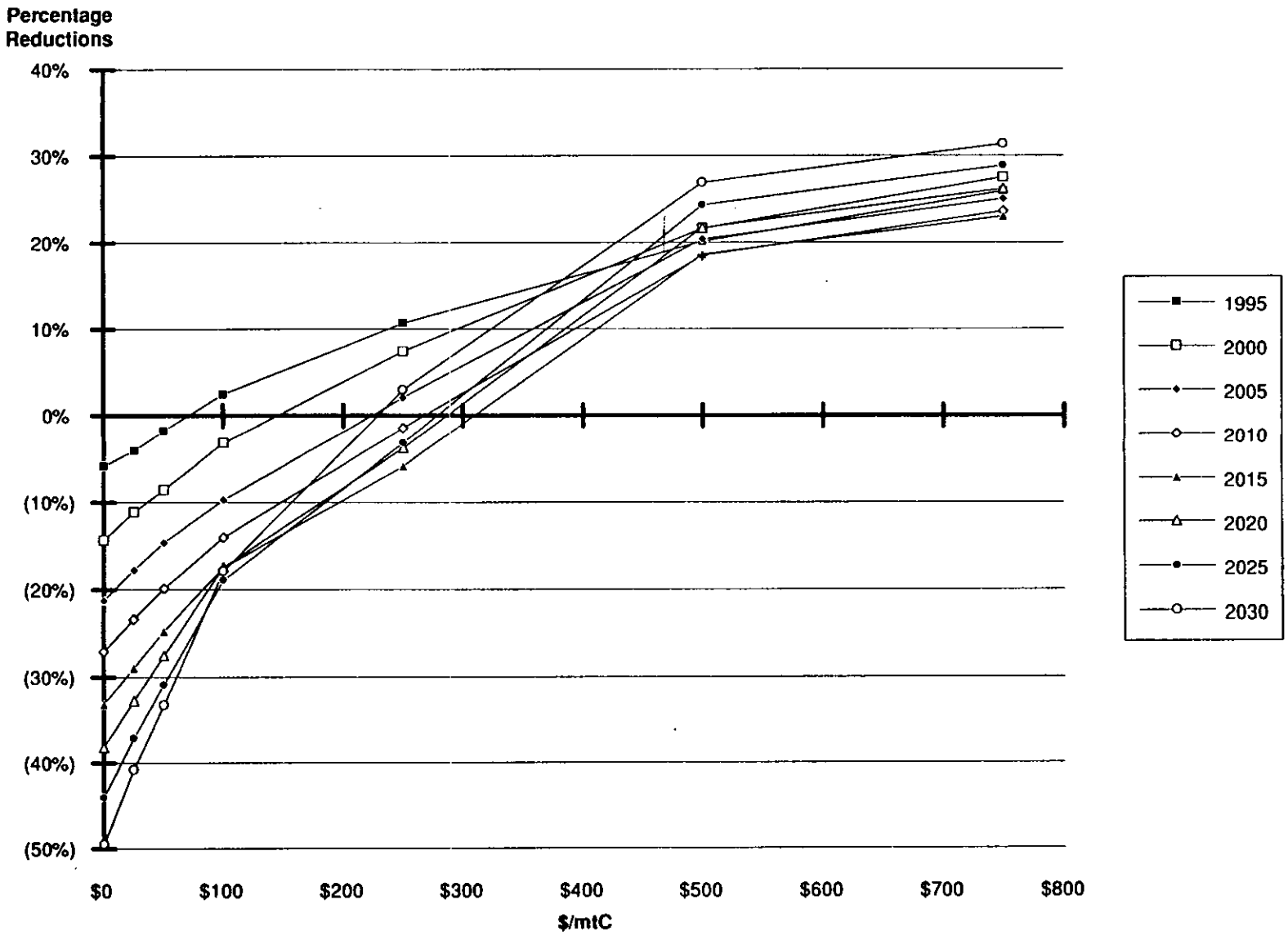

Figure 6.31. Carbon Taxes, NES Without Nuclear: % Carbon Emissions Reductions Relative to 1990 vs. Marginal Cost ($/mtC)

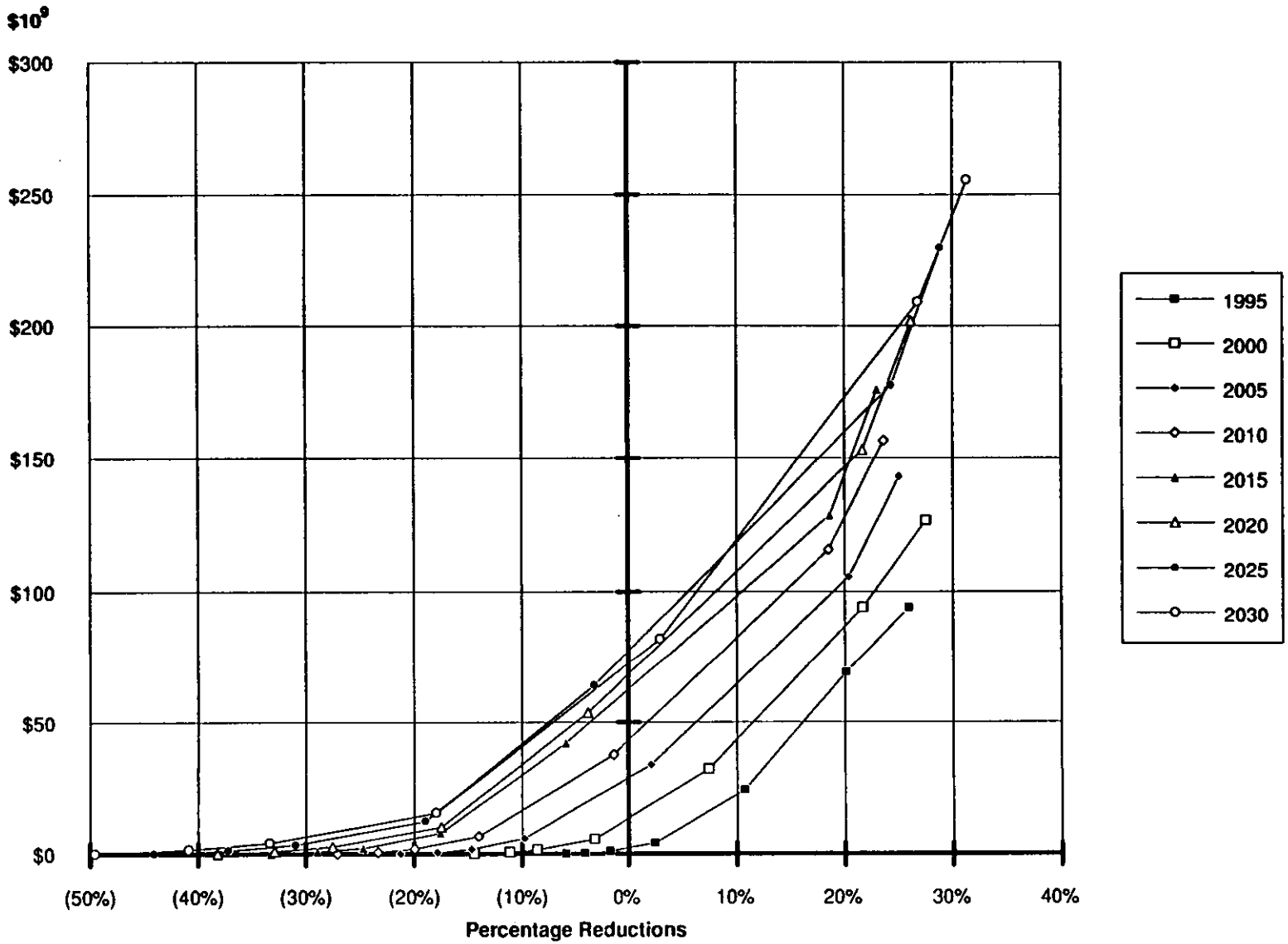

Figure 6.32. Carbon Taxes, NES Without Nuclear: Total Cost vs. % Carbon Emissions Reductions Relative to 1990

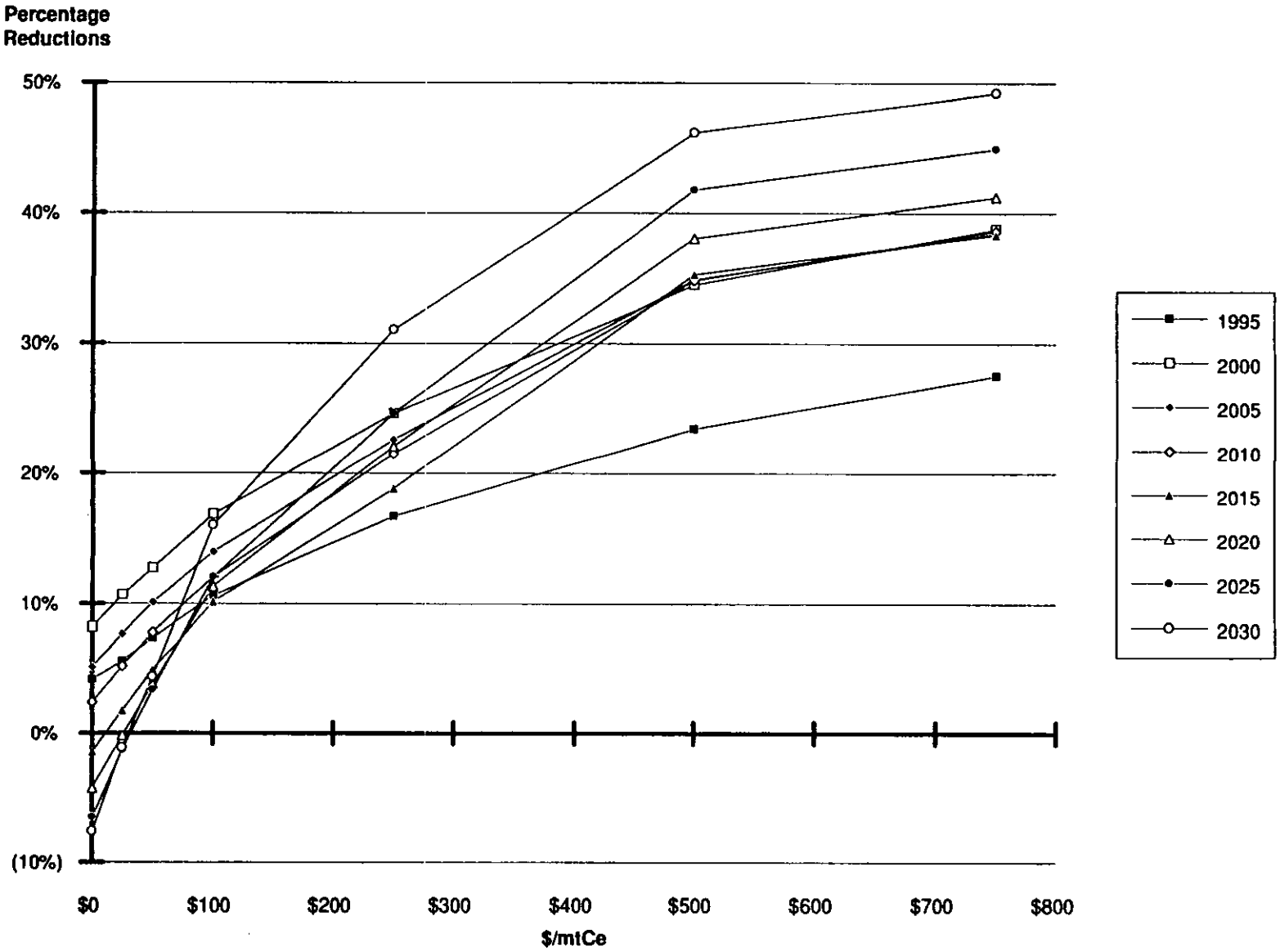

Figure 6.33. GWP Taxes, NES Without Nuclear: % GWP-Weighted Emissions Reductions Relative to 1990 vs. Marginal Cost

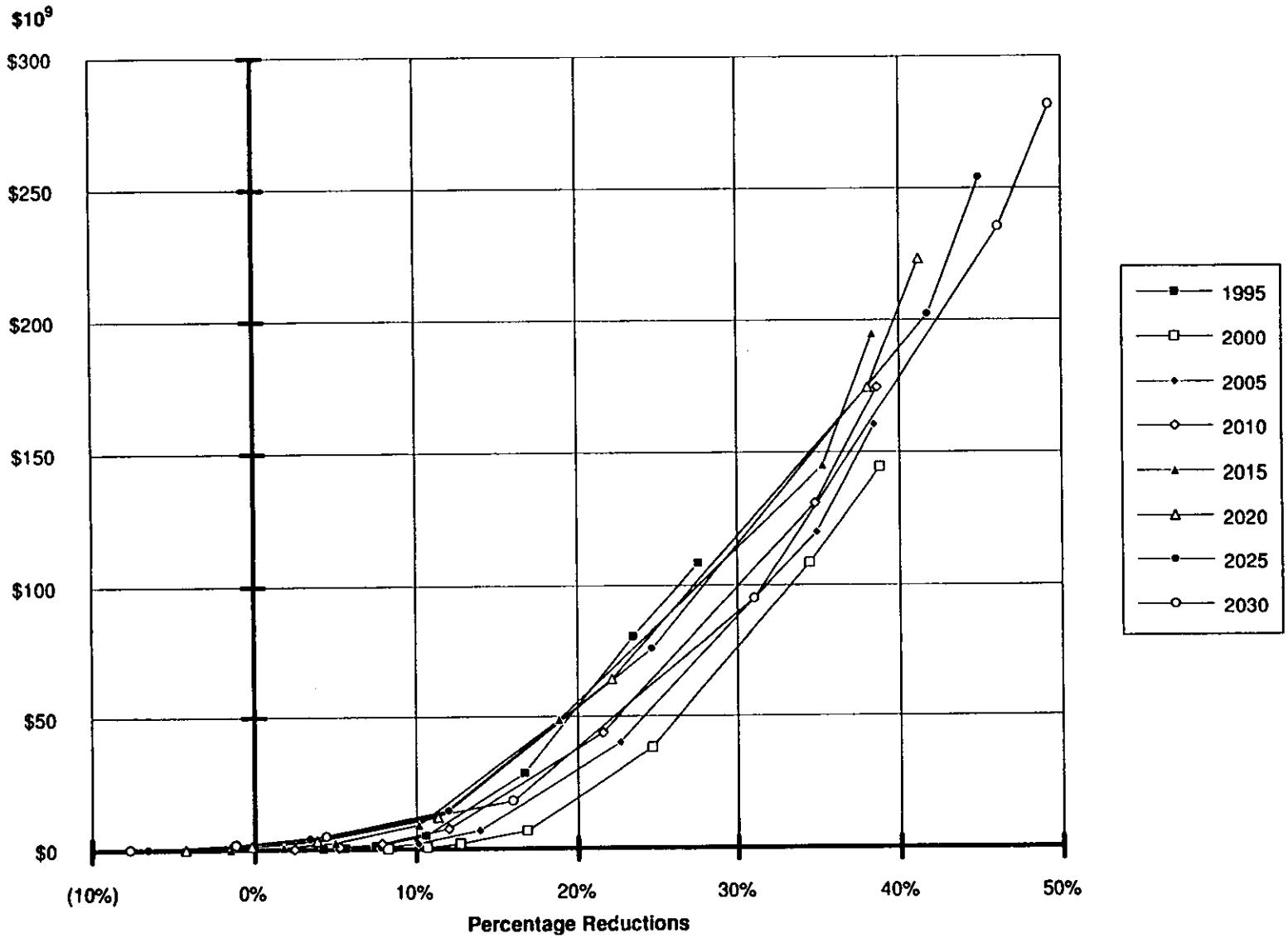

Figure 6.34. GWP Taxes, NES Without Nuclear: Total Cost vs. % GWP-Weighted Emissions Reductions Relative to 1990

7.0 REGULATORY INSTRUMENTS

7.1 INTRODUCTION

In Chapter 6, we considered fiscal policies in the form of taxes applied to fossil fuels based on their carbon content and on their contribution to total GWP. In this chapter, we explore individual policy instruments that are regulatory in nature. The regulatory policy measures studied in this chapter are:

1. Reforestation
2. Powerplant Efficiency Standards
3. Buildings Energy Efficiency Standards
4. Transportation Energy Efficiency Standards.

The first two policy measures primarily affect the electricity generating sector, while the remaining two are aimed at specific energy end-use sectors. The first measure, Reforestation, is evaluated in the context of a policy requiring all new major fossil fuel-fired stationary combustion facilities to plant trees to absorb the lifetime-equivalent new carbon emissions from the plants. The Powerplant Efficiency Standards require new fossil fuel powerplants to employ the most efficient generating technology available at the time of construction. Buildings Energy Efficiency Standards are efficiency requirements for heating, cooling, and other energy-consuming equipment in both residential and commercial buildings. The Transportation Energy Efficiency Standards are fuel efficiency standards for conventionally fueled light duty vehicles.

This set of measures illustrates some of the types of regulatory responses available for reducing greenhouse gas emissions. It is not intended to be an exhaustive list. For a more complete list of global climate change policy measures, see DOE (1989).

We also performed a sensitivity analysis on the costs and effectiveness of the reforestation strategy using the NES Actions Case without new nuclear power as an alternative reference point. We chose the Reforestation Case from the policies in this chapter for the sensitivity analysis because it is the most effective in reducing net greenhouse gas emissions.

Finally, we discuss the problem of reconciling work such as that presented here, which considers the entire energy-economy system and its interactions, with technology assessment studies such as NAS (1991), Carlsmith et al. (1990), Haites (1990), Goldemberg et al. (1987), and Cheng, Steinberg, and Beller (1985).

7.2 STANDARDS: REFORESTATION

7.2.1 Assumptions

The Reforestation Case is modeled as a requirement that mandates the planting of trees in the continental United States to fix or sequester the lifetime carbon emissions of all new fossil fuel powerplants. The reforestation policy also applies to all new industrial cogeneration and industrial steam facilities. The cost of tree planting is capitalized and added to the initial costs of constructing a fossil fuel powerplant. No specific regulatory instruments were considered as the basis for this analysis.

The costs and resource constraints used in this study are taken from a tree-planting study performed by the U.S. Forest Service (Moulton and Richards 1990). The Forest Service study examined the potential of capturing up to 725 TgC/yr by planting trees on up to 344 million acres in the United States. The analysis was performed by examining individual counties, matching appropriate trees to county-specific soils and growing conditions, and calculating full levelized costs incorporating land rental rates and maintenance costs.

However, major uncertainties are associated with the implementation and feasibility of a reforestation program of this magnitude. Several issues may prove

critical to a comprehensive evaluation of both the costs and the effectiveness of the policy; these need to be addressed. One significant issue is the problem of monitoring compliance with the policy. Monitoring would require implementation of a vast system of detailed regulations and procedures for demonstrating and verifying compliance. Enforcement may, in fact, require a system to monitor all land-use activities in the United States.

Another critical issue concerns the disposal of mature trees, which have reached the age at which they no longer sequester carbon at a sufficient rate. Burning the forests to clear land for further reforestation would have the net effect of re-releasing the captured carbon into the atmosphere. Harvesting the wood for commercial use might have undesirable economic effects on the domestic timber industry. With no tree disposal policy, however, all available land is eventually exhausted, and the reforestation policy becomes, in effect, a moratorium on fossil-fuel powerplants. Using this logic, it could be argued that reforestation is best considered a temporary strategy for reducing net carbon emissions while we make a long-term transition to less carbon-intensive fuels and more efficient processes.

The amount and type of land designated in the Forest Service study for potential reforestation should be viewed in relationship to the total land area of the United States in order to fully appreciate the magnitude of the reforestation program. The study found approximately 344 million acres in the United States that it considered for reforestation. Of this total, 79 million acres are forestland, 41 million acres are pastureland, and 224 million acres are cropland. Of the total cropland considered, 12 million acres are considered marginal cropland, 105 million acres are cropland with high soil erosion problems, and the remaining 112 million acres are wet cropland (with potential for groundwater contamination). As a comparison, the World Resources Institute (1990) reports that, in the United States, there is a total of 2265 million acres of land, of which 655 million are forestland, 597 million are pasture, and 469 million are currently classified as cropland. The amount of cropland designated for reforestation in the Forest Service study comprises almost half of the current total cropland in the United States. The point emphasized here is that a comprehensive understanding of the ramifications of a vast reforestation program must exist before such a program is implemented. An alternative reforestation scenario is discussed at the end of this section as a sensitivity analysis in which less land is available for foresting than stated in the Forest Service study.

The resource constraints and marginal costs of the Forest Service reforestation study have been incorporated into the Fossil2 Energy Model. Specifically, the cost assumptions for this option correspond to the High-Cost Trees Case discussed in Chapter 8, in which land rental rates are tripled as a conservatively high cost estimate. The reforestation option is invoked in Fossil2 by assigning the year in which the policy is assumed to be implemented.[a]

One limitation of the analysis is that the implication for land use is not integrated into a general equilibrium modeling framework that determines the cost of land in a realistic manner. There is, for example, no forward-looking behavior in the analysis. Nevertheless, work by Adams et al.[b] indicates that the effect on land prices of a realistic land market analysis, consistent with the work of Moulton and Richards, is bounded by the Moulton and Richards base case and triple land price case, with land prices closer to the base case in early years and closer to the triple land price case by the year 2030.

As reflected in Fossil2, the reforestation option reduces net carbon emissions in two ways. First, the cost of complying with the reforestation policy is added to the capital costs of the electricity-generating technologies that compete for market shares of new capacity in the model. For each technology, Fossil2 computes the cost of planting the trees that would be required to sequester the carbon emissions over the

(a) See Figures 8.1 and 8.16 in this volume for the Forest Service marginal and total cost data.

(b) Adams, D., R. M. Adams, J. M. Callaway, C. C. Chang and B. A. McCarl. 1991. *The Economics of Sequestering Carbon on Agricultural Land in the U.S.: A Preliminary Analysis of Social Cost and Impacts on Timber Markets.* Mimeo.

lifetime of a powerplant. This number is then converted into a capitalized cost component for new capacity of each generating technology. Powerplants that employ technologies and fuels having higher rates of carbon emissions are consequently subjected to higher cost requirements for reforestation. The cost of complying with reforestation is proportional to the rate of carbon emissions for each technology. This cost can therefore be considered equivalent to a carbon cost penalty or tax per unit of carbon emissions, which encourages the construction of less carbon-intensive generating technologies. The second way in which reforestation reduces net carbon emissions is directly through the sequestration or capture of carbon by the trees that have been planted. Fossil2 computes the amount of carbon sequestered each year by the trees that have been planted in compliance with the reforestation requirement.

7.2.2 A Comparison to the NES Actions Case

The implications of the Reforestation Case just described are discussed below with regard to energy prices, energy production, energy consumption, energy transformation, and greenhouse gas emissions.

Energy Prices

With the significant exception of coal, prices of all fuels are generally higher in all years under the Reforestation Case. Coal is more carbon-intensive than are oil and gas, so coal plants endure the highest penalty to capital costs from complying with reforestation. Coal technologies are therefore placed at a relative disadvantage in the market for new generating capacity, and the decline in coal price reflects its reduced demand in the electric utility sector. Correspondingly, the prices of natural gas and oil rise as the demand for these resources grows to meet the gap left by the cutback in coal plants.

Table 7.1 shows the energy price trajectory for the Reforestation Case over the time horizon of the study. The price of coal at the minemouth still rises slightly in this case, from $1.04/mBtu in 1990 to $1.38/mBtu in 2030, but its price in 2030 is 6% less than it is under the NES Actions in that same year. Similarly, the utility coal price is about 5% less in 2030 than for the NES Actions. The price of refiner crude oil is only slightly increased by reforestation, due to oil's relatively small share in electricity generation. However, the wellhead price of gas shows a marked increase, compared to the NES Actions. Natural gas has a lower carbon content than oil and coal, so the reforestation mandate makes the construction of natural-gas-burning electric plants more attractive in the market for new generating capacity. This enlarged demand for natural gas results in a wellhead price of $8.27/mBtu in 2030, a 13% increase over the NES Actions in the same year.

Table 7.1. Energy Prices in the Reforestation Case (1989$/mBtu)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.46	$3.46	$2.38	$1.07	$8.48
2000	$4.55	$4.55	$3.91	$1.11	$9.70
2005	$5.02	$5.02	$4.27	$1.13	$10.22
2010	$5.51	$5.51	$5.35	$1.22	$10.76
2015	$6.15	$6.15	$6.49	$1.27	$11.47
2020	$6.59	$6.59	$6.90	$1.33	$11.96
2025	$6.92	$6.92	$7.10	$1.35	$12.33
2030	$7.12	$7.12	$8.27	$1.38	$12.55

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.22	$1.69	$18.88	$20.06
2000	$7.69	$1.73	$20.85	$26.42
2005	$8.08	$1.75	$22.32	$29.12
2010	$9.10	$1.88	$22.36	$31.97
2015	$10.22	$1.96	$22.15	$35.65
2020	$10.66	$2.03	$23.41	$38.24
2025	$10.90	$2.05	$23.61	$40.16
2030	$12.00	$2.10	$23.45	$41.30

Energy prices in the end-use sectors generally follow the same pattern in this case. The price of gasoline is largely unaffected by reforestation, but the residential gas price is 8% higher than the NES value in 2030. Reforestation also results in higher costs for electricity. The average electricity price with reforestation grows from $18.70/mBtu in 1990 to

$23.45/mBtu in 2030, an 8% increase over the corresponding NES price in 2030 of $21.77.

Energy Consumption

The energy consumption results, shown in Table 7.2, are largely driven by the same market forces discussed in the previous section on energy prices. For the period of approximately 2000 to 2020, total energy consumption is lower than in the NES by approximately 1%. By 2030, however, the energy market appears to have readjusted to the reforestation mandate, and total primary consumption differs from the NES by less than 0.5%. In contrast, energy consumption by fuel changes dramatically compared to the NES.

The consumption of coal declines from 19 quads in 1990 to 18.2 quads in 2030, 44% less than the NES value in 2030 of 32.3 quads. Nuclear electric plants have no net emissions of CO_2, and the cost of building nuclear plants is therefore not penalized by the reforestation mandate. Thus, nuclear plants are placed at a significant advantage under this option. The annual consumption of nuclear fuel rises from 5.9 quads in 1990 to 20.6 quads by 2030. Compared to the NES Actions Case, nuclear energy consumption is a full 65% higher in 2030. As mentioned earlier, natural gas is the least penalized of the fossil fuels under reforestation. Gas consumption makes up much of the remaining gap (after nuclear energy) left by the reduction in coal consumption and is 14% higher than the NES in 2030. The consumption of renewable energy sources is also augmented by reforestation and increases to 25.3 quads in 2030, compared to 22.4 quads in the NES.

Energy Transformation

Because reforestation is a regulatory policy directed at electricity-generating facilities, the differences in energy consumption results between the Reforestation Case and the NES Actions Case are generally due to differences in energy input to electricity production. The decrease in coal consumption and the coinciding increase in nuclear energy consumption described in the previous section can be attributed almost entirely to their use in electricity generation. As shown in Figure 7.1, coal accounts for just over one-half of the energy used for electricity generation in 1990. In the NES Actions Case, coal's share declines just slightly to 49.4% in 2030, with nuclear power and natural gas comprising 21.5% and 6.8%, respectively. In the Reforestation Case, however, coal's share drops considerably to only 25% in 2030, while nuclear and gas climb to 35.4% and 11.2%, respectively. The use of renewable energy sources for electricity is also accelerated, claiming a

Table 7.2. Energy Consumption in the Reforestation Case (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.7	22.2	20.0	6.0	7.7	1.0	91.5
2000	35.8	24.8	21.6	6.2	9.1	1.2	98.8
2005	37.2	24.5	23.0	6.6	10.6	2.1	104.1
2010	38.0	24.1	25.0	7.1	12.2	3.4	109.8
2015	38.5	25.9	24.4	7.4	15.0	3.4	114.6
2020	38.2	25.7	22.0	11.0	18.9	3.5	119.3
2025	37.2	24.4	19.8	16.3	22.5	3.5	123.7
2030	36.5	22.9	18.2	20.6	25.3	3.5	127.1

25.9% share of the total in 2030 (compared to 21.1% in NES), while the share of oil-burning powerplants remains relatively insignificant. Table 7.3 shows electricity fuel consumption for all fuels over the study horizon in the Reforestation Case.

Table 7.3. Electricity Fuel Consumption in the Reforestation Case (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.6	5.3	17.1	6.0	4.6	34.7
2000	1.0	6.8	18.6	6.2	5.6	38.3
2005	1.1	6.3	19.7	6.6	6.5	40.3
2010	1.2	6.2	21.4	7.1	7.3	43.2
2015	1.8	8.3	20.6	7.4	8.4	46.5
2020	2.0	8.6	18.3	11.0	10.9	50.9
2025	1.6	7.2	16.1	16.3	13.2	54.5
2030	1.5	6.5	14.6	20.6	15.1	58.3

End-Use Energy Consumption

Although it directly affects only the electricity generating plants, the Reforestation Case impacts end-use energy consumption by changing the prices of electricity and end-use fuels. As with total primary energy consumption, reforestation decreases total end-use energy consumption slightly relative to the NES, but consumption stabilizes by 2030, when it is within 1% of the corresponding NES value. The relative contribution of each end-use sector to the total energy consumed is not significantly different from that found in the NES Actions Case.

Table 7.4 shows energy consumption by fuel in the residential sector. The share of electricity is reduced from 5.4 quads under the NES in 2030 to 5.2 quads with reforestation. Residential natural gas consumption rises slightly to make up the energy gap left by the electricity use reduction. Energy consumption in the commercial sector is given in Table 7.5. In the commercial sector, the total energy consumed across all fuels decreases by 0.1 quads in 2030 with reforestation. This total is the result of a 0.2 quad or 4% decrease in electricity countered by a 0.1 quad increase in oil consumption. Table 7.6 shows industrial sector energy consumption by fuel. The same pattern is clear here. Electricity consumption is reduced slightly, while oil use grows to make up some of the difference. The fourth major end-use sector, transportation, is affected only to the extent that increased oil prices reduce the demand for motor fuels, a 1% difference from the NES in 2030. Reforestation results in minimal or no changes in coal and renewables consumption in each of the end-use sectors.

Table 7.4. Residential Energy Consumption in the Reforestation Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.6	4.9	0.1	0.9	3.2	10.7
1995	1.3	4.8	0.1	1.0	3.5	10.8
2000	1.2	5.1	0.1	1.1	3.8	11.3
2005	1.0	5.2	0.1	1.2	4.0	11.5
2010	1.0	5.2	0.1	1.4	4.2	11.8
2015	0.9	5.1	0.1	1.5	4.5	12.0
2020	0.8	5.0	0.1	1.6	4.8	12.2
2025	0.8	4.9	0.1	1.7	5.0	12.4
2030	0.7	4.7	0.1	1.8	5.2	12.5

Table 7.5. Commercial Energy Consumption in the Reforestation Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.0	2.8	0.1	0.1	2.9	6.9
1995	0.9	2.7	0.1	0.1	3.4	7.2
2000	0.8	2.8	0.1	0.1	3.9	7.7
2005	0.8	2.8	0.1	0.1	4.3	8.1
2010	0.8	2.8	0.1	0.2	4.8	8.7
2015	0.8	2.9	0.0	0.2	5.4	9.3
2020	0.8	2.9	0.0	0.3	5.8	9.8
2025	0.8	3.0	0.0	0.3	6.3	10.4
2030	0.8	3.0	0.0	0.4	6.7	11.0

Table 7.6. Industrial Energy Consumption in the Reforestation Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	8.7	8.2	2.8	1.8	3.1	24.6
1995	9.3	8.8	2.6	1.8	3.5	25.9
2000	9.6	9.2	2.7	2.1	4.0	27.6
2005	10.3	9.0	3.1	2.4	4.1	28.8
2010	11.2	8.5	3.4	2.7	4.2	30.1
2015	11.8	8.3	3.5	3.0	4.4	31.0
2020	12.4	8.0	3.5	3.2	4.7	31.9
2025	13.1	8.0	3.5	3.6	5.0	33.2
2030	14.2	7.4	3.4	3.9	5.4	34.3

Table 7.7. Energy Supply in the Reforestation Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.8	20.3	22.6	6.0	7.7	72.4
2000	18.3	22.5	24.9	6.2	9.1	81.1
2005	22.0	21.6	27.3	6.6	10.6	88.2
2010	21.5	21.2	30.8	7.1	12.2	92.9
2015	17.7	23.1	30.8	7.4	15.0	94.0
2020	15.0	23.1	28.8	11.0	18.9	96.9
2025	12.6	21.8	26.9	16.3	22.5	100.1
2030	11.0	19.9	19.9	20.6	25.3	102.2

Energy Production and International Trade

Total indigenous energy production is projected to be 102.9 quads in 2030 under the NES Actions Case. In the Reforestation Case, total production decreases by only about 1%, to 102.2 quads. As with energy consumption, though, reforestation results in dramatic adjustments of the contribution of individual fuels to the total energy supply. Total indigenous energy supply by fuels is shown in Table 7.7. Again, the greatest impact is on coal. Indigenous coal production grows slowly from 21.6 quads in 1990 to 25.4 quads in 2030 with reforestation, compared to an increase to 39.5 quads in the NES. The supply of nuclear energy is higher by 8.1 quads in 2030 to compensate for much of the difference. Renewables and gas also increase their shares of total production relative to the NES in 2030, from 22% to 25% and from 17% to 20%, respectively.

Net energy imports are up by 1.2 quads, relative to the NES, in 2030 to 21.3 quads, as shown in Table 7.8. Natural gas imports rise to 3 quads, compared to 2.6 quads in the NES in 2030. Oil imports also increase slightly, from 24.8 quads to 25.5 quads. Note that no explicit consideration is given to international trade issues. No change is assumed in energy trade policies, but Fossil2 treats the United States as an essentially closed economy. Coal exports do not change in the Reforestation Case, but this phenomenon is an artifact of the Fossil2 Model. In actuality,

Table 7.8. Energy Trade in the Reforestation Case (quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	6.5	1.4	(2.6)	0.1	0.0	15.4
1995	18.9	1.9	(2.6)	0.2	0.7	19.1
2000	17.4	2.3	(3.3)	0.2	1.0	17.7
2005	15.0	2.8	(4.3)	0.2	1.9	15.9
2010	16.4	3.0	(5.8)	0.2	3.2	17.0
2015	21.2	3.1	(6.4)	0.3	3.2	20.7
2020	23.5	2.7	(6.8)	0.3	3.2	22.5
2025	25.0	2.9	(7.1)	0.3	3.2	23.6
2030	26.0	3.4	(7.2)	0.4	3.2	24.8

it is reasonable to assume that coal exports would increase at least slightly with a scenario such as this one, which penalizes domestic coal use. Similarly, though there would be an incentive to import electricity directly, energy trade in the Fossil2 Model is relatively price insensitive.

Greenhouse Gas Emissions

Reforestation has a profound effect on net energy-related greenhouse gas emissions. The Reforestation Case is unique among the policies studied because it involves a mechanism for carbon emissions uptake (i.e., a physical sink for removal of CO_2 from the atmosphere--the planting of trees), rather than

relying entirely on economic policies or standards aimed at reducing the consumption of fossil fuels. The resulting carbon emissions in this case should be considered net carbon emissions because, for each type of fossil fuel-burning powerplant, the totals account for carbon uptake from the trees planted in compliance with the reforestation mandate.

Table 7.9 shows net CO_2 emissions (by carbon weight) for the Reforestation Case. Total net carbon emissions are reduced considerably, compared to the NES Actions Case. The total of 841 TgC in 2030 is more than 50% lower than for the NES in the same year. Net emissions from coal undergo the largest reduction with a 2030 value of 64 TgC, a full 92% reduction relative to the NES in the same year. Coal is hit the hardest, not only because it has the highest carbon content, but because its largest demand comes from electric utilities. Net emissions from gas and oil are also reduced, but not to the same extent as coal. Carbon emissions from oil are almost unaffected by reforestation because the bulk of demand for oil lies outside the electric utility sector.

Although the primary impact of reforestation is to reduce CO_2 emissions, methane emissions are also affected. Methane emissions by source for this case are shown in Table 7.10. Due to the reduced demand for coal, methane emissions from coal mining are reduced sharply compared to the NES Actions Case. Emissions from natural gas production and natural gas transmission and distribution, however, are about 13% higher in 2030 than in the NES. This increase is due to the increased demand for natural gas, which is penalized the least of the fossil fuels under reforestation. The total methane emissions do decrease in this case and at 13.9 $TgCH_4$ in 2030, are 10% lower than in the NES Actions Case. Methane emissions rates from coal mining and natural gas production, transmission and distribution are, of course, less certain than carbon emissions (Chapter 3).

Figure 7.2 displays the energy-related GWP results of the Reforestation Case. As expected from the CO_2 emissions results, the relative contribution to total GWP from CO_2 is greatly diminished over time. Reforestation results in 47% reduction in total annual GWP by 2030 from the 1990 value, which ranks it clearly among the most effective cases in this study for reducing energy-related GWP. Energy-related GWP results are shown by greenhouse gas in Table 7.11.

Table 7.9. Carbon Emissions in the Reforestation Case (by fuel--TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total	Carbon Emissions Reduction (% 1990)	Carbon Emissions Reduction (% from NES Actions)
1990	546	274	477	2	1299	--	--
1995	539	298	461	3	1301	0%	5%
2000	542	292	330	5	1169	10%	21%
2005	560	260	206	8	1034	20%	34%
2010	570	241	160	8	978	25%	40%
2015	573	227	116	11	926	29%	45%
2020	567	213	80	22	882	32%	48%
2025	559	212	68	25	864	34%	49%
2030	550	203	64	25	841	35%	51%

Table 7.10. Methane Emissions in the Reforestation Case ($TgCH_4/yr$)

Year	Coal Mines	Natural Gas Product	Natural Gas Trans. & Dist.	Total
1990	4.1	2.1	5.6	11.8
1995	4.3	2.4	6.5	13.2
2000	4.8	2.6	7.2	14.6
2005	5.2	2.5	7.1	14.9
2010	5.9	2.5	7.0	15.4
2015	5.9	2.7	7.6	16.1
2020	5.5	2.7	7.5	15.7
2025	5.1	2.6	7.1	14.8
2030	4.8	2.3	6.7	13.9

7.2.3 The Cost of Greenhouse Gas Emissions Reductions

Approach to Computing Cost

As discussed in the introduction to this section, in many ways the reforestation regulation is like a carbon tax on new and newly life-extended fossil fuel capacity. Net carbon emissions are reduced in the Reforestation Case relative to the Reference Case for two reasons. The first is sink enhancement--trees absorb and sequester carbon. The relationship between cost and emissions reductions can be established and separated from other costs and emissions reductions. The second important feature is the price effect. The added cost of bringing on-line a new fossil fuel powerplant, relative to other forms of electric power generation, encourages the adoption of non-fossil power technologies, and makes the electric utility industry less carbon-intensive. In addition, the added cost of new powerplants, both fossil and non-fossil fuel, raises the price of electricity. This encourages final consumers to conserve electricity, including power produced by existing fossil-fueled powerplants. At the point of end-use, the added cost also encourages a substitution away from electricity in favor of other fuels, including non-fossil.

The calculation of the total cost of carbon emissions reductions can be thought of as the sum of two components: reductions from sink enhancement and reductions from fuel substitution and conservation. The relevant marginal cost schedule can therefore be separated into two parts. The marginal cost schedule for carbon emissions reductions is taken from Moulton and Richards (1990). The marginal cost schedule for emissions reductions resulting from the higher cost of new fossil fuel powerplants must be derived.

Since the effect of reforestation is to apply a carbon fee to new fossil fuel powerplant capacity, the cost of the price effect, fuel substitution, and energy

Table 7.11. GWP-Weighted Energy-Related Emissions by Gas and by Year in the Reforestation Case ($TgCO_2$ Equivalent)

Year	CO_2	CO	CH_4	N_2O	CFCs & Oth	HCFCs	GWP	% Reduction from NES Actions
1990	4527	455	626	17	1657	144	7458	--
1995	4531	455	493	18	1062	326	6885	4%
2000	4073	409	554	19	306	299	5715	16%
2005	3602	362	586	21	326	254	5150	27%
2010	3407	342	605	22	179	366	4922	32%
2015	3227	324	612	22	58	458	4701	37%
2020	3073	309	597	20	5	470	4473	40%
2025	3008	302	566	19	3	350	4249	42%
2030	2931	294	535	17	2	172	3952	44%

conservation can be computed by applying carbon fees to new fossil fuel capacity and using this information to map out the relevant marginal cost schedule. The construction of the relevant marginal cost schedule for the carbon fee on new fossil fuel powerplant capacity is a variation on the approach taken in Chapter 6 in the computation of marginal and total cost of carbon emissions reductions resulting from a simple carbon tax. This case differs from the simple carbon tax in one important regard: the tax rate increases from period to period. The calculation of total cost has been modified somewhat from the approach described in Chapter 6 to account for the non-constant carbon fee. (See Appendix K.)

One of the interesting implications of this analysis is that the least-cost approach to achieving any specific goal in any particular year is to set in place the optimal tax rate at the earliest possible point in time and then leave that rate in effect until the desired terminal date. This does not mean that a fixed carbon tax is optimal. It would be optimal only under limited circumstances; it is therefore not dynamically optimal. The construct of a dynamic optimum requires some mechanism for evaluating intervening states. Furthermore, it says nothing about the costs of adjustment. For example, a sudden, large change in prices may require substantial economic adjustment. A sudden, large reallocation in economic resources to shift from one sector to another could result in substantial dislocations, that is, unemployment of resources. Fossil2 makes no allowance for such adjustment costs.

The Cost of Carbon Emissions Reductions

The methods described above can be applied to compute the total cost associated with carbon emissions reductions from this policy instrument. Table 7.12 displays total costs of carbon emissions reductions and associated energy system and reforestation components. Note that the role of forests is extremely important in reducing emissions in the early years, but declines in later years.

In 1995, the cost from reforestation of reducing carbon emissions by 75 million metric tonnes of carbon, relative to the NES Actions Case, is about

Table 7.12. The Total Cost of Carbon Emissions Reductions From Reforestation

Year	Carbon Emissions Reduction (TgC/yr)[a]	Reforestation Carbon Uptake (TgC/yr)	(%)[b]	Total Cost in Billions of 1989$ Energy	Reforestation	Total
1995	75	74	99%	0.0	1.0	1.0
2000	317	302	95%	0.2	7.4	7.6
2005	539	495	92%	0.8	15.3	16.1
2010	662	612	92%	1.1	21.6	22.7
2015	769	690	90%	2.4	28.0	30.4
2020	827	685	83%	5.6	27.6	33.2
2025	846	619	73%	8.3	22.1	30.4
2030	866	571	66%	10.0	19.0	29.0

(a) Relative to the NES Actions Case.

(b) Percent of carbon emissions reduction, relative to the NES Actions Case, provided by carbon uptake by forests in reforestation program.

$1.0 billion; in 2030, the cost of reducing carbon emissions by 868 million metric tonnes increases to $29.0 billion.

The relationship between marginal, average, and total cost and emissions reductions, relative to 1990 levels, is displayed in Table 7.13. The Reforestation Case yields net fossil fuel carbon emissions reductions, relative to 1990, in all years.

From Table 7.13, note that the marginal cost of carbon emissions never exceeds $94/mtC and that the average cost never exceeds $40/mtC. This single policy achieves a 32% emissions reduction relative to 1990 levels by the year 2020, and these reductions are not eroded during the course of the following decade. Table 7.14 also shows the total costs of emissions reductions from reforestation, but in terms of energy-related GWP rather than just carbon emissions reductions.

From Table 7.14, trees provide almost all the net GWP reduction in the early years, but their contribution decreases to 67% by 2030. The reforestation policy achieves a 23% reduction in GWP, relative to 1990, by the year 2000 with a total cost of $8 billion. At a total cost of $29 billion in 2030, this single policy instrument achieves a 47% reduction in GWP from 1990 levels.

Table 7.13. The Relationship Between Marginal, Average and Total Costs of Net Carbon Emissions Reductions from Reforestation

Year	Marginal Cost ($/mtC)	Average Cost ($/mtC)	Total Cost (bil$/yr)	Emission Reduction (% 1990)
1995	18	13	1	0%
2000	41	24	8	10%
2005	51	30	16	20%
2010	87	34	23	25%
2015	94	40	30	29%
2020	94	40	33	32%
2025	88	36	30	34%
2030	80	33	29	35%

Table 7.14. The Total Cost of Energy-Related GWP Reductions from Reforestation

Year	Net Energy-Related GWP Reduction ($TgCO_2e/yr$)[a]	Reforestation GWP Uptake ($TgCO_2e/yr$)	Total Cost (%)[b]	GWP Reduction (bil$/yr)	(% 1990)
1995	258	271	105%	1	8%
2000	1128	1107	98%	8	23%
2005	1914	1815	95%	16	31%
2010	2311	2244	97%	23	34%
2015	2721	2530	93%	30	37%
2020	2958	2512	85%	33	40%
2025	3044	2270	75%	30	43%
2030	3130	2094	67%	29	47%

(a) Relative to the NES Actions Case.

(b) Ratio of GWP reduction, relative to the NES Actions Case, provided by carbon uptake by forests in reforestation program. The ratio may exceed 100% when other greenhouse gases besides carbon dioxide increase and counteract some of the reduction in GWP from reforestation.

7.2.4 Sensitivity Analysis: Reforestation, NES Actions Without Nuclear

As we did for the tax cases in Chapter 6, we have conducted a sensitivity analysis on the Reforestation Case using the NES Actions with no new and no life-extended nuclear capacity. The effect of this analysis is to define a different starting point from which carbon emissions are to be reduced. The baseline carbon emissions trajectory for the NES Actions without nuclear scenario is provided in Chapter 5.

Energy Prices

Table 7.15 shows the projected energy prices for the reforestation without nuclear scenario. From the table, the resource fuel prices are all higher than the projections for both the NES Actions Case and the Reforestation Case (Reforestation Case will refer to the Reforestation Case constructed with the NES Actions Case results as its baseline). Without the growth in nuclear power, the demand for gas rises and pushes its price to $9.06/mBtu in 2030, an increase of 24% relative to the NES Actions Case. The price of oil is not affected greatly here, and the price of coal at the minemouth is depressed by only about 11% relative to the NES Actions projection in 2030.

Table 7.15. Energy Prices in the Reforestation Case, NES Without Nuclear (1989$/mBtu)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.46	$3.46	$2.38	$1.07	$8.48
2000	$4.55	$4.55	$3.92	$1.11	$9.70
2005	$5.02	$5.02	$4.27	$1.13	$10.22
2010	$5.51	$5.51	$5.38	$1.22	$10.76
2015	$6.13	$6.13	$6.44	$1.29	$11.46
2020	$6.55	$6.55	$6.88	$1.35	$11.92
2025	$6.94	$6.94	$8.40	$1.37	$12.35
2030	$7.17	$7.17	$9.06	$1.41	$12.61

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.22	$1.69	$18.88	$20.06
2000	$7.69	$1.73	$20.98	$26.42
2005	$8.08	$1.75	$22.68	$29.11
2010	$9.13	$1.88	$23.10	$31.95
2015	$10.17	$1.97	$23.17	$35.57
2020	$10.63	$2.05	$25.52	$37.99
2025	$12.11	$2.08	$27.65	$40.27
2030	$12.74	$2.14	$28.67	$41.60

The absence of new nuclear generating capacity has a major impact on the price of electricity. At $28.87/mBtu in 2030, the average price of electricity in this case is projected to be a full 32% highly than in the NES Actions Case. In the Reforestation Case (with nuclear), this price difference in 2030 was just 8%. The residential gas price is also higher here, due to the increased demand for gas for electricity generation.

Energy Consumption

In the Reforestation Case, nuclear energy consumption is projected to reach 20.6 quads/yr in 2030. Without this nuclear power, two effects are evident. As shown in Table 7.16, one major effect is that total energy consumption declines relative to the NES Actions Case, reaching 122 quads in 2030, compared to approximately 126 quads under the NES Actions. The remaining gap left by the absence of nuclear is met through increases in the demand for fossil fuels and renewable energy sources.

Without nuclear power, coal consumption declines, but not as much as it does in the Reforestation Case with nuclear power, reaching 22 quads in 2030--about 4 quads higher than in the Reforestation Case. Gas consumption also increases by about 4 quads in 2030. The rest of the gap left by nuclear power's absence is filled by a 7-quad increase in the consumption of renewable energy sources.

Greenhouse Gas Emissions

The net carbon emissions and net GWP-weighted greenhouse gas emissions for this case are provided in Tables 7.17 and 7.18, respectively. There is little difference between the emissions shown here and the emissions under the Reforestation Case constructed

Table 7.16. Energy Consumption in the Reforestation Case, NES Without Nuclear (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.7	22.2	20.0	6.0	7.7	1.0	91.5
2000	35.8	24.8	21.5	6.2	9.1	1.2	98.8
2005	37.2	24.5	22.9	6.4	10.7	2.1	104.1
2010	37.9	24.2	25.2	6.4	12.3	3.4	109.8
2015	38.2	25.5	25.4	4.5	16.7	3.4	114.6
2020	37.6	25.9	24.4	3.5	22.8	3.5	119.3
2025	37.8	27.8	22.9	1.8	28.2	3.5	123.7
2030	37.1	26.7	22.0	0.4	32.3	3.5	127.1

Table 7.17. Reforestation, NES Actions Without Nuclear Case: Carbon Emissions by Fuel (TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total
1990	546	274	477	2	1299
1995	539	298	461	3	1301
2000	542	391	329	5	1168
2005	560	260	205	8	1033
2010	570	242	160	9	979
2015	571	226	128	18	944
2020	566	219	95	33	913
2025	560	216	77	34	886
2030	552	207	73	33	865

with the full NES Actions results as the baseline. For the NES Actions results with nuclear power, emissions are slightly lower in the later years when the growth in new nuclear capacity has its impact.

Costs of Greenhouse Gas Emissions Reductions

As in the carbon and GWP tax cases in Chapter 6, the effect of the assumption about nuclear power has its greatest impact on the cost to meet emissions reductions targets in the later years of the study. Tables 7.19 and 7.20 summarize the cost results for the sensitivity case. Comparing these figures with the results with the full NES Actions baseline, significant differences in total costs start after 2010. By 2030, the total cost is about 70% higher than in the Reforestation Case constructed with the full NES results baseline.

7.2.5 Sensitivity Analysis: Reforestation with Reduced Land Availability

Assumptions

In acknowledgement of the uncertainty associated with the reforestation policy, we have also constructed a conservative sensitivity analysis, an alternative reforestation scenario in which the available land is reduced from the amount stated in the Forest Service study (Moulton and Richards 1990). This

Table 7.18. Reforestation, NES Actions Without Nuclear Case: GWP-Weighted[a] Energy-Related Greenhouse Gas Emissions ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs[b]	HCFCs[c]	Total
1990	4528	455	626	17	1689	144	7459
1995	4531	455	493	18	1062	326	6885
2000	4068	409	554	19	360	299	5710
2005	3597	361	585	20	326	254	5144
2010	3411	343	607	22	179	366	4928
2015	3288	330	613	22	58	458	4769
2020	3180	320	608	21	5	470	4604
2025	3087	310	606	21	3	350	4378
2030	3013	303	582	20	2	172	4091

(a) 100-year integration period.
(b) CFCs include CH_3, CCl_3, CCl_4, and halons.
(c) HCFCs include HCFC and HFC.

Table 7.19. The Total Cost of Carbon Emissions Reductions From Reforestation, NES Actions Without Nuclear

Year	Carbon Emissions Reduction (TgC/yr)[a]	Reforestation Carbon Uptake (TgC/yr)	(%)[b]	Total Cost in Billions of 1989$ Energy	Reforestation	Total
1995	75	74	99%	0.0	1.0	1.0
2000	319	302	95%	0.2	7.4	7.4
2005	543	493	91%	0.9	15.3	15.6
2010	672	617	92%	1.2	21.6	22.0
2015	787	693	88%	2.9	28.0	30.1
2020	882	713	81%	6.3	36.3	41.8
2025	985	742	75%	9.5	38.1	46.8
2030	1077	717	67%	14.8	36.7	50.7

(a) Relative to the NES Actions Case.
(b) Percent of carbon emissions reduction, relative to the NES Actions Case, provided by carbon uptake by forests in reforestation program.

scenario, which will be referred to as the "Reforestation with Reduced Land Case," uses the Forest Service cost data with land rental at three times the market value (high-cost trees, as before), but assumes that only one-half of the carbon sequestration potential is available at each level of cost. This strategy is thought to provide a lower bound on the carbon reduction potential of the reforestation policy.

In this chapter, the interpretation of the reforestation policy under the reduced land constraint is not altered; that is, new fossil fuel-fired electric plants

Table 7.20. The Relationship Between Marginal, Average, and Total Costs of Net Carbon Emissions Reductions for Reforestation, NES Actions Without Nuclear

Year	Marginal Cost ($/mtC)	Average Cost ($/mtC)	Total Cost (bil$/yr)	Emissions Reduction (% 1990)
1995	18	13	1	0%
2000	41	23	7	10%
2005	51	29	16	20%
2010	87	33	22	25%
2015	94	38	30	27%
2020	96	47	42	30%
2025	104	48	47	32%
2030	96	47	51	33%

may not be constructed without a compensating offset in carbon emissions through the planting of trees. In the original Reforestation Case, the total amount of carbon emissions from electricity generation never exceeds the total carbon sequestration available from trees. In the Reforestation with Reduced Land Case, however, the available sequestration potential quickly becomes a binding constraint. The reforestation policy, interpreted strictly, thus becomes a *de facto* (and *de jure*, for that matter) moratorium on new fossil fuel-fired capacity. The effect of the reforestation policy in either case is to eliminate the net carbon emissions from electricity generation by the end of the study period. The difference in effectiveness between these two cases is mainly the difference in the costs associated with achieving this reduction in carbon emissions.

This approach differs from that taken in the GWP Tax with Deposit Refund Case discussed in Chapter 8 of this volume. In Chapter 8, a similar sensitivity analysis is conducted for the Deposit Refund Case with the same assumption, that only one-half of the carbon sequestration potential is available at each level of cost. The effect of this land availability constraint is much simpler to quantify in that case. Specifically, the constraint results in a smaller pool of carbon sequestration from which the fossil fuel taxes can be offset. Beyond the point at which the maximum carbon sequestration has been used, the case becomes a simple fossil fuel carbon tax case, as in Chapter 6 of this volume.

The Reforestation with Reduced Land Case was modeled in Fossil2 by incorporating a cost curve of available carbon sequestration from trees, as before, but modifying it to account for the different land availability. As described above, the reforestation policy as interpreted in this chapter becomes a fossil fuel-fired electricity moratorium when all available sequestration potential is exhausted. The moratorium was modeled by applying an extreme cost penalty on fossil fuel capacity at points above the maximum of the sequestration supply curve. Even at extreme costs, however, it was not feasible, in the Fossil2 Model, to completely drive new fossil fuel capacity out of the market. Non-fossil fuel capacity was not able to come into operation at a rate sufficient to meet the growing electricity demand. For the Reduced Land Case reported below, it became necessary to allow the reforestation to exceed the intended maximum of 363 TgC/yr (one-half of the original 725 TgC/yr) in some years, though at extremely high costs, to compensate for the new fossil fuel capacity in excess of the intended limit.

Cost of Carbon Emissions Reductions

Tables 7.21 and 7.22 show the net carbon emissions reduction and associated costs for the Reforestation with Reduced Land Case. As expected, there is little difference in the net carbon emissions reduction (and, consequently, GWP-weighted emissions) between this case and the original Reforestation Case. The reforestation mandate has the effect of eliminating the net carbon emissions from electricity generation by the end of the study period; therefore, both cases have approximately the same emissions reduction, relative to the NES Actions Case. The slight difference comes from the differences in feedback of electricity prices to the end-use sectors. However, as these tables demonstrate, the associated costs are much higher in the Reduced Land Case.

Table 7.21. The Total Cost of Carbon Emissions Reductions from Instrument with Reduced Land Availability

Year	Carbon Emissions Reduction (TgC/yr)[a]	Reforestation Carbon Uptake (TgC/yr)	(%)[b]	Total Cost in Billions of 1989$ Energy	Reforestation	Total
1995	76	74	98%	0.0	3.3	3.3
2000	320	297	93%	1.6	25.0	26.6
2005	582	405	70%	42.9	38.1	81.0
2010	685	394	57%	96.8	38.1	134.9
2015	750	478	64%	64.8	38.1	102.9
2020	800	545	68%	32.0	38.1	70.1
2025	824	483	59%	39.7	38.1	77.8
2030	837	420	50%	47.1	38.1	85.2

(a) Relative to the NES Actions Case.
(b) Percent of carbon emissions reduction, relative to the NES Actions Case, provided by carbon uptake by forests in reforestation program.

Table 7.22. The Relationship Between Marginal, Average, and Total Costs of Net Carbon Emissions Reductions for Reforestation with Reduced Land Availability

Year	Marginal Cost ($/mtC)	Average Cost ($/mtC)	Total Cost (bil$/yr)	Emission Reduction (% 1990)
1995	30	42	3	0%
2000	165	82	27	10%
2005	1548	138	81	24%
2010	1395	196	135	26%
2015	2473	136	103	27%
2020	3323	87	70	30%
2025	2536	94	78	32%
2030	1734	101	85	33%

The sensitivity analysis demonstrates that a strict reforestation program would be extremely expensive, in the absence of other mitigation strategies, if the amount of available land were much less than that stated in the Forest Service study. However, some caution should be used in interpreting the cost figures shown. As Table 7.21 indicates, the bulk of the total cost is the energy cost portion or the cost to restrict fossil fuel capacity entering the market. A moratorium on fossil fuels in the near future is an extreme case to replicate in the Fossil2 Model, and the cost results for such a policy cannot reflect the major changes in the energy economy that would surely occur if the policy were enacted. These extreme levels of cost do not occur when the sensitivity analysis is applied to the GWP Tax with Deposit Refund Case discussed in Chapter 8. In that case, consumers are still allowed to use fossil fuels when all of the available land has been planted, but they must pay a tax to do so.

7.2.6 Summary of Findings: Reforestation Case

The Reforestation Case is potentially an extremely powerful regulatory instrument for reducing net carbon emissions and energy-related GWP. Net carbon emissions are stabilized almost immediately and continue to decrease, reaching a 35% reduction from 1990 levels by the year 2030. GWP-weighted emissions are also reduced substantially, a full 47% from 1990 values in 2030. The marginal and average costs of carbon emissions reductions from reforestation over the study period do not exceed $94/mtC and $40/mtC, respectively, which makes the Reforestation Case a relatively inexpensive measure for reducing

net carbon emissions. As noted in the assumptions section for the Reforestation Case, there are critical issues such as implementation strategies, compliance monitoring, and disposal of mature trees that will have to receive careful consideration before such a program is initiated.

The costs of the reforestation policy are, however, dependent on the underlying assumptions concerning the availability and cost of land dedicated to planting the trees. Under the reduced land assumptions studied here, the total cost of reducing net carbon emissions by 33% relative to 1990 is increased by a factor of three compared to the base Reforestation Case. In the reduced land case, however, the interpretation of the policy is such that no new fossil fuel powerplants can be constructed after the supply of reforestation offsets is exhausted. This interpretation is significant since, in each year after 2005, more than 50% of the total cost projection for the reduced land case is due to the cost incurred by switching completely away from fossil fuels.

7.2.7 Limitations of the Reforestation Analysis

As discussed in the assumptions section for this case, there are several unaddressed issues associated with the analysis of the reforestation policy. First, there is some uncertainty about the relationship between the number of hectares planted, levelized costs of acquiring land and planting and maintaining trees, and the annual rate of carbon uptake. We have acknowledged this uncertainty by including the reduced land sensitivity analysis case. On the other hand, no allowance is made in our analysis for a CO_2 fertilization effect. The annual rate of uptake has been treated as if it were constant for a 40-year period, at the end of which no further carbon uptake occurs. This is a simplification. In reality, the relationship is more complex, and a more sophisticated model of the carbon uptake of a reforestation program could be designed. However, it is unlikely to significantly alter the general findings of this analysis.

It is important to note that we have made no attempt to describe the mechanism by which such a policy would be implemented and administered. It is possible that the institutional structures necessary to implement such a program would have implications for all land use within the United States.

There is also no attempt to describe how a reforestation program would interact with other parts of the economy. We have explicitly assumed that the demand for land by energy-related activities does not conflict with the demand for land for reforestation. In addition, we have not included estimates of how the demand for land would affect agricultural or forest product prices, although we have assumed that land rental rates for reforestation triple under the program. Similarly, we have not included side benefits that might accrue to watersheds, wildlife habitat, soil erosion control, and other conservation-related activities. Furthermore, we have made no estimates of how changing land-use patterns would affect the emissions of other greenhouse gases. For example, the greater stocks of forests would be expected to be associated with greater releases of short-lived greenhouse gases such as CH_4, CO, and nitrogen compounds from a greater area of land area subject to forest fires.

In addition, we have not examined how the program will deal with the maturation of trees. It is important to note that the carbon uptake of those trees planted in the first years of the program will decline sharply in the year 2030. We have already noted that if the trees are kept in place, they will represent an above-ground storage of carbon. But these trees cannot be oxidized without releasing the stored carbon to the atmosphere. The trees could be used as a source of biomass energy, but that biomass would add net carbon to the atmosphere if harvest were greater than the carbon uptake from second plantings. The trees could be harvested and applied to uses that tie up carbon for long periods of time--for example, as building material, or in furniture, railroad ties, or telephone poles. This would certainly affect the market for forest products. The trees could also be harvested and removed to long-term storage sites where oxidation would occur only slowly, such as in deep mines. If trees were required to remain in place, the land upon which they were planted would no longer be available for further use as a site for carbon

removal. Significant additions of land would then become much more costly, as sites for reforestation would come into increasing conflict with other land uses. We therefore conclude that reforestation is only a medium-term mechanism for net carbon emissions reductions. An important piece of future work will be to examine the options available for net carbon emissions reductions in the post-2030 period.

Additional discussion of the limitations of the reforestation analysis is provided in Chapter 8 for the Carbon Tax with Deposit Refund for Reforestation Cases.

7.3 UTILITY STANDARDS: POWERPLANT EFFICIENCY STANDARDS

7.3.1 Assumptions

The objective of Powerplant Efficiency Standards is to accelerate adoption of technologies that consume less fuel per unit of generated electricity than do conventional coal plants. The Powerplant Efficiency Standards Case, as explored in this study, assumes the imposition of a capital cost penalty on the construction of any new or life-extended fossil fuel-powered electricity-generating capacity that does not use the most efficient generating technology available. The heat rate in Btu/kWh is used as the measure of efficiency, and the penalties are applied to both new utility and non-utility plants and are assumed to start in 1994 (when new coal technologies are assumed to be commercial in the NES). For each technology, the cost penalty is computed as the capitalized charge per kilowatt of generating capacity equivalent to a carbon tax rate of $300/mtC if it were applied throughout the operating life of the powerplant. The capital charge for a candidate powerplant is calculated using its heat rate, its capacity factor, its operating life, the utility discount rate, and the carbon content of its fossil fuel.[a] With this method, the marginal cost for reducing CO_2 emissions under the Powerplant Efficiency Standards is therefore equal across all affected generating technologies. With the single exception of these efficiency cost penalties, all underlying assumptions in this case are identical to the NES.

From the NES Actions Case assumptions described in Chapter 5, conventional pulverized coal steam is the most efficient coal plant technology until 1994, when Integrated Gasification Combined Cycle (IGCC), with a heat rate of 9220 Btu/kWh, becomes commercially available. IGCC is overtaken in 1996 by Pressurized Fluid Bed (PFB), with a heat rate of 8400 Btu/kWh, and PFB is considered the target technology for the remainder of the time horizon. From the list of fossil-fueled generating technologies considered in the NES (detailed in Chapter 5), after 1995 the capital cost penalty will not apply to the following technologies: PFB, Coal Fuel Cell, Gas Combined Cycle, and Gas Intercooled Steam-Injection Turbine (ISTIG). This strategy leaves at least one coal baseline technology (PFB), as well as some gas-fired intermediate and peaking load technologies unpenalized. Table 7.23 shows the capital charges for the technologies affected by the efficiency standards. Note that the purpose of the penalties is to drive the more emissions intensive (but economically attractive) technologies completely out of of the market; subsequently, the capital charges for some of the technologies may be much higher than their base capital costs.

(a) The capital charge in $/kW for each technology is calculated as.

Capital Charge = HR * CF * LIFE * CARB * TAX * HOURS * 1/CR

where HR = heat rate in Btu/kWh
CF = capacity factor (fraction of time operating)
LIFE = expected plant operating lifetime (years)
CARB = fuel carbon content in mtC/Btu
TAX = marginal cost penalty in $/mtC
HOURS = 8760 hours per year
CR = capital recovery factor at discount rate of 9.2% and assumed plant lifetime.

Table 7.23. Capital Charges for Powerplant Efficiency Standards Case

Technology	Capital Charge (1989$/kw)
Coal Steam	4732
Coal Steam with FGD	4765
AFB	4805
IGCC[a]	4544
Coal Gasification ISTIG	4204
Life-Extended Coal[b]	4061
Oil Steam	1579
Gas Steam	1109
Life-Extended Oil Steam[b]	1414
Life-Extended Gas Steam[b]	981
Oil Combustion Turbine	751
Gas Combustion Turbine	521

(a) IGCC penalized after 1995.
(b) Assumed 20-year additional life for life-extended plants.

The Powerplant Efficiency Standards Case is modeled by entering the cost penalties for each technology in Fossil2, which then adds them to the total capital costs of each. The adoption of the most efficient electricity-generating technology is therefore not mandated explicitly in the model. Instead, Powerplant Efficiency Standards are manifested by making efficient technologies more attractive in the market for new electric generating capacity. The rate of penetration of new technologies is limited by the extent of the market for new capacity and the rate of substitution between technologies. The market for new capacity is determined by the rate of growth of electricity demand and the assumed rate of retirement of existing capacity.

7.3.2 A Comparison to the NES Actions Case

The Powerplant Efficiency Standards Case differs from the Reforestation Case in that not all fossil-fuel electric technologies are affected here. Rather than drive the market for new capacity exclusively towards non-fossil fuels, the standards act to redistribute the share of fossil fuel technologies to the more thermally efficient types. What occurs is a marked increase in natural gas-fired capacity as well as a shift from conventional pulverized coal plants to the more efficient PFB plants. Table 7.24 shows the net summer generating capability of coal-fired plants by technology compared to the net summer generating capability of all gas technologies under the Powerplant Efficiency Standards Case.

Table 7.24. Net Summer Generating Capability for Coal-Fired and Gas-Fired Plants Under the Powerplant Efficiency Standards (GW)

Year	Pulv. Coal	AFB	PFB	IGCC	Coal ISTIG	Total Coal	Total Gas
1990	298.5	0.0	0.0	0.0	0.0	298.5	132.2
1995	285.7	0.0	0.0	0.0	0.0	285.8	171.9
2000	187.1	0.6	2.5	10.0	0.0	200.2	331.3
2005	138.7	0.9	10.5	49.7	0.0	199.9	327.3
2010	117.7	0.9	13.0	53.2	0.1	184.8	320.5
2015	96.7	0.8	20.7	54.3	0.2	172.7	317.8
2020	73.4	0.8	54.3	56.0	0.5	184.9	308.1
2025	57.4	0.7	89.6	57.3	0.6	205.6	289.5
2030	47.5	0.7	125.9	58.2	1.0	233.2	263.2

From the Fossil2 Model results in Table 7.24, the amount of pulverized coal capacity shows a definite decline in each year from 1990 onward. Also evident is the steady growth in both PFB and IGCC capacity. This growth rate, however, lags behind the shift away from pulverized coal capacity. As a consequence, the total coal-fired capacity declines until reaching a minimum level in 2015, when it resumes a positive growth rate. This reversal in the growth trend of the total coal capacity accounts for some of the energy results for this case. Gas combined cycle and STIG plants compensate for most of the resulting gap in generating capacity because of their unpenalized capital costs and relatively fast construction rates, compared to nuclear and PFB plants. Oil, nuclear, and renewable electric plants are also affected by the standards, but to a lesser extent than the coal and gas technologies.

The implications of the Powerplant Efficiency Standards Case with respect to energy prices, energy supply and consumption, and greenhouse gas emissions are discussed below.

Energy Prices

The increased demand for natural gas for electricity generation under the Powerplant Efficiency Standards drives its price at the wellhead up by 35%, relative to the NES in 2030. Minemouth coal prices are depressed slightly as the standards come into effect, but they do recover sufficiently to match the value in the NES Actions Case by the year 2020. After 2020, the price of coal stabilizes around $1.35/mBtu as nuclear and renewable fuels begin to capture a larger market share, and coal price at the minemouth in 2030 is subsequently 6% less than in the NES in 2030. The price of oil does not differ significantly from the NES Case. Table 7.25 shows the resource and end-use energy price trajectories for the Powerplant Efficiency Standards Case over the study horizon.

In the end-use sectors, the average price of electricity jumps to 30% higher than the NES in 2000.

Table 7.25. Energy Prices in the Powerplant Efficiency Standards Case (1989$/mBtu)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.46	$3.46	$2.39	$1.06	$8.49
2000	$4.65	$4.65	$4.52	$1.01	$9.81
2005	$4.98	$4.98	$4.90	$1.05	$10.17
2010	$5.50	$5.50	$6.41	$1.19	$10.75
2015	$6.17	$6.17	$7.63	$1.34	$11.50
2020	$6.63	$6.63	$7.90	$1.36	$12.01
2025	$6.95	$6.95	$8.63	$1.35	$12.37
2030	$7.16	$7.16	$9.92	$1.38	$12.60

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.23	$1.68	$18.90	$20.07
2000	$8.27	$1.63	$25.95	$27.00
2005	$8.66	$1.67	$26.91	$28.87
2010	$10.10	$1.85	$25.57	$31.90
2015	$11.30	$2.05	$24.85	$35.82
2020	$11.60	$2.08	$25.11	$38.45
2025	$12.31	$2.06	$24.72	$40.33
2030	$13.45	$2.10	$24.42	$41.53

Electricity prices peak at just under $27/mBtu in 2005, but then decline and by 2030 reach a point just 12% higher than the NES. Note that electricity prices are higher here than in the Reforestation Case until after 2025, when the prices of the two cases match quite closely. The price schedule for utility coal follows that of minemouth coal closely. Residential gas prices rise steadily and are 21% higher than the NES in 2030 and approximately 5% higher than in the Reforestation Case. As expected from the world oil price, the price of motor gasoline is largely unaffected by the Powerplant Efficiency Standards.

Energy Consumption

Primary energy consumption by fuel for the Powerplant Efficiency Standards Case is shown in Table 7.26 below. The powerplant standards result in a reduction in total primary energy consumption of as much as 6% relative to the NES in the year 2000. As will be discussed later, much of the reduction is due to the resulting increased efficiency of electric generation, since total end-use energy consumption is only about 1% less than under the NES in the same time period.

The efficiency standards result in an almost 50% reduction in coal consumption compared to the NES in 2030. Natural gas and nuclear energy compensate for much of the reduction, with consumption totals increased by 25% and 29%, respectively, relative to the NES in 2030. Compared to the Reforestation Case, nuclear energy has a smaller share in this case, while coal consumption is about 75% higher in 2030. Consumption of oil and renewable energy sources does not change significantly, relative to the NES, by the end of the study period.

Energy Transformation

As with reforestation, the direct effects of the Powerplant Efficiency Standards are on electricity generation. Many of the differences in energy consumption results between this case and the NES Actions Case can therefore be accounted for by changes in the transformation of energy from resource fuels to electricity. Because coal and nuclear energy are

Table 7.26. Energy Consumption in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.8	22.6	19.5	6.0	7.7	0.8	91.5
2000	37.1	26.3	13.1	6.2	9.8	1.2	93.7
2005	37.3	27.4	13.9	6.7	11.5	2.1	98.8
2010	38.4	28.7	14.4	7.1	12.9	3.4	105.5
2015	38.9	30.8	14.5	7.3	15.4	3.4	110.3
2020	38.5	29.9	15.1	10.1	18.0	3.5	115.0
2025	37.6	27.6	16.1	13.5	20.9	3.5	119.2
2030	36.8	25.2	17.5	16.1	23.4	3.5	122.4

primarily used for electricity generation in this country, their use as inputs to electricity generation generally follows the same pattern as their total primary consumption results. As Figure 7.3 shows, coal consumption by utilities decreases as the standards come into effect and stabilizes for the remainder of the study period. Gas consumption reacts more quickly than nuclear to make up the gap left by coal, and by 2030 the consumption of natural gas for electricity generation is over 150% higher than in the NES Actions Case. Nuclear and renewable energy sources gain larger shares in this sector, starting in approximately 2015. Table 7.27 shows these same results in numeric form.

End-Use Energy Consumption

Powerplant Efficiency Standards do not have a large impact on total end-use energy consumption. They do, however, affect the market shares of fuels used within each end-use sector through price feedback. Tables 7.28, 7.29, and 7.30 below show the energy consumption in the residential, commercial, and industrial sectors, respectively.

From Table 7.28, electricity consumption is reduced somewhat, compared to the NES, while natural gas use increases slightly. The prices of both are higher than under the NES, and the net change in

Table 7.27. Electricity Fuel Consumption in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.7	5.7	16.6	6.0	4.6	34.6
2000	1.5	9.7	9.8	6.2	6.3	33.6
2005	1.0	9.4	10.4	6.7	7.5	35.0
2010	1.2	10.9	10.8	7.1	8.2	38.3
2015	1.7	13.7	10.5	7.3	8.9	42.1
2020	1.7	13.2	10.9	10.1	10.2	46.1
2025	1.2	11.4	11.9	13.5	11.8	49.8
2030	1.0	10.2	13.2	16.1	13.4	53.9

Table 7.28. Residential Energy Consumption in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.6	4.9	0.1	0.9	3.2	10.7
1995	1.3	4.8	0.1	1.0	3.5	10.8
2000	1.2	5.1	0.1	1.0	3.7	11.1
2005	1.1	5.3	0.1	1.2	3.7	11.4
2010	1.0	5.4	0.1	1.4	3.9	11.8
2015	0.9	5.3	0.1	1.5	4.2	12.0
2020	0.9	5.1	0.1	1.6		2
2025	0.8	5.0	0.1	1.7	4.8	12.4
2030	0.8	4.6	0.1	1.8	5.1	12.4

Table 7.29. Commercial Energy Consumption in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.0	2.8	0.1	0.1	2.9	6.9
1995	0.9	2.7	0.1	0.1	3.4	7.2
2000	0.9	2.8	0.1	0.1	3.7	7.5
2005	0.9	2.9	0.1	0.1	4.0	7.9
2010	0.9	2.9	0.1	0.2	4.5	8.5
2015	0.9	2.9	0.0	0.2	5.0	9.1
2020	0.9	2.9	0.0	0.3	5.6	9.8
2025	1.0	3.0	0.0	0.3	6.1	10.3
2030	1.0	2.9	0.0	0.4	6.5	10.9

Table 7.30. Industrial Energy Consumption in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	8.7	8.2	2.8	1.8	3.1	24.6
1995	9.3	8.8	2.6	1.8	3.5	26.0
2000	9.6	8.8	2.8	2.0	3.6	26.8
2005	10.5	8.6	3.2	2.3	3.6	28.2
2010	11.6	8.0	3.7	2.7	3.9	29.8
2015	12.3	7.6	3.9	2.9	4.4	31.0
2020	13.0	7.2	3.9	3.2	4.7	32.0
2025	13.8	6.9	4.0	3.5	5.1	33.3
2030	14.9	6.1	4.0	3.8	5.5	34.4

consumption is small. Oil consumption shows the largest relative change, with an increase of 12% relative to the NES in 2030, since its price is not greatly increased. In the commercial sector (Table 7.29), oil shows an even larger relative increase, though the amount consumed remains small in absolute terms. In contrast to the residential sector, the total energy consumption in the commercial sector is reduced by 2%, relative to the NES, in 2030. In the industrial sector, coal has more applications and therefore more potential for use. The industrial sector can take advantage of the relatively lower price of coal and substitute it where natural gas would have been used. From Table 7.30, coal consumption in this sector is 17% higher than in the NES in 2030, while gas falls to a value 18% lower. Oil consumption also increases slightly, while electricity consumption is reduced by about 3% in 2030. As with reforestation, the energy consumption in the transportation sector is only affected slightly through increased oil prices.

Energy Production and International Trade

The Powerplant Efficiency Standards reduce total indigenous energy supply by 6% relative to the NES Actions Case, to 96.2 quads in 2030. As Table 7.31 shows, most of this difference is due to coal production, which is down by 38% in 2030. The production of natural gas increases significantly to make up much of the difference. Indigenous production of nuclear and renewable energy sources also increases relative to the NES, but production of each is about 25% less than in the Reforestation Case in 2030. Again, one major difference between the two cases is that all fossil fuels are affected by reforestation, while the more efficient fossil fuel electric technologies escape penalty here.

Net imports of energy increase by 13%, relative to the NES in 2030. Natural gas imports increase by 45%, but gas imports remain small, compared to oil imports. From Table 7.32, oil imports reach 26.1 quads in 2030, which is 6% higher than under the NES. Coal exports are extremely insensitive in Fossil2, and the model results show no change from the NES Actions Case, a result that appears unrealistic in light of the reduced domestic consumption of coal in this case. Even a slight increase in coal exports would counteract the additional imports of oil and gas caused by the Powerplant Efficiency Standards and thus would show either no change or even a positive change in net energy imports, compared to the NES. Of course, this scenario presumes no corresponding policies in other countries.

Greenhouse Gas Emissions

Net CO_2 emissions (by carbon weight) for the Powerplant Efficiency Standards Case are shown by fuel in Table 7.33. The total CO_2 emissions from fossil fuels of 1428 TgC in 2030 are about 17% lower than in the NES Actions Case during the same year.

Table 7.31. Energy Supply in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.8	20.8	22.0	6.0	7.7	72.3
2000	18.6	23.8	16.4	6.2	9.8	74.8
2005	22.5	24.5	18.3	6.7	11.5	83.5
2010	21.9	25.3	19.8	7.1	12.9	87.1
2015	17.7	27.5	20.6	7.3	15.4	88.4
2020	14.7	26.9	21.9	10.1	18.0	91.6
2025	12.5	24.4	23.2	13.5	20.9	94.5
2030	10.7	21.5	24.6	16.1	23.4	96.2

Table 7.32. Energy Trade in the Powerplant Efficiency Standards Case (by fuel--quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	16.5	1.4	(2.6)	0.1	0.0	15.4
1995	19.0	1.9	(2.6)	0.2	0.7	19.1
2000	18.5	2.5	(3.3)	0.2	1.0	18.9
2005	14.8	2.8	(4.3)	0.2	1.9	15.4
2010	16.5	3.4	(5.3)	0.2	3.2	17.9
2015	21.2	3.4	(6.1)	0.3	3.2	21.9
2020	23.7	3.0	(6.8)	0.3	3.2	23.4
2025	25.0	3.3	(7.1)	0.3	3.2	24.7
2030	26.1	3.7	(7.2)	0.3	3.2	26.2

Table 7.33. Carbon Emissions in the Powerplant Efficiency Standards Case (by fuel--TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total	Carbon Emissions Reduction (% from NES Actions)
1990	546	274	477	2	1299	--
1995	550	319	497	3	1370	0%
2000	575	386	330	9	1300	13%
2005	595	383	356	12	1347	14%
2010	620	399	377	12	1408	14%
2015	636	430	375	13	1453	14%
2020	634	416	386	15	1451	15%
2025	623	384	411	17	1435	16%
2030	613	350	446	19	1428	16%

However, this total is almost 75% higher than the corresponding value in the Reforestation Case. The decrease in coal consumption due to the efficiency standards accounts for most of the difference between this case and the NES. CO_2 emissions from coal burning are 46% lower in 2030 than in the NES, but CO_2 emissions from natural gas rise to 350 TgC in 2030, an increase of 26% relative the NES. Emissions from oil increase slightly under the efficiency standards.

Fossil fuel-related emissions of methane are also reduced relative to the NES. The contribution to methane emissions from coal mining declines substantially, due to the lower coal production requirements. The increased demand for natural gas results in a net growth in methane emissions relative to the NES, associated with gas production losses and transmission and distribution. However, this increase is not sufficiently large to offset the reduction in coal-related methane emissions that occurs in this case. Table 7.34 shows methane emissions by source over the study period.

Figure 7.4 displays the energy-related GWP results for the Powerplant Efficiency Standards Case. The

Table 7.34. Methane Emissions in the Powerplant Efficiency Standards Case ($TgCH_4/yr$)

Year	Natural Coal Mines	Nat. Gas Gas Prod	Trans.& Dist.	Total
1990	4.1	2.1	5.6	11.8
1995	4.2	2.4	6.6	13.2
2000	3.1	2.8	7.7	14.6
2005	3.5	2.9	8.0	14.4
2010	3.8	3.0	8.4	14.1
2015	3.9	3.2	9.0	15.2
2020	4.2	3.1	8.7	16.0
2025	4.4	2.9	8.1	15.3
2030	4.7	2.5	7.4	14.6

figure shows a distinct drop in annual GWP over the first 10 years as the efficiency standards take effect. Total annual GWP levels off to 6099 $TgCO_2e$ in 2000, rises slightly to 6458 $TgCO_2e$ by 2015, and remains relatively constant through 2030. The efficiency standards are successful in counteracting much of the growth in GWP from CO_2 that occurs in the NES Actions Case. GWP-weighted emissions for this case are also shown in Table 7.35.

7.3.3 The Cost of Greenhouse Gas Emissions

Approach to Computing Cost

Because the capital charges on the penalized technologies in this case are based on equal marginal costs per metric tonne of carbon, the cost of the Powerplant Efficiency Standards Case can be calculated in the same manner as the tax cases discussed

Table 7.35. GWP-Weighted Energy-Related Emissions by Gas and by Year in the Powerplant Efficiency Standards Case ($TgCO_2$ Equivalent)

Year	CO_2	CO	CH_4	N_2O	CFCs	HCFCs	GWP	% Reduction from NES Actions
1990	4527	455	626	17	1689	144	7458	--
1995	4744	477	495	18	1062	326	7121	0%
2000	4446	447	532	15	360	299	6099	11%
2005	4548	457	574	15	326	254	6174	13%
2010	4696	472	599	16	179	366	6328	13%
2015	4852	487	612	16	58	458	6483	13%
2020	4846	487	604	16	5	470	6428	13%
2025	4791	481	577	17	3	350	6220	15%
2030	4766	479	550	17	2	172	5985	15%

in Chapter 6. In this case, a marginal cost schedule is constructed by plotting reductions in annual carbon emissions against marginal costs at $50 intervals up to the $300 level used as the efficiency standard. Total cost is computed for each year by integrating the marginal cost function over the carbon emissions reduction achieved by the standards. Refer to Chapter 6 for a detailed description of this procedure.

The Cost of Reducing Carbon Emissions

The relationship between CO_2 emissions reduction, total cost, and average cost is given in Table 7.36. The reductions in CO_2 emissions from the standards become tangible in the year 2000. In 2000, it costs approximately $9.2 billion to reduce emissions by 187 TgC, relative to the NES. In 2030, a cost of $13.7 billion achieves a reduction of 279 TgC. The average cost is stable throughout the study period--near $50 per metric tonne of carbon reduced.

Table 7.37 shows the relationship between total costs and GWP reductions for the Powerplant Efficiency Standards. The standards achieve an 18% reduction in energy-related GWP, relative to 1990 levels, by the year 2000, but annual GWP then grows slightly as more PFB coal plants come into operation. By 2030, however, the trend is again reversed, and a 20% reduction in GWP relative to 1990 levels is achieved.

Table 7.36. Cost of Carbon Emissions Reduction in the Powerplant Efficiency Standards Case

Year	Carbon Emissions Reduction (TgC/yr) [a]	Total Cost (bil $/yr)	Average Cost ($/mtC)
1990	0	$0.00	$0
1995	6	$0.30	$50
2000	187	$9.23	$49
2005	227	$11.20	$49
2010	232	$11.47	$49
2015	243	$12.09	$50
2020	258	$12.82	$50
2025	274	$13.56	$50
2030	279	$13.71	$50

(a) Relative to the NES Actions Case.

Table 7.37. Cost of GWP Reduction in the Powerplant Efficiency Standards Case

Year	GWP Reductions ($TgCO_2e$/yr) [a]	Total Cost (bil $/yr)	GWP Reduction (% 1990)
1995	22	$0	5%
2000	744	$9	18%
2005	890	$11	17%
2010	905	$11	15%
2015	984	$12	14%
2020	1003	$13	14%
2025	1073	$14	17%
2030	1097	$14	20%

(a) Relative to the NES Actions Case.

7.3.4 Summary of Findings: Powerplant Efficiency Standards Case

The Powerplant Efficiency Standards Case, by itself, is not as powerful in reducing carbon emissions as the Reforestation Case discussed in the previous section. However, it does achieve a fair level of emissions reduction relative to the NES Actions Case at a relatively low cost. These standards do not achieve stabilization in carbon emissions over the study period. They do, however, restrain the growth in emissions so that resulting carbon emissions in 2030 are just 10% above 1990 levels. In 2030, the standards result in a 16% reduction in carbon emissions relative to the NES Actions Case in that year at an average cost of $50/mtc. The potential carbon emissions reductions achieved in the Powerplant Efficiency Standards Case is limited by the heat rate of the most efficient baseline fossil

fuel technology (in this case, PFB), since it will operate without penalty by the definition of the standards.

7.4 BUILDINGS STANDARDS

This section of the report uses the Fossil2 Model to examine the effects of imposing minimum efficiency levels for energy-using equipment in residential and commercial buildings. The methodology and assumptions used in the analysis are presented in Section 7.4.1. The effects of Buildings Standards on GWP are discussed in Section 7.4.2. Section 7.4.3 looks at the impacts of these standards on the U.S. energy economy. Finally, Section 7.4.4 examines the cost of imposing these standards on the economy. The analysis reveals that, since the very efficient technology is already embodied in the NES Actions, higher standards achieve very small additional decreases in total GWPs, have relatively little building impact on the energy economy, and are very costly at the margin.

7.4.1 Assumptions and Approach

Buildings standards are minimum efficiency levels for energy-using equipment in residential and commercial buildings. Rather than set equal standards arbitrarily across all types of energy-consuming equipment and all fuels, an economic strategy was used in this study to explore the minimum cost of fossil fuel CO_2 emissions reductions associated with the implementation of buildings standards. In accordance with basic economic principles, if total cost of carbon emissions reduction is to be at a minimum, the cost of the last unit of carbon emission reduction must be equal in all endeavors. Thus, if one standard is set such that the marginal cost of a tonne of carbon emission reduction is $200, while a second standard reduces carbon at the marginal rate of $100 per tonne, total cost cannot be at a minimum. Clearly, the same emissions reduction can be achieved at lower cost by increasing the stringency of the second standard and reducing the stringency of the first standard in this example.

As will be discussed in the section on costs, the implementation of buildings standards in this manner does not achieve a carbon emissions reduction objective at minimum cost. This occurs because of what is referred to as the take-back problem. This means that, while a standard may require that a more efficient technology be used throughout the economy, some of the savings are taken back because the standard 1) lowers the marginal cost of providing energy services, 2) provides no incentive for inter-fuel substitution, and 3) fails to create incentives for the substitution of other goods and services for energy services. The method of cost employed in this analysis is incapable of capturing any of the benefits of standards. As noted earlier, standards reduce some transaction costs; specifically, once a standard has been set, the cost of gathering and processing information is reduced for many economic actors. The empirical question of whether or not the reduction in transaction costs offsets the cost of a reduced set of alternatives from which to select energy-using devices and the costs of the take-back problem is an issue that this study does not address.

The strategy employed to construct the Buildings Standards Case is as follows. The level of energy efficiency in all buildings energy end uses achieved with carbon taxes of $250/mtC, $500/mtC, and $1000/mtC was obtained. In other words, there is a set of standards associated with each of the successively higher carbon taxes. As the carbon tax increases, the standards, too, become increasingly rigid (costly). These levels of efficiency were then mandated as the minimum technology efficiency standards for all new investments in the Buildings Standards Cases. These standards are said to be the "efficient" set of buildings standards because they were created such that the capitalized marginal cost of carbon emissions reductions is equal across applications. It should be emphasized that the Buildings Standards Case does not include actual carbon taxes.

In Fossil2, Buildings Standards are defined in terms of marginal costs of investments in energy-conserving equipment (stated in $/mBtu) for the

various end-use categories. For each end use and fuel type, a marginal cost value corresponds to a certain level of energy efficiency, which is part of the conservation supply curve of energy efficient technologies stored in Fossil2. (The conservation supply curve characteristics are maintained by the AES Corporation.) As described in Chapter 4, investment in energy-efficient technologies depends upon both fuel costs and consumer discount rates. Higher fuel prices cause investment in costlier, more efficient technologies to be more economically attractive.

Except for the imposition of the buildings standards, the assumptions employed in the Buildings Standards Case are identical to those of the NES Actions Case.

7.4.2 Comparison of GWP-Weighted Emissions Reductions to the NES

The GWPs for the three Buildings Standards Cases are shown by greenhouse gas group in Table 7.38. The differences between these GWP projections and those in the NES Actions Case in

Table 7.38a. NES with $250/mtC Buildings Standards GWP-Weighted Energy-Related Emissions by Gas and by Year ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs	HCFCs	GWP	% Reduction from NES Actions
1990	4527	455	626	17	1689	144	7458	--
1995	4643	467	482	18	1062	326	6997	2%
2000	4954	498	542	19	360	299	6672	2%
2005	5192	522	577	21	326	254	6891	2%
2010	5355	538	595	23	179	366	7056	2%
2015	5535	556	602	23	58	458	7232	2%
2020	5588	561	598	24	5	470	7246	2%
2025	5597	562	582	24	3	350	7119	2%
2030	5615	564	564	25	2	172	6942	2%

Table 7.38b. NES with $500/mtC Buildings Standards GWP-Weighted Energy-Related Emissions by Gas and by Year ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs	HCFCs	GWP	% Reduction from NES Actions
1990	4527	455	626	17	1689	144	7458	--
1995	4616	464	480	18	1062	326	6965	2%
2000	4925	495	539	19	360	299	6637	3%
2005	5157	518	574	21	326	254	6849	3%
2010	5312	534	593	22	179	366	7006	3%
2015	5484	551	599	23	58	458	7173	3%
2020	5534	556	595	23	5	470	7182	3%
2025	5538	556	578	24	3	350	7050	3%
2030	5553	558	561	24	2	172	6871	3%

Table 7.38c. NES with $1000/mtC Buildings Standards GWP-Weighted Energy-Related Emissions by Gas and by Year ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFCs	HCFCs	GWP	% Reduction from NES Actions
1990	4527	455	626	17	1689	144	7458	--
1995	4594	462	477	18	1062	326	6938	3%
2000	4892	492	535	19	360	299	6597	4%
2005	5116	514	570	21	326	254	6801	4%
2010	5262	529	588	22	179	366	6946	4%
2015	5429	546	594	23	58	458	7108	4%
2020	5477	550	589	23	5	470	7114	4%
2025	5476	550	573	24	3	350	6976	4%
2030	5487	551	556	24	2	172	6792	4%

Chapter 5 are very small. Under the NES Actions Case, total GWPs decrease from 7458 $TgCO_2e$ in 1987 to 7082 $TgCO_2e$ in 2030. In the $250/mtC Building Efficiency Standards Case, total GWP in 2030 is 6942 $TgCO_2$, about 2% lower than the NES Actions values. The corresponding GWP estimates for the two more stringent Building Efficiency Cases are 6871 $TgCO_2$ and 6792 $TgCO_2$, respectively, or 3% and 4% lower than the NES Actions GWP value.

The reason that the Buildings Standards in this set of scenarios do not have a very large impact on emissions of greenhouse gases is not that Buildings Standards, *per se*, are ineffective. This analysis suggests instead that, given the high level of technical efficiency already embodied in the NES Actions Case, Building Standards are not an effective tool for reducing the global warming potential of the gases released by the U.S. energy economy.

7.4.3 Energy Results Compared to the NES Actions Case

Overall, the standards presented here did not have much of an impact on the energy economy of the United States. While some modest reductions in energy use by the residential and commercial sectors were achieved, these reductions did not lead to large-scale fuel switching, nor to any significant changes in the supply and demand situation for primary energy resources. The impact of these standards on CO_2 and CH_4 emissions was equally small. Because these impacts are not very large, the detail accorded to them in this section has been cut back sharply.

Energy Prices

The energy price impacts of the three Buildings Standards Cases are presented in Table 7.39. The only important feature of interest in these tables is the simulated effects of the standards on wellhead gas prices. In the NES Actions Case, the wellhead price of natural gas increases from $1.62 in 1987 to $7.33 in 2030. However, for the $250/mtC standard, the price of natural gas in 2030 is $7.06, and in the $1000/mtC Case, it falls to $6.83. This decrease in wellhead gas prices occurs because improved buildings efficiency has the effect of shifting the aggregate demand for natural gas at the wellhead inward, lowering both natural gas prices (in relative and absolute terms) and production.

Primary Energy Consumption

The simulated effects of the three building efficiency standards on primary energy consumption are shown in Table 7.40. Overall, the standards have the effect of decreasing energy consumption, albeit by only a small amount. In the NES Actions Case, total primary energy consumption increases

Table 7.39a. Energy Prices: NES with $250/mtC Buildings Standards (1989$/mBtu)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.45	$3.45	$2.26	$1.06	$8.48
2000	$4.55	$4.55	$3.43	$1.11	$9.70
2005	$5.03	$5.03	$4.00	$1.15	$10.23
2010	$5.51	$5.51	$4.91	$1.24	$10.77
2015	$6.14	$6.14	$5.72	$1.30	$11.46
2020	$6.54	$6.54	$6.40	$1.37	$11.91
2025	$6.87	$6.87	$6.50	$1.41	$12.27
2030	$7.06	$7.06	$7.06	$1.46	$12.48

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.12	$1.68	$18.94	$20.04
2000	$7.24	$1.74	$19.68	$26.39
2005	$7.85	$1.78	$20.37	$29.18
2010	$8.72	$1.91	$20.84	$31.99
2015	$8.72	$2.00	$20.64	$35.60
2020	$9.50	$2.08	$21.53	$37.95
2025	$10.17	$2.14	$21.89	$39.85
2030	$10.33	$2.21	$21.80	$40.96

from 79.5 quads in 1987 to 123.1 quads in 2030. Under the Standards Cases, the rate of increase of consumption is slowed somewhat. In the $250/mtC Case, total consumption in 2030 is 121.7 quads. In the $1000/mtC Case, the comparable value is 119.8 quads, less than 3% below the NES Actions value. Most of this decrease comes in the form of reductions (from the NES Actions Case) in coal and gas use.

Energy Transformation

Electricity fuel consumption for the three buildings standards scenarios is shown in Table 7.41. Increases in the level of the buildings standards reduce total fuel consumption by a very small amount. In the NES Reference Case, total fuel use by the electricity sector increases from 28.1 quads in 1987 to 58.1 quads in 2030. In the $250/mtC Buildings Standards Case, fuel consumption in 2030 is just 0.9 quads below the NES in the same year, and for the $1000/mtC Case, fuel consumption in 2030 is only 1.9 quads or 3.3% lower than for the NES Actions Case. Most of this decrease is due to lower coal use by the utilities. Coal use drops because more efficient buildings standards cause a slight decrease in the demand for electricity which, in turn, lowers coal use.

The effects of the three buildings standards levels on electricity consumption are shown in Table 7.42. The differences in electricity consumption parallel those in fuel consumption, but are predictably smaller in magnitude. In the NES Actions Case, consumption increases from 8.5 quads in 1987 to 18 quads in 2030. However, even under the most

Table 7.39b. Energy Prices: NES with $500/mtC Buildings Standards (1989$/mBtu)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.45	$3.45	$2.26	$1.06	$8.48
2000	$4.55	$4.55	$3.33	$1.12	$9.70
2005	$5.03	$5.03	$4.00	$1.15	$10.23
2010	$5.52	$5.52	$4.84	$1.24	$10.77
2015	$6.14	$6.14	$5.65	$1.30	$11.46
2020	$6.54	$6.54	$6.34	$1.36	$11.91
2025	$6.87	$6.87	$6.47	$1.40	$12.27
2030	$7.06	$7.06	$7.00	$1.46	$12.48

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.12	$1.68	$18.99	$20.04
2000	$7.15	$1.74	$19.62	$26.40
2005	$7.85	$1.78	$20.25	$29.18
2010	$8.65	$1.91	$20.74	$32.00
2015	$9.44	$1.99	$20.58	$35.60
2020	$10.11	$2.08	$21.50	$37.93
2025	$10.30	$2.13	$21.87	$39.84
2030	$10.83	$2.20	$21.78	$40.95

stringent of the three Buildings Standards Cases, total electricity production in 2030 is just 0.6 quad lower than in the NES Actions Case. Virtually all of this decreased consumption is due to a reduction in commercial buildings energy consumption, although a small fraction is due to a decline in residential buildings consumption.

End-Use Energy Consumption

Total end-use energy consumption for each of the three Buildings Standards Cases is shown in Table 7.43. There is a roughly 2-quad difference between the values for total end-use energy consumption in the NES Actions Case and the $1000/mtC Buildings Standards Case. All of this decrease is due to reduced consumption in the residential and commercial sectors, since energy use in the industrial and transportation sectors increases very slightly.

Energy Production

The effects of the buildings efficiency standards on domestic energy production are shown in Table 7.44. In the NES Actions Case, domestic energy production increases from 68.2 quads in 1987 to 102.9 quads in 2030. Under the Buildings Standards Cases, domestic supplies drop slightly, relative to the Reference Case: the decline ranges from 1.1 quads under the $250/mtC Buildings Standards to 2.7 quads under the $1000/mtC Buildings Standards. In the $1,000 Case, total domestic supply in 2030 is 100.2 quads, only about 2.5% lower than in

Table 7.39c. Energy Prices: NES with $1,000/mtC Buildings Standards (1989$/mBtu)

Year	World Oil	Refiner Crude	Wellhead Gas	Minemouth Coal	Gasoline
1990	$2.90	$2.89	$1.78	$1.04	$7.86
1995	$3.45	$3.45	$2.24	$1.06	$8.48
2000	$4.55	$4.55	$3.19	$1.12	$9.70
2005	$5.03	$5.03	$3.87	$1.15	$10.23
2010	$5.51	$5.51	$4.64	$1.24	$10.76
2015	$6.13	$6.13	$5.46	$1.30	$11.46
2020	$6.53	$6.53	$6.17	$1.36	$11.89
2025	$6.86	$6.86	$6.38	$1.40	$12.26
2030	$7.05	$7.06	$6.83	$1.45	$12.47

Year	Residential Gas	Utility Coal	Average Elec	World Oil Price ($/bbl)
1990	$5.69	$1.57	$18.65	$16.81
1995	$6.10	$1.68	$19.00	$20.04
2000	$7.03	$1.74	$19.58	$26.39
2005	$7.76	$1.78	$20.20	$29.16
2010	$8.47	$1.91	20.69	$31.97
2015	$9.25	$1.99	20.53	$35.57
2020	$9.95	$2.08	$21.42	$37.88
2025	$10.22	$2.13	$21.83	$39.79
2030	$10.67	$2.20	$21.74	$40.88

Table 7.40a. Energy Consumption: NES with $250/mtC Buildings Standards (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.5	21.2	19.5	6.0	7.7	0.8	89.6
2000	35.6	23.3	21.8	6.2	8.8	1.2	96.9
2005	37.2	22.9	24.1	6.5	10.2	2.1	103.1
2010	37.8	22.2	26.7	7.0	11.9	3.4	108.9
2015	38.1	23.1	27.7	7.0	14.5	3.4	113.8
2020	37.6	22.9	28.3	8.4	17.3	3.5	117.9
2025	36.5	21.6	29.5	10.5	20.2	3.5	121.8
2030	35.6	20.2	31.0	12.5	22.5	3.5	125.3

Table 7.40b. Energy Consumption: NES with $500/mtC Buildings Standards (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.4	21.0	19.3	6.0	7.7	0.8	89.2
2000	35.6	23.0	21.6	6.2	8.8	1.2	96.4
2005	37.2	22.7	23.9	6.5	10.2	2.1	102.5
2010	37.7	22.0	26.3	7.0	11.9	3.4	108.4
2015	38.1	23.0	27.2	7.0	14.5	3.4	113.2
2020	37.6	22.7	27.7	8.4	17.3	3.5	117.2
2025	36.5	21.4	29.0	10.5	20.2	3.5	121.0
2030	35.6	20.1	30.3	12.4	22.5	3.5	124.4

Table 7.40c. Energy Consumption: NES with $1,000/mtC Buildings Standards (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	85.4
1995	34.4	20.7	19.2	6.0	7.7	0.8	88.8
2000	35.5	22.6	21.6	6.2	8.8	1.2	95.8
2005	37.1	22.4	23.7	6.5	10.1	2.1	101.9
2010	37.6	21.6	26.1	7.0	11.9	3.4	107.6
2015	37.9	22.4	27.0	7.0	14.5	3.4	112.3
2020	37.4	22.2	27.5	8.3	17.3	3.5	116.3
2025	36.3	20.9	28.7	10.4	20.1	3.5	120.0
2030	35.4	19.6	30.0	12.3	22.4	3.5	123.3

the NES Actions Case. This is due to a slight decline in natural gas production and a roughly 2-quad reduction in coal production going to the electric utility sector. However, since the supply of coal is very price-inelastic, the price change associated with this 2-quad drop in production is very small.

The international trade impacts of the buildings standards, shown in Table 7.45, are also very small. In the NES Actions Case, net imports increase from 15.4 quads of energy in 1990 to 23.7 quads in 2030. This is due largely to imports of oil. Under the buildings standards, oil imports are virtually unchanged, and the total trade balances decrease by less than 1 quad.

Energy-Related Greenhouse Gas Emissions

Given how little impact the higher building efficiency standards have on energy production and consumption in the United States, one can predict that the decrease in emissions due to these higher standards is also quite small. This is shown in Tables 7.46 and 7.47. Fossil-fuel CO_2 emissions in the NES Actions Case increase from 1300 TgC/yr in

Table 7.41a. Electricity Fuel Consumption: NES with $250/mtC Buildings Standard (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.5	5.1	16.6	6.0	4.6	33.8
2000	1.0	6.2	18.8	6.2	5.4	37.6
2005	1.2	6.0	20.8	6.5	6.2	40.6
2010	1.2	5.3	23.1	7.0	7.0	43.6
2015	1.6	6.5	23.9	7.0	7.9	47.0
2020	1.5	6.6	24.6	8.4	9.4	50.5
2025	1.1	5.3	25.9	10.5	10.9	53.7
2030	0.8	4.3	27.4	12.5	12.3	57.2

Table 7.41b. Electricity Fuel Consumption: NES with $500/mtC Buildings Standard (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.5	5.0	16.4	6.0	4.6	33.5
2000	1.0	6.0	18.7	6.2	5.3	37.3
2005	1.2	5.9	20.6	6.5	6.1	40.3
2010	1.2	5.3	22.7	7.0	7.0	43.2
2015	1.6	6.5	23.5	7.0	7.9	46.5
2020	1.6	6.6	24.1	8.4	9.4	50.0
2025	1.1	5.3	25.3	10.5	10.9	53.1
2030	0.8	4.3	26.8	12.4	12.2	56.5

Table 7.41c. Electricity Fuel Consumption: NES with $1,000/mtC Buildings Standard (by fuel--quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	1.7	2.7	16.4	5.9	3.9	30.6
1995	1.5	5.0	16.3	6.0	4.6	33.4
2000	1.0	6.0	18.6	6.2	5.3	37.2
2005	1.2	6.0	20.4	6.5	6.1	40.2
2010	1.2	5.4	22.5	7.0	7.0	43.1
2015	1.6	6.5	23.3	7.0	7.8	46.3
2020	1.5	6.6	23.9	8.3	9.4	49.8
2025	1.1	5.3	25.1	10.4	10.9	52.8
2030	0.8	4.3	26.5	12.3	12.2	56.1

Table 7.42a. Electricity Consumption: NES with $250/mtC Buildings Standard (by end use--quads)

Year	Res	Com	Ind	Tran	Total
1990	3.2	2.9	3.1	0.0	9.2
1995	3.4	3.3	3.5	0.0	10.2
2000	3.7	3.7	4.1	0.0	11.4
2005	4.0	4.2	4.4	0.0	12.5
2010	4.2	4.7	4.4	0.1	13.4
2015	4.5	5.2	4.6	0.2	14.6
2020	4.8	5.7	5.0	0.2	15.7
2025	5.1	6.2	5.3	0.3	16.9
2030	5.3	6.7	5.7	0.4	18.1

Table 7.42b. Electricity Consumption: NES with $500/mtC Buildings Standard (by end use--quads)

Year	Res	Com	Ind	Tran	Total
1990	3.2	2.9	3.1	0.0	9.2
1995	3.4	3.2	3.5	0.0	10.1
2000	3.6	3.6	4.1	0.0	11.3
2005	3.9	4.1	4.4	0.0	12.4
2010	4.2	4.6	4.4	0.1	13.3
2015	4.4	5.2	4.6	0.2	14.4
2020	4.7	5.6	5.0	0.3	15.6
2025	4.9	6.1	5.3	0.3	16.6
2030	5.2	6.6	5.7	0.4	17.8

Table 7.42c. Electricity Consumption: NES with $1,000/mtC Buildings Standard (by end use--quads)

Year	Res	Com	Ind	Tran	Total
1990	3.2	2.9	3.1	0.0	9.2
1995	3.4	3.2	3.5	0.0	10.1
2000	3.7	3.5	4.1	0.0	11.3
2005	4.0	4.0	4.4	0.0	12.3
2010	4.3	4.5	4.4	0.1	13.3
2015	4.6	5.0	4.6	0.2	14.3
2020	4.8	5.4	5.0	0.3	15.5
2025	5.0	5.9	5.3	0.3	16.6
2030	5.3	6.4	5.7	0.4	17.7

Table 7.43a. Total End-Use Energy Consumption: NES With $250/mtC Buildings Standard (quads)

Year	Res	Com	Ind	Tran	Total
1990	10.7	6.9	24.6	22.4	64.6
1995	9.9	6.9	25.9	23.5	66.2
2000	9.9	7.3	27.7	25.7	70.7
2005	10.2	7.9	29.1	27.5	74.7
2010	10.5	8.4	30.3	29.0	78.3
2015	10.8	9.1	31.2	29.7	80.8
2020	11.1	9.7	32.1	29.6	82.4
2025	11.4	10.3	33.4	29.2	84.2
2030	11.8	10.9	34.6	27.9	85.3

Table 7.43b. Total End-Use Energy Consumption: NES with $500/mtC Buildings Standard (quads)

Year	Res	Com	Ind	Tran	Total
1990	10.7	6.9	24.6	22.4	64.6
1995	9.8	6.8	25.9	23.5	66.0
2000	9.7	7.2	27.7	25.7	70.4
2005	10.9	7.8	29.1	27.5	74.4
2010	10.3	8.4	30.4	29.0	78.0
2015	10.6	9.0	31.2	29.7	80.5
2020	10.8	9.6	32.1	29.6	82.1
2025	11.1	10.2	33.4	29.2	83.9
2030	11.5	10.9	34.6	27.9	84.9

Table 7.43c. Total End-Use Energy Consumption: NES with $1,000/mtC Buildings Standard (quads)

Year	Res	Com	Ind	Tran	Total
1990	10.7	6.9	24.6	22.4	64.6
1995	9.6	6.8	25.9	23.5	65.7
2000	9.4	7.1	27.7	25.7	69.9
2005	9.5	7.6	29.2	27.6	73.9
2010	9.8	8.2	30.4	29.0	77.3
2015	10.0	8.7	31.2	29.7	79.7
2020	10.3	9.3	32.1	29.6	81.4
2025	10.6	9.9	33.4	29.2	83.0
2030	10.9	10.6	34.7	29.0	84.1

Table 7.44a. Energy Supply: NES with $250/mtC Buildings Standard (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.6	19.3	22.0	6.0	7.7	70.7
2000	18.1	21.0	25.1	6.2	8.8	79.3
2005	21.7	20.1	28.5	6.5	10.2	87.0
2010	21.3	19.5	32.5	7.0	11.9	92.2
2015	17.5	20.6	34.1	7.0	14.5	93.7
2020	15.1	20.5	35.0	8.4	17.3	96.4
2025	12.6	19.3	36.6	10.5	20.2	99.2
2030	11.0	17.8	38.1	12.5	22.5	101.8

Table 7.44b. Energy Supply: NES with $500/mtC Buildings Standard (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.6	19.1	21.8	6.0	7.7	70.3
2000	18.1	20.7	25.0	6.2	8.8	78.7
2005	21.8	19.9	28.2	6.5	10.2	86.5
2010	21.3	19.4	32.1	7.0	11.9	91.6
2015	17.5	20.5	33.6	7.0	14.5	93.1
2020	15.1	20.4	34.5	8.4	17.3	95.8
2025	12.6	19.1	36.1	10.5	20.2	.5
2030	11.0	17.7	37.5	12.4	22.5	101.1

Table 7.44c. Energy Supply: NES with $1,000/mtC Buildings Standard (quads)

Year	Oil	Gas	Coal	Nuc	Rnew	Total
1990	17.9	17.8	21.6	5.9	6.8	70.0
1995	15.6	18.9	21.8	6.0	7.7	69.9
2000	18.0	20.3	24.9	6.2	8.8	78.2
2005	21.7	19.6	28.1	6.5	10.1	86.0
2010	21.2	19.0	31.9	7.0	11.9	90.9
2015	17.5	20.1	33.4	7.0	14.5	92.4
2020	15.1	20.0	34.3	8.3	17.3	95.0
2025	12.6	18.7	35.8	10.4	20.1	97.6
2030	11.0	17.3	37.2	12.3	22.4	100.2

Table 7.45a. Energy Trade: NES with $250/mtC Buildings Standard (quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	16.5	1.4	(2.6)	0.1	0.0	15.3
1995	18.8	1.9	(2.6)	0.2	0.7	18.1
2000	17.5	2.3	(3.3)	0.2	1.0	16.4
2005	15.4	2.8	(4.3)	0.2	1.9	13.9
2010	16.4	2.6	(5.8)	0.2	3.2	13.3
2015	20.6	2.5	(6.4)	0.3	3.2	16.7
2020	22.5	2.4	(6.8)	0.3	3.2	18.0
2025	23.9	2.3	(7.1)	0.3	3.2	19.1
2030	24.6	2.5	(7.2)	0.4	3.2	19.9

Table 7.45b. Energy Trade: NES with $500/mtC Buildings Standard (quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	16.5	1.4	(2.6)	0.1	0.0	15.3
1995	18.8	1.9	(2.6)	0.2	0.7	18.1
2000	17.5	2.3	(3.3)	0.2	1.0	16.4
2005	15.4	2.8	(4.3)	0.2	1.9	13.9
2010	16.5	2.6	(5.8)	0.2	3.2	13.3
2015	20.6	2.5	(6.4)	0.3	3.2	16.6
2020	22.4	2.3	(6.8)	0.3	3.2	18.0
2025	23.8	2.3	(7.1)	0.3	3.2	19.0
2030	24.6	2.4	(7.2)	0.4	3.2	19.9

Table 7.45c. Energy Trade: NES with $1,000/mtC Buildings Standard (quads)

Year	Oil	Gas	Coal	Electricity	Alcohol	Net Energy Imports
1990	16.5	1.4	(2.6)	0.1	0.0	15.3
1995	18.8	1.8	(2.6)	0.2	0.7	18.1
2000	17.5	2.3	(3.3)	0.2	1.0	16.4
2005	15.3	2.8	(4.3)	0.2	1.9	13.8
2010	16.4	2.6	(5.8)	0.2	3.2	13.2
2015	20.5	2.4	(6.4)	0.3	3.2	16.5
2020	22.3	2.3	(6.8)	0.3	3.2	17.8
2025	23.7	2.2	(7.1)	0.3	3.2	18.9
2030	24.4	2.4	(7.2)	0.4	3.2	19.6

Table 7.46a. Carbon Emissions: NES with $250/mtC Buildings Standard (by fuel--TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total	Carbon Emissions Reduction (% from NES Actions)
1990	546	274	477	2	1299	--
1995	542	298	497	3	1340	3%
2000	560	327	555	4	1446	3%
2005	591	319	616	5	1532	3%
2010	604	306	681	6	1597	3%
2015	616	319	706	8	1649	3%
2020	614	315	720	14	1664	3%
2025	599	297	753	17	1667	3%
2030	586	279	789	18	1672	2%

Table 7.46b. Carbon Emissions: NES with $500/mtC Buildings Standard (by fuel--TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total	Carbon Emissions Reduction (% from NES Actions)
1990	546	274	477	2	1299	--
1995	542	296	492	3	1333	3%
2000	560	322	552	4	1437	3%
2005	590	316	610	5	1521	3%
2010	603	304	671	6	1585	3%
2015	616	317	694	8	1634	4%
2020	614	313	707	14	1649	4%
2025	599	295	739	17	1650	4%
2030	585	277	773	18	1654	3%

1990 to 1707 TgC/yr 2030. Higher building efficiency standards cause these 2030 levels to decrease to 1672 TgC/yr in the $250 standards case, to 1654 TgC/yr in the $500 Case, and to 1635 TgC/yr in the case of the most stringent standard. This last value is only 4% lower than the value in the NES Actions. Methane emission reductions from the NES Actions Case are on the same relative order of magnitude. Under the NES Actions, total methane emissions increase from 10.8 $TgCH_4$ to 15.5 $TgCH_4$ over the simulation period. Under the higher buildings standards, these 2030 values fall slightly, but never more than about 4.0% lower than the NES Actions figure.

7.4.4 The Cost of Greenhouse Gas Emissions Reductions

The GWP and energy results sections of this chapter have shown that the imposition of higher buildings efficiency standards on the U.S. energy economy produces small reductions in greenhouse

Table 7.46c. Carbon Emissions: NES with $1,000/mtC Buildings Standard (by fuel--TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total	Carbon Emissions Reduction (% from NES Actions)
1990	546	274	477	2	1299	--
1995	541	292	491	3	1326	4%
2000	558	316	551	4	1428	4%
2005	588	311	605	5	1510	4%
2010	601	298	666	6	1570	4%
2015	612	309	689	8	1619	5%
2020	610	306	702	14	1632	5%
2025	596	287	732	17	1632	5%
2030	582	270	765	18	1635	4%

Table 7.47a. Methane Emissions: NES with $250/mtC Buildings Standard ($TgCH_4$/yr)

Year	Coal Mines	Natural Gas Prod	Nat. Gas Trans.& Dist.	Total
1990	4.1	2.1	5.6	11.8
1995	4.2	2.3	6.2	12.6
2000	4.8	2.5	6.8	14.0
2005	5.4	2.4	6.7	14.5
2010	6.2	2.3	6.5	15.0
2015	6.5	2.4	6.7	15.7
2020	6.7	2.4	6.7	15.8
2025	7.0	2.3	6.3	15.5
2030	7.3	2.1	5.9	15.3

gas emissions and the GWP from these emissions. However, the marginal costs of these standards, which are associated with the $250/mtC, $500/mtC, and $1000/mtC, tax levels, are relatively high in terms of what is achieved.

Approach to Computing Cost

The cost of the buildings standards have been computed using a procedure that differs from that employed in Chapter 6 for the Carbon Tax Cases. This procedure accounts for the extra cost of emissions reductions associated with a regulation and the accompanying take-back problems. It does not compute the potential benefits associated with reduced transactions costs. Consequently, these costs should be viewed as an upper bound. The procedure was as follows. The methods for computing the cost of carbon emissions reductions in the Buildings Standards Case are somewhat different than those used in Chapter 6 to compute the marginal, average, and total costs of emissions reductions. When a carbon tax was imposed, it was possible to interpret the tax as the difference between the marginal cost of producing carbon-based fuels and the marginal product of using those fuels in the production of new final goods and services. We will refer to the difference between the

Table 7.47b. Methane Emissions: NES with $500/mtC Buildings Standard ($TgCH_4$/yr)

Year	Coal Mines	Natural Gas Prod	Nat. Gas Trans.& Dist.	Total
1990	4.1	2.1	5.6	11.8
1995	4.2	2.2	6.1	12.5
2000	4.8	2.4	6.7	13.9
2005	5.4	2.3	6.6	14.3
2010	6.1	2.3	6.4	14.8
2015	6.4	2.4	6.7	15.5
2020	6.6	2.4	6.6	15.6
2025	6.9	2.2	6.3	15.4
2030	7.2	2.1	5.9	15.1

Table 7.47c. Methane Emissions: NES with $1,000/mtC Buildings Standard ($TgCH_4$/yr)

Year	Coal Mines	Natural Gas Prod	Nat. Gas Trans.& Dist.	Total
1990	4.1	2.1	5.6	11.8
1995	4.2	2.2	6.1	12.4
2000	4.7	2.4	6.6	13.7
2005	5.4	2.3	6.5	14.2
2010	6.1	2.2	6.3	14.6
2015	6.4	2.4	6.6	15.3
2020	6.5	2.3	6.5	15.4
2025	6.8	2.2	6.1	15.1
2030	7.1	2.0	5.7	14.9

marginal cost of producing carbon and the marginal product of carbon in producing GNP as the marginal cost of carbon emissions. The tax rate is simply the marginal cost of carbon emissions reductions. In Chapter 6, total cost was calculated by obtaining a mapping between the various tax rates and associated carbon emissions reductions and integrating over emissions reductions. This integral provided an estimate of the GNP lost to society.

When a tax is imposed, the tax provides an incentive for consumers of energy to substitute non-fossil fuels for fossil fuels, to substitute other goods and services for energy, and to substitute capital and other factors of production for energy in the production of energy services. When standards are imposed, there is no tax to provide an incentive for consumers of energy to substitute non-fossil fuels for fossil fuels and to substitute other goods and services for energy. The standards do, however, mandate the substitution of capital for energy in the production of energy services.

Figure 7.5 illustrates the relationships between the analysis of a tax and the analysis of standards. Schedule MP(co2), the marginal product of carbon in terms of GNP, shows the relationship between the CO_2 release with each additional unit of fossil fuels and the increase in GNP obtained by using the energy and release of CO_2. MC(co2) is the

marginal cost of carbon schedule. It shows the cost, in terms of GNP, of producing each additional unit of fossil fuel carbon. GNP increases whenever the marginal product of carbon exceeds the marginal cost of carbon. In a competitive economy, fossil fuels will continue to be used to the point at which the marginal product of using carbon fuels exactly equals the marginal cost of producing carbon fuels. In Figure 7.5, this occurs at Point A, with a marginal cost of carbon of MC(ref) and a carbon emission of CO2(ref).

As discussed earlier, when a carbon tax, TAX, equal to the interval T-U is imposed, carbon emissions are reduced as long as the marginal product is higher than the marginal cost plus the tax. As long as the marginal product of carbon is greater than the marginal cost plus the tax, producers increase their profits or decrease their losses by reducing the use of carbon-based fuels. An economy facing a carbon tax of TAX therefore reduces its carbon emission to CO2(tax), and its GNP by the area defined by the Points A, T, and U.

The imposition of a set of buildings standards mandating the level of energy efficiency in capital equipment that would have been obtained under a carbon tax, TAX, does not result in a reduction of carbon emissions to the level CO2(tax). The reason is that the tax, which provided an economic penalty for energy consumption, does not accompany the energy-conserving technology. The higher energy consumption and carbon emissions associated with the decline in energy service costs accompanying efficiency standards are referred to as the take-back problem.

To analyze the take-back problem, we begin by noting that the imposition of standards reduces some of the degrees of freedom available to the users of energy. Specifically, the substitution of energy for capital is foreclosed. This results in a kink in the marginal product of carbon schedule, causing the schedule to be less elastic at carbon costs less than MC(tx)+TAX in Figure 7.5. The option to use less conservation technology and to substitute non-fossil fuels for fossil fuels, and other factors of production for energy conservation is no longer available. The available marginal product of carbon schedule is therefore limited to the schedule MP'(co2) below Point T.

The carbon emissions associated with the pre-standard economy are diminished by the standard and begin to fall because the marginal cost of carbon production, MC(ref), now exceeds the constrained marginal product of carbon given along the MP'(co2) schedule. Emissions continue to decline until the marginal cost of carbon emissions falls and the constrained marginal product of carbon emissions rises to MC(std), associated with Point S in Figure 7.5.

We note that at this new equilibrium, carbon emissions are higher than under a Carbon Tax Case that yields the same level of conservation, unless the elasticity of the MP'(co2) schedule is zero; that is, CO2(std) is greater than CO2(tax). But both are lower than the pre-policy Reference Case.

The total cost in foregone GNP is equal to the area defined by the Points A, S, and T. This is greater than the costs that would have been obtained had a carbon tax been used to generate the carbon emission reduction to CO_2(std). In the latter case, the GNP loss would have been equal to the area defined by the Points A, B and S. The GNP loss is less than the loss that would have been associated with a tax sufficient to produce the level of energy efficiency associated with the tax, TAX.

This analysis suggests that an estimate of the total cost, TC(std), of a carbon emissions reduction to level CO_2(std) could be obtained by computing the total cost associated with the carbon tax, TC(tax), and then subtracting the area T-S-U.

One of the clear implications is that standards will achieve a given emissions reduction at a cost in excess of that which would have been required to achieve the same reduction using a carbon tax. This result holds if the economy is operating efficiently. As we have already noted, the presence of market imperfections can modify or reverse this

conclusion; that is, if a standard corrects a market imperfection and thereby improves overall economy efficiency, it is possible for the benefits of this improvement to more than offset increased costs due to static inefficiency, even if the regulation represents a second-best policy instrument.

The Cost of Reducing Carbon Emissions

The relationships between costs and reductions in carbon emissions and in GWP for three Buildings Standards Cases are shown in Tables 7.48a, b, and c, respectively. The total costs given are the additional total cost of the more stringent buildings standards, since the standards in the NES Actions Case are used as the reference point for measuring all costs. Total costs in the $250/mtC Case range from $2 billion to $5 billion a year. For the $500/mtC and $1,000/mtC Cases, the comparable cost estimates are $7 billion to $13 billion and $11 billion to $18 billion per year, respectively.

As indicated above, the marginal costs are the tax rates associated with each standard. The average costs are shown in Tables 7.48a, b, and c. Here, the average cost ranges from $57/mtC to $114/mtC in the $250/mtCCase to $224/mtC to $241/mtC in the case of the most stringent standard. The ranges

Table 7.48a. Relationship Between Costs and Emissions Reductions $250/mtC Buildings Standard Case

Year	Total Cost (bil $/yr)	Carbon Reduction (TgC/yr)	Average Cost ($/mtC)	GWP Reduction ($TgCO_2e$/yr)	GWP Reduction (% 1990)
1995	$2	35	$57	146	6%
2000	$3	41	$73	171	11%
2005	$3	42	$71	173	8%
2010	$4	43	$93	177	5%
2015	$4	47	$85	190	3%
2020	$5	46	$109	185	3%
2025	$4	43	$93	174	5%
2030	$4	35	$114	140	7%

Table 7.48b. Relationship Between Costs and Emissions Reductions $500/mtC Buildings Standard Case

Year	Total Cost (bil $/yr)	Carbon Reduction (TgC/yr)	Average Cost ($/mtC)	GWP Reduction ($TgCO_2e$/yr)	GWP Reduction (% 1990)
1995	$7	$43	163	178	7%
2000	$10	49	$204	206	11%
2005	$10	52	$192	215	8%
2010	$11	56	$196	227	6%
2015	$13	61	$213	249	4%
2020	$13	61	$213	249	4%
2025	$13	60	$217	243	5%
2030	$11	53	$208	211	8%

Table 7.48c. Relationship Between Costs and Emissions Reductions $1000/mtC Buildings Standard Case

Year	Total Cost (bil $/yr)	Carbon Reduction (TgC/yr)	Average Cost ($/mtC)	GWP Reduction ($TgCO_2e$/yr)	GWP Reduction (% 1990)
1995	$11	49	$224	205	7%
2000	$14	58	$241	246	12%
2005	$15	63	$238	263	9%
2010	$16	70	$229	287	7%
2015	$18	77	$234	314	5%
2020	$18	77	$234	317	5%
2025	$18	78	$231	317	6%
2030	$17	72	$236	290	9%

of average costs, shown here, are generally lower than the corresponding ranges of average costs for the carbon and GWP taxes covered in Chapter 6. Thus, the average costs associated with the $250/mtC and $500/mtC Buildings Standards Cases are slightly lower than the average costs for the comparable Carbon and GWP Tax Cases. The average costs for the $1000/mtC Buildings Case are just about the same as the average costs for the $750/mtC Tax Cases, suggesting that these costs would be even lower than the average costs associated with $1000/mtC Tax Cases (which were not included as part of the analysis in Chapter 6).

Tables 7.48a, b, and c also indicate that the Buildings Standards Cases are not powerful instruments for reducing GWP beyond the reductions obtained by the NES Actions Case. For instance, in 2030, the $1000/mtC standards achieve only a 9% reduction in annual GWP relative to 1990 levels. Although such a reduction is still important, the percentage reduction achieved is several times less than that of the Reforestation, Powerplant Efficiency Standards, and Fiscal Policy Cases.

7.4.5 Summary of Findings: Buildings Standards Cases

The Buildings Standards Cases, when acting in isolation from other greenhouse gas policies, are not as effective as other policies studied here in reducing carbon and GWP-weighted emissions relative to the NES Actions scenario. This finding does not mean that such standards are not, in general, useful and effective measures for reducing emissions and energy consumption. Instead, it indicates the success of the NES Actions in achieving a high level of energy efficiency in buildings; therefore, there is a smaller incremental gain to be captured in applying buildings standards that go beyond the NES. Buildings standards may still play an important role as part of a comprehensive policy for reducing domestic energy consumption and greenhouse gas emissions.

7.5 TRANSPORTATION FUEL EFFICIENCY IMPROVEMENTS

An important part of the current debate about transportation energy efficiency standards is centered on the relationship between the impacts of these standards on energy consumption and CO_2 emissions and the corresponding effects of the NES (DOE 1991a,b). While a number of analyses have been conducted of transportation energy efficiency standards in conjunction with existing policies, the purpose of this analysis is to investigate the impacts of increasing transportation fuel efficiency of conventionally-powered vehicles beyond that achieved by the actions contained in the NES. As such, this analysis is really not a policy analysis of fuel

efficiency standards, but is intended to be a more limited, parametric analysis of the impacts of higher fuel efficiency on the production of greenhouse gases and on the energy economy of the United States.

In the discussion that follows we address the methodology and assumptions used to model increased fuel efficiency; the effects of these increases on GWP; the impacts of increasing the fuel efficiency of conventionally-powered vehicles on the U.S. energy economy; and the cost of increasing the fuel efficiency of conventionally-powered vehicles. In broad terms, the analysis reveals that the additional effects of even fairly large increases in fuel efficiency on emissions and energy use are relatively small. This is because substantial reductions in non-renewable energy use and transportation-related emissions are achieved in the NES Actions Case through the introduction and rapid growth of passenger vehicles driven either by electricity or by fuel cells and turbine engines running on methanol and natural gas. As the fleet of non-conventionally-powered vehicles in the NES Actions Case grows rapidly over time, increasing the fuel efficiency of conventionally-powered vehicles has a smaller and smaller effect on the fuel efficiency of light duty vehicles.

7.5.1 Assumptions and Approach

The NES Actions Case assumes substantial growth in not only the number of non-conventionally-powered vehicles in the passenger vehicle fleet, but also the percentage of these vehicles in relation to the passenger fleet as a whole. Some indication of this can be seen in Table 7.49, which shows the number of passenger vehicles in service, classified by type of fuel, for the period 1990 to 2030. In 1990, the share of non-conventionally-fueled passenger vehicles is zero. By 2010, this share has grown to 30% and, by the end of the period, just over 56% of total passenger vehicles in service are non-gasoline-driven. Indeed, in 2030, methanol-powered vehicles constitute exactly the same percentage of the total as do gasoline-powered vehicles, or about 43%. More importantly, what this table does not show is that by 2010, only 10% of the new non-conventionally-fueled vehicles sold in the United States are powered by heat engines. By 2030, all of the new non-gasoline-powered vehicles in the NES Actions light duty vehicle fleet are powered by non-conventional engines (i.e., electric motors, fuel cells and turbines).

Table 7.49. Number of Passenger Vehicles in the NES Actions Case by Type of Fuel (millions)

Year	Gasoline	Methanol	Nat. Gas	Electric	Total
1990	164.89	0.00	0.00	0.00	164.29
1995	175.17	0.51	0.40	0.00	176.08
2000	184.63	6.20	1.50	0.20	192.53
2005	176.12	27.60	3.10	1.00	207.87
2010	154.71	58.60	4.20	4.40	221.91
2015	144.99	75.00	3.40	10.20	233.59
2020	136.76	85.10	3.30	16.50	241.66
2025	121.31	98.90	3.90	24.70	248.81
2030	111.28	111.50	3.70	29.70	256.18

The growth in the number of non-gasoline-powered vehicles in the NES Actions Case has a marked impact on transportation energy use. It causes about a 10-quad (about 25%) decrease in energy use by the transportation sector, relative to the Current Policy Base Case. However, from a modeling standpoint, the assumed growth of non-conventionally-fueled (and -powered) vehicles in the NES Actions raises at least two important sets of methodological issues. The first set of issues is related to the fact that the effective fuel economy of non-conventionally-powered vehicles is quite a bit higher than that of gasoline vehicles. For example, in 2030, the assumed on-road fuel efficiency of gasoline-powered vehicles in the NES Actions Case is 22.75 mpg, while the average efficiency for all passenger vehicles is 33.5 mpg. The difference is explained by the fact that the average efficiency of the non-conventionally-powered passenger vehicles is about 50 mpg. This raises two important policy-related questions. First, does it make any sense to analyze further increases in fuel efficiency as an approach to reducing greenhouse gas emissions? Second, should the increases in fuel efficiency be applied to all new passenger vehicles, or just those fueled by gasoline?

The first question can be partially answered by conducting a sensitivity analysis to determine the magnitude of the incremental effect of higher fuel efficiency on energy use and greenhouse gas emissions. The answer to the second question is that this, too, will depend on the incremental effects of different approaches to distributing the fuel efficiency increases across the fuel types. For the purposes of this analysis, we examined increases in fuel efficiency only in the gasoline-powered segment of the new vehicle market. Since these increases had a relatively small impact on energy use and emissions, the decision was made not to extend higher fuel efficiencies to non-conventionally-fueled vehicles. However, a more important factor that dictated this approach was simply that the alternative vehicles that increasingly penetrate the market in the NES Actions are not powered by conventional engines. Instead, the alternative vehicles assumed in the NES Actions are powered by electricity, fuel cells, and turbine engines, all of which have very high fuel efficiencies. The fuel efficiency gains achieved by conventionally-powered vehicles are based on engine and drive train technologies that are simply not applicable to the alternative technology vehicles in the NES Actions.

The second set of issues created by the assumptions about non-conventionally-powered vehicles in the NES Actions Case relates to the ability to use existing models to accurately characterize the impacts of efficiency increases on the fleet as a whole. Because existing transportation models available for use in this study focus primarily on gasoline-fueled and -powered vehicles, it is very difficult to use them to estimate the effects of fuel economy increases on the composition of the fleet as a whole and on the number of vehicle miles traveled by conventional and non-conventional vehicles. Changes in these variables feed back into the transportation system and influence the overall effectiveness of fuel economy increases, further complicating the problems associated with using existing models to estimate how fuel efficiency increases impact the total size of the fleet and the total number of miles driven. Because the models do not capture these interactions, some simplifying assumptions about the relationship between these two segments of the fleet must be adopted.

Given the above limitations, the approach adopted in this analysis is more along the lines of a sensitivity analysis than it is an effort to project the effects of increases in transportation energy efficiency into the future. An existing econometric model (Santini and Vyas 1989) was used to try to duplicate the NES Actions Case and to assess the effects of two different sets of transportation energy efficiency "growth paths" (to be discussed shortly) on average fleet efficiency, total vehicle miles traveled, fuel use, and total vehicles, all for gasoline-powered vehicles. As indicated above, the composition of the passenger vehicle fleet in the NES Actions Case made it very difficult to duplicate the NES results (assumptions) for vehicle miles, fuel use, and total vehicles. Therefore, it was decided that as a first approximation, only the results

regarding the effects of the two fuel economy growth paths on the average mpg of gasoline-powered passenger vehicles would be changed in the Fossil2 Model. The values for total vehicles and total vehicle miles traveled would not be altered. Simulating the effects of these fuel efficiency increases on fuel use and emissions would then provide information regarding the benefits of improving the sophistication of the methodology. As it turned out, both of the fuel efficiency growth paths had a marginal impact on energy use and emissions. It does not appear that improving the sophistication of the analysis with regard to gasoline-powered vehicles would alter these results.

Table 7.50 shows the values for the new car transportation energy efficiency increases (test) mpg and the average (actual, on-road) mpg for gasoline-fueled vehicles used in the two Transportation Energy Efficiency Increase Cases. The first case is modeled after the Bryan Bill, now before Congress, which calls for proportional increases in new car fuel efficiency reaching about 40 mpg in 2005 and remaining constant thereafter. The second case, labeled Bryan Plus, derives its name from the fact that it requires steady increases in the fuel efficiency of new gasoline-fueled vehicles of about 1.9% per year from 2005 until 2030. For purposes of comparison, the table also shows the average mpg for gasoline-fueled vehicles in the NES Actions Case. Table 7.51 presents the average fuel economy for all vehicles used in the NES Actions and two Transportation Energy Efficiency Increase Cases. The technical feasibility of achieving the mpg figures in the Bryan Plus Case was not considered. Rather, these mpg estimates were developed for the purposes of sensitivity analysis to determine the physical magnitude of the energy conservation and emission reduction benefits associated with very high mandated mpg estimates.

The estimation of the costs of fuel efficiency increases is also problematic because of the way in which the interactions between conventionally- and non-conventionally-fueled passenger vehicles are accounted for in the transportation models available for this analysis. The cost estimates are based on work by Greene et al.[a] on a slightly different version of the Bryan Bill than the one used in this analysis. The cost estimates developed by Greene et al. consist of the following components:

(a) NES Energy Strategy Working Group on Automotive Fuel Economy. 1991. Costs and Benefits of Automotive Fuel Economy Improvement: A Partial Analysis. Oak Ridge National Laboratory, Oak Ridge, Tennessee (draft).

Table 7.50. Fuel Economy Assumptions For Gasoline-Fueled Passenger Vehicles in Transportation Energy Efficiency Increase Cases (mpg)

Year	NES Avg. (Actual mpg)	Bryan Trans. Eff. (Test mpg)	Bryan Avg. (Actual mpg)	Bryan Plus Trans. Eff. (Test mpg)	Bryan Plus Avg. (Actual mpg)
1990	19.7	27.6	19.7	27.6	19.7
1995	20.0	33.2	20.4	33.2	20.4
2000	20.6	38.8	22.0	38.8	22.0
2005	20.8	40.0	23.5	42.9	23.8
2010	21.1	40.0	26.0	46.7	27.7
2015	21.9	40.0	27.6	49.9	31.5
2020	22.4	40.0	29.0	53.3	35.2
2025	22.6	40.0	30.4	55.2	38.6
2030	22.8	40.0	31.7	60.0	42.5

Table 7.51. Average Fuel Economy of All Passenger Vehicles in the NES Actions and Transportation Energy Efficiency Increase Cases (mpg)

Year	NES	Bryan	Bryan Plus
1990	19.7	19.7	19.7
1995	20.1	20.4	20.4
2000	20.8	22.1	22.1
2005	22.1	24.7	25.0
2010	24.2	28.5	29.9
2015	26.3	31.1	34.1
2020	28.5	34.1	38.7
2025	31.0	37.4	42.9
2030	33.5	40.9	47.6

1. the difference in the cost of the technology required to achieve the higher fuel efficiency, as measured in the retail price change

2. the direct fuel savings of higher mpg, as a benefit that offsets costs.

These cost estimates do not include:

1. the portion of the change in consumer and producer surplus associated with each fuel efficiency increase that is not captured by the difference in retail price

2. the monopsony effect that is due to changes in world oil prices

3. the energy security benefits from energy conservation

4. the safety cost associated with lighter vehicles, which could be positive or negative.

On balance, most analysts would agree that the cost estimates provided here understate, systematically, the true social cost of each fuel efficiency increase. This is because the magnitude of the loss in consumer and producer surpluses that is not included in the estimates is larger than any offsetting components that are also not included in the estimate.[a]

The data from Greene et al. on the costs and mpg targets associated with several different fuel economy trajectories for gasoline-powered passenger cars and light trucks were used to estimate the parameters of two statistical models, relating the increment in new car and light truck prices to changes in the test mpg of these vehicles. These models were used to translate the transportation energy efficiency mpg estimates in this study into estimates of the cost differences per vehicle associated with these alternative fuel economy trajectories. These cost differences were then multiplied by the total number of new gasoline-fueled passenger vehicles to obtain estimates of the total cost (net of fuel savings) associated with each fuel efficiency trajectory on a year-by-year basis.

The interaction problems described above make it difficult to use models available for this study to calculate new car sales. Since new car sales are highly volatile, a decision was made to integrate this variability into the sensitivity analysis. Over the last 10 years, annual new car sales have ranged from roughly 8% to 12% of the total fleet of passenger vehicles. For this analysis, new car sales were derived by multiplying the number of gasoline-fueled vehicles from the Fossil2 Model by 0.10. Average costs were determined by dividing the total cost estimates by the fossil fuel emissions differences (between the NES Actions Case and the Fuel Efficiency Increase Cases) in each year.

7.5.2 Comparison of GWP-Weighted Emissions Reductions Relative to the NES Actions Case

Tables 7.52 and 7.53 show the impact of the two Transportation Energy Efficiency Increase Cases on the GWP of six different gases. The decreases in total GWP relative to the NES Actions Case are small. In the Bryan Case, these differences range

(a) This statement is based on a concept of social cost that is tied to the objective of economic efficiency. Other objectives will lead to different social cost concepts and accounts.

Table 7.52. GWP-Weighted Energy-Related Emissions by Gas and by Year: NES, Bryan Transportation Energy Efficiency Increase Case ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFC & Other	HCFCs	Total
1990	4527	455	626	17	1689	144	7458
1995	4757	478	493	18	1062	326	7134
2000	5066	509	555	20	360	299	6809
2005	5281	531	589	22	326	254	7002
2010	5422	545	604	23	179	366	7139
2015	5613	564	612	24	58	458	7328
2020	5659	569	607	24	5	470	7333
2025	5661	589	589	25	3	350	7198
2030	5654	568	568	25	2	172	6989

Table 7.53. GWP-Weighted Energy-Related Emissions by Gas and by Year: NES Bryan-Plus Transportation Energy Efficiency Increase Case ($TgCO_2e$)

Year	CO_2	CO	CH_4	N_2O	CFC & Other	HCFCs	Total
1990	4527	455	626	17	1689	144	7458
1995	4757	478	493	18	1062	326	7134
2000	5066	509	555	20	360	299	6809
2005	5276	530	589	22	326	254	6996
2010	5399	542	604	23	179	366	7114
2015	5570	560	611	24	58	458	7280
2020	5603	563	606	24	5	470	7271
2025	5604	563	589	25	3	350	7134
2030	5595	562	567	25	2	172	6923

from 9 $TgCO_2$ in 1995 to 93 $TgCO_2$ in 2030. In the Bryan Plus Case, the equivalent range of GWP reductions is 9 $TgCO_2$ to 159 $TgCO_2$. These reductions are quite small in percentage terms. For example, the percentage differences between the total GWP estimates in the NES Actions Case and those in the Bryan Case range from 1.0% to 1.3%. The corresponding range for the Bryan Plus Case is just a little higher, from less than 1% to about 1.6%. The analysis suggests that using transportation energy efficiency standards to increase the fuel economy of passenger vehicles beyond that in the NES Actions Case produces very small reductions in greenhouse gas emissions.

7.5.3 Energy Results Compared With the NES Actions Case

In general, the transportation energy efficiency increases presented here had only a small impact on the energy economy of the United States. While some modest reductions in oil and gasoline prices

and in transportation energy use were achieved, these reductions did not lead to large-scale fuel switching, nor to any significant changes in the supply and demand situation for primary energy resources.

Primary Energy Consumption

Tables 7.54 and 7.55 show the differences between primary energy consumption, by fuel, in the NES Actions Case and the two Transportation Energy Efficiency Increase Cases. Numbers in parentheses indicate decreases in magnitude. This convention is followed throughout the remainder of the tables. Most of the decreases in primary energy use occur because the effects of the energy efficiency increases are concentrated in the consumption of oil. Under the Bryan Case, oil consumption decreases range from 2% to 4% relative to the NES Actions Case during the simulation period. In the

Table 7.54. Primary Energy Consumption: Bryan Transportation Energy Efficiency Increase Case (quads)

Year	Oil	Gas	Coal	Nuclear	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	0
1995	34.6	22.2	20.0	6.0	7.7	0.8	(0.2)
2000	35.4	24.7	22.3	6.2	9.0	1.2	(0.6)
2005	36.3	23.9	25.0	6.5	10.3	2.1	(1.1)
2010	36.5	22.7	27.8	7.0	11.8	3.4	(1.7)
2015	36.8	23.7	28.8	6.9	14.4	3.4	(1.7)
2020	36.2	23.4	29.5	8.3	17.2	3.5	(1.8)
2025	35.0	21.8	30.9	10.5	20.1	3.5	(1.8)
2030	34.1	20.1	32.3	12.5	22.3	3.5	(1.7)

Table 7.55. Primary Energy Consumption: Bryan Plus Transportation Energy Efficiency Increase Case (quads)

Year	Oil	Gas	Coal	Nuclear	Rnew	Alcohol & Electricity Imports	Total
1990	34.4	19.2	19.0	5.9	6.8	0.1	0
1995	34.6	22.2	20.0	6.0	7.7	0.8	(0.2)
2000	35.4	24.7	22.3	6.2	9.0	1.2	(0.6)
2005	36.2	23.9	25.0	6.5	10.3	2.1	(1.2)
2010	36.1	22.7	27.8	7.0	11.8	3.4	(2.2)
2015	36.1	23.7	28.8	6.9	14.3	3.4	(2.6)
2020	35.2	23.3	29.5	8.3	17.2	3.5	(3.0)
2025	34.0	21.8	30.9	10.5	20.0	3.5	(3.0)
2030	33.1	20.0	32.3	12.5	22.3	3.5	(3.0)

Bryan Plus Case, these figures are on the order of 4% to 7% lower than in the NES Actions Case. Overall, total primary energy consumption decreases in the two cases range from 1% to 2% in the Bryan Case and 1% to 3% in the Bryan Plus Case--generally quite small. What cannot be seen here, but is still of interest, is that virtually all of the decrease in oil consumption that occurs as a result of the increases in energy efficiency is concentrated in the transportation sector. The spillover effects of these energy efficiency increases into other fuel markets and other sectors are insignificant. In the Bryan Case, the decreases in oil consumption by the transportation sector relative to the NES Actions Case range from 3% to 7%, while in the Bryan Plus Case, these decreases are on the order of 2% to 7%.

End-Use Energy Consumption

The difference between total end-use energy consumption in the NES Actions Case and the two Transportation Energy Efficiency Increase Cases is shown by sector in Tables 7.56 and 7.57. All of the changes in end-use energy consumption are concentrated entirely in the transportation sector. In the Bryan Case, energy use in the transportation sector

Table 7.56. End-Use Energy Consumption: Bryan Transportation Energy Efficiency Increase Case (quads)

Year	Res	Com	Ind	Tran	Total
1990	0	0	0	0	0
1995	0	0	0	(0.2)	(0.2)
2000	0	0	0	(0.6)	(0.6)
2005	0	0	0	(1.1)	(1.1)
2010	0	0	0	(1.7)	(1.7)
2015	0	0	0	(1.8)	(1.8)
2020	0	0	0	(1.8)	(1.8)
2025	0	0	0	(1.8)	(1.8)
2030	0	0	0	(1.7)	(1.7)

Table 7.57. End-Use Energy Consumption: Bryan Plus Transportation Energy Efficiency Increase Case (quads)

Year	Res	Com	Ind	Tran	Total
1990	0	0	0	0	0
1995	0	0	0	(0.2)	(0.2)
2000	0	0	0	(0.6)	(0.6)
2005	0	0	0	(1.3)	(1.3)
2010	0	0	0.1	(2.3)	(2.2)
2015	0	0	0.1	(2.7)	(2.6)
2020	0	0	0.1	(3.0)	(2.9)
2025	0	0	0.1	(3.1)	(3.0)
2030	0	0	0.1	(3.1)	(3.0)

decreases relative to the NES Actions Case by about 1% in 2000 up to about 6% in the year 2010. Thereafter, energy consumption in the transportation sector continues to be about 6% lower than in the NES Actions Case. The pattern is similar, but larger in the Bryan Plus Case, where the decreases in consumption relative to the NES Actions Case grow from about 1% in 2000 to 11% in 2025 and 2030. The decreases in both primary and end-use consumption are concentrated in transportation-related oil consumption because the decrease in the price of oil that occurs as a result of the energy efficiency increases is quite small and has no effect on other end uses or on energy transformation by electric utilities. While the decrease in end-use energy consumption in the transportation sector is not small, the changes in total end-use energy consumption are quite small. In the Bryan Case, the decreases in total end-use energy consumption relative to the NES Actions range from less than 1% in 1995 to about 2% in 2030. In the Bryan Plus Case, these decreases are on the order of less than 1% to 3.5%.

7.5.4 The Cost of Greenhouse Gas Emissions Reductions

Tables 7.58 and 7.59 show the estimated average cost of new gasoline-fueled vehicles, minus fuel savings; the total number of new gasoline-fueled vehicles; and the estimated total net cost of new vehicles for the two Energy Efficiency Increase Cases. These total cost estimates include the undiscounted future cost of new gasoline-fueled vehicles and the net fuel savings that result from increased fuel economy. However, as previously mentioned, these are only private costs. The social cost of the increases in energy efficiency is higher, because the private costs do not capture all of the economic welfare losses associated with the fuel economy increases.

In the Bryan Case, these costs are estimated to be about $9.6 billion in 1995, rising to a maximum of $23.2 billion in 2005, then declining with new car sales to $14.8 billion in 2030. The total cost estimates are identical in the two cases between 1990 and 2000. After that period, estimated costs rise steadily in the Bryan Plus Case from $29.8 billion in 2005 to just under $50 billion in 2030.

Finally, Table 7.60 shows the average cost estimates associated with using the two fuel economy cases to reduce carbon emissions. For the Bryan Case, these estimated costs range from $4800/mtC in 1995 to $355/mtC in 2030. For the Bryan Plus Case, the average estimated cost of reducing fossil fuel CO_2 emissions is estimated to be 4800/mtC in 1995. By 2030, the estimated average cost falls so that it is $1264/mtC. These costs are relatively high when one considers that they only include the additional cost of new vehicles minus fuel savings. Also, since average costs must lie below marginal costs when average costs are increasing (as they are with more efficient vehicles), then the average cost estimates shown in Table 7.60 must lie below the marginal costs. How much lower cannot be determined without additional analysis, since the estimates shown here do not include the full social costs associated with increased fuel efficiency. Thus, the carbon taxes required to achieve GWP reductions equivalent to those shown in Table 7.60 would be even higher than the average cost estimates.

7.5.5 Summary of Findings: Transportation Energy Efficiency Increase Cases

The objective of this analysis has been to determine what impact additional increases in the fuel efficiency of conventionally-powered vehicles will have on emissions of greenhouse gases and on the cost of these efficiency gains when they occur in conjunction with the policy actions contemplated under the NES. We have found, first of all, that increases in the fuel economy of conventionally-powered light duty vehicles cause only a small decrease in emissions of greenhouse gases relative to those reductions achieved by the NES Actions. In addition, this study has also shown that additional increases in fuel efficiency produce similarly small decreases in both primary and end-use energy consumption. As expected, most of the decreases in energy consumption that occurred as a result of

Table 7.58. Estimated New Vehicle Cost, Sales and Total Cost, Net of Fuel Savings, for the Bryan Fuel Economy Case

Year	Avg. New Vehicles Cost ($/Vehicle)	New Conv. Vehicle Sales (Million)	Total Cost, New Conv. Vehicles ($Billions)
1990	0	16.4	0
1995	546	17.6	9.6
2000	1177	18.4	21.6
2005	1316	17.6	23.2
2010	1316	15.4	20.2
2015	1316	14.4	19.0
2020	1316	13.7	17.8
2025	1316	12.2	16.0
2030	1316	11.2	14.8

Table 7.59. Estimated New Vehicle Cost, Sales and Total Cost, Net of Fuel Savings, for the Bryan Plus Fuel Economy Case

Year	Avg. New Vehicles Cost ($/Vehicle)	New Conv. Vehicle Sales (Million)	Total Cost, New Conv. Vehicles ($Billions)
1990	0	16.4	0
1995	546	17.6	9.6
2000	1177	18.4	21.6
2005	1694	17.6	29.8
2010	2232	15.4	34.4
2015	2704	14.4	39.0
2020	3270	13.7	44.4
2025	3589	12.2	43.8
2030	4454	11.2	49.8

additional transportation energy efficiency increases were concentrated in petroleum and gasoline consumption. The relatively small impacts of additional increases in fuel economy can be explained by the fact that the actions taken under the NES virtually exhaust all of the cost-effective emissions reduction and energy conservation potential in the energy economy of the United States. For example, in the year 2030, more than 50% of the fleet of passenger vehicles in the NES Actions Case consists of alternatively-powered vehicles. As a result of this, only a small reservoir of efficiency improvements is available from conventionally-powered vehicles. In general, this analysis has revealed that increases in fuel efficiency in conjunction with the policy actions contemplated under the NES are potentially very expensive.

Finally, it is important to remember that this study is a sensitivity analysis. Given model limitations, this study was designed to examine the robustness of greenhouse gas emissions over a range of assumptions regarding levels of fuel efficiency and sales of more efficient, conventionally-fueled passenger vehicles, using the NES Actions Case as a baseline. Consequently, the estimated impacts

Table 7.60. Average Cost of Achieving Fossil Fuel Emission Reductions for the Transportation Energy Efficiency Increase Cases

Year	Bryan Case ($mtC/yr)	GWP Reduction ($TgCO_2e/yr$)	Bryan Plus Case ($mtC/yr)	GWP Reduction ($TgCO_2e/yr$)
1995	4800	9	4800	9
2000	2400	34	2400	34
2005	1450	62	1654	68
2010	480	94	1110	119
2015	792	94	1054	142
2020	712	98	1082	160
2025	640	95	1068	159
2030	355	93	1264	159

presented here should not be viewed as predictions, but as indications of the range of results that may foreseeably occur in the future, given the assumptions of the analysis.

7.6 ALTERNATIVE APPROACHES TO MODELING THE COST OF EMISSIONS REDUCTIONS

In the analysis presented here, we have employed techniques to measure the cost of regulations that presume that the institutional underpinnings of the economy remain in effect throughout the course of the analysis. The approach we have employed always shows positive costs for regulatory strategies. A number of studies have been conducted that indicate that costs of emissions reductions may, in fact, be negative. These include, for example, NAS (1991), Carlsmith et al. (1990), Haites (1990), Goldemberg et al. (1987), and Cheng et al. (1985). The potential for confusion when studies disagree even as to the sign of the cost term is great.

The approach used to develop cost estimates generally determines the sign of the result. Technology potential analysis studies generally find that total costs are low or negative. This is the result of the fact that a comparison is made between present average technology practice and the projected best available practice. A paradigm technology is compared to an average practice technology and the difference is reported as the cost savings available. This is sometimes referred to as the "bottom-up" approach.

In contrast, energy system modelers generally compute costs by comparing a reference case, which is assumed to already have minimized costs, with a perturbation. This approach generally leads to positive costs and is sometimes referred to as the "top-down" approach.

No work to date has been completely successful in reconciling these two alternative approaches. Nevertheless, recent work has helped to identify the additional steps required to translate potential gains into realized gains. Grubb (1991) summarized contributions in a workshop on costs of fossil fuel CO_2 emissions reductions, as shown in Figure 7.6. Apparently available emissions reductions due to technology potential can be broken down into six parts:

1) **Business as Usual Achievements:** Some of the gains will be achieved even if no policy is enacted. The technology is cost-effective by any

measure; it clearly provides the services of technologies it replaces and does so with the same or fewer undesirable side effects to the consumer;

2) **Non-Greenhouse Externalities:** The technology is desirable and its implementation is cost-effective when the value of its non-greenhouse attributes are assessed. The substitution of HCFC technology for CFC technology is an example. Here the value of the reduced ozone depletion potential more than compensates for any additional costs associated with the implementation of the alternative technology. Policy action is required to bring such a technology into existence. Policies that are desirable on grounds other than greenhouse gas emissions reductions, but which also reduce greenhouse gas emissions are sometimes referred to as "No Regrets" options;

3) **Correctable Market Imperfections:** In a perfectly competitive economy, there is no need for intervention into the market place except to provide public goods and to alter undesirable distributions of wealth. In the real world, there are a great many instances in which markets do not work perfectly. There are costs of acquiring and processing information, there is unequal access to capital, and there are costs to making and enforcing transactions. Countless examples abound. Apartment dwellers have little incentive to undertake cost-effective conservation measures because their expected residence time is too short to allow investments to pay off. Energy is too small a cost factor to justify the investment in retrofit technologies. The cost of acquiring information about the efficiency and cost characteristics of an energy-conserving technology is too great and the uncertainty in future costs and benefits too great to justify acquiring new energy-conserving technologies. The interest rate consumers can obtain for investments is much greater than for large firms.

4) **Takeback and Feedback:** If policies such as energy efficiency standards require the use of more energy-efficient technology, some of the gains that would have been obtained if the provision of energy service had remained constant can be lost if consumers respond to the reduced cost of providing that energy service by consuming it in greater quantity. For example, if cars become more fuel efficient, the cost of a passenger kilometer of road travel is reduced. Drivers will find it cheaper to drive cars and can therefore be expected to increase driving. This increase in driving results in more energy consumption than would have been estimated if the number of passenger kilometers traveled had been assumed constant.

   In addition, there are potential feedback problems. If the economy becomes more capital intensive as a result of the use of a lower threshold discount rate, then there will be an increase in the demand for capital. As a consequence, the real interest rate would be bid up by an amount dependent upon the elasticity of supply of savings. Since there is no reason to believe that the energy sector is the only sector for which the apparent consumer discount rate exceeds the social discount rate, extending this principle to the entire economy would result in an even greater increase in the demand for capital and a consequently higher real interest rate.

5) **Hidden Costs:** While technology cost estimates can identify general patterns, there are numerous specific applications that do not fit the general model. The existence of heterogeneous, non-standard applications for energy services leads to the less-than-expected gains from the policy-induced introduction of a technology.

6) **Consumer Resistance:** The technology may provide the energy service in a cost-effective manner, but it may have some other undesirable attributes from the perspective of consumers. Public transportation may require longer commuting times or impose inconvenient schedules on commuters.

The key problems are to identify the extent to which apparently available carbon emissions

reductions are achievable, and if such potential gains exist, to identify policy instruments capable of accessing these gains without incurring greater real social costs.

With regard to computing the extent of apparently available gains that are potentially available, only the extent of items 2 and 3 are at issue. Item 1 is not available because it is included in the reference case. Items 4, 5, and 6 are not available because they represent real, irreducible net costs. The NES Actions have identified a great number of individual actions that, without raising taxes, improve overall energy system efficiency. As we discuss in Chapter 11, the NES Actions Case is not inconsistent with the results of the NAS (1991) bottom-up analysis.

We have been unable to identify any measures beyond NES Actions capable of reducing greenhouse gas emissions for which benefits exceed costs. This does not mean that, at some future date, attractive policy instruments will not be identified.

7.6.1 Sensitivity of the Results to the Apparent Consumer Discount Rate

One of the contributions of the bottom-up approach has been to identify the fact that there is a possibility of providing the same energy services with greater capital inputs and lower energy inputs than are reflected in average practice.[a] We attempt to bound the value of emissions reduction potential by conducting a sensitivity analysis. To do this we compare two cases. The first is the NES Actions Case; the second is the NES Actions Case with the required internal rate of return on capital by end-use activities reduced to 5%. We shall refer to this latter case as the "Discount Rate Sensitivity Case."

By reducing the apparent consumer discount rate to 5%, we act as if all of the difference between the observed values and 5% can be attributed to market imperfections. This assumption is extreme. In fact, all of the difference between the observed apparent consumer discount rate and the 5% rate we have chosen may reflect real, irreducible costs included in items 5 and 6 above. We note, however, that by embedding the analysis in the Fossil2 modeling structure, the effects of the takeback phenomenon are explicitly considered.[b]

This analysis does not argue that the computed reduction in the cost of greenhouse gas emissions reductions is either potentially available or achievable with any identifiable policy instrument. This analysis is conducted purely as a sensitivity and is an attempt to express the bottom-up approach within a top-down analysis structure. We further note that one of the effects of the successful implementation of the NES Actions is to capture potentially available gains from efficient energy technologies.

The effect on GWP of reducing the internal rate of return in the Fossil2 Model to 5% on the effectiveness of various carbon tax rates and the associated total cost of carbon emissions reductions can be seen in Figures 7.7 through 7.15. In general, in terms of GWP-weighted energy-related emissions, both the total and marginal cost of emissions reductions are lower in the Discount Rate Sensitivity Case than in the NES Actions Case, but the amount by which costs are lower varies considerably. The lower costs reflect the fact that at lower internal rates of return, investments in energy-efficient end-use technologies are greater at any carbon tax rate.

As shown in Table 7.61, the Discount Rate Sensitivity Case reduces the tax rate necessary to hold carbon emissions constant through the year 2000, relative to 1990, from approximately $140/mtC to zero, and the tax rate necessary to reduce emissions by 20%, relative to 1990, from approximately $500/mtC to approximately $350/mtC.

(a) We note that the fact that while individual end-use energy applications may be more capital intensive than the technologies they replace, the full energy system capital intensity may either increase or decrease, depending on the specific energy technology under consideration and relevant prices and interest rates.

(b) We note that Fossil2 takes the demand for energy services as given. Therefore, no accounting is made for the feedback effect on the demand for energy services.

Table 7.61. Discount Rate Sensitivity Case: Marginal Cost ($/mtC) vs. Carbon Emissions Reductions Relative to 1990

	Carbon Tax Rate ($/mtC)						
Year	$0	$25	$50	$100	$250	$500	$750
1995	5%	6%	8%	10%	18%	24%	29%
2000	1%	4%	6%	9%	17%	25%	30%
2005	-6%	-2%	0%	4%	12%	23%	28%
2010	-12%	-8%	-5%	-1%	10%	21%	26%
2015	-16%	-13%	-11%	-5%	9%	22%	26%
2020	-16%	-12%	-10%	-4%	12%	26%	29%
2025	-15%	-9%	-5%	2%	17%	29%	33%
2030	-14%	-7%	-2%	6%	21%	32%	36%

Note: Negative values indicate an increase, relative to 1990.

For the year 2010, we note that there is very little difference between the NES Actions and Discount Rate Sensitivity Cases for tax rates of $250/mtC and above. The maximum tax rates explored for these two cases were $750/mtC, and in neither case did carbon emissions reductions relative to 1990 exceed 30%. In both cases, the marginal cost of reducing emissions by 20% relative to 1990 was approximately $500/mtC in the year 2010. The costs of holding emissions constant were $200/mtC in the year 2010 for the NES Actions Case and $100/mtC for the Discount Rate Sensitivity Case.

By the year 2030, the marginal cost of holding carbon emissions constant relative to 1990 fell to $100/mtC in the NES Actions Case and to $50/mtC for the Discount Rate Sensitivity Case. The cost of reducing emissions by 20%, relative to 1990, fell for both cases to approximately $250/mtC.

In the year 2000, the total cost of holding emissions constant relative to 1990 for the NES Actions Case is approximately $15 billion lower for the Discount Rate Sensitivity Case. The difference in total cost to achieve a 20% reduction in emissions relative to 1990 in the year 2000 is much greater, approximately $50 billion/year.

For the year 2010, the cost of holding emissions constant is approximately $20 billion lower in the Discount Rate Sensitivity Case than in the NES Actions Case. The difference in total cost for an emissions reduction of 20%, relative to 1990, in the year 2010 is approximately $50 billion/year.

For the year 2030, the cost of holding emissions constant is approximately $10 billion lower in the Discount Rate Sensitivity Case than in the NES Actions Case, increasing to approximately $45 billion when emissions are reduced by 20% relative to 1990 emissions.

The effects of the Discount Rate Sensitivity Case assumptions on the cost of reducing GWP-weighted emissions with a comprehensive program of GWP taxes and reforestation credits has also been studied. (See Chapter 8 for a full discussion of this comprehensive program, which combines GWP taxes with a deposit refund for reforestation using the high-cost tree assumptions.)

Figures 7.13, 7.14, and 7.15 illustrate the effect of the Discount Rate Sensitivity Case on the total cost incurred in reducing GWP-weighted emissions with the comprehensive program in the years 2000,

2010, and 2030. From Figure 7.13, the total cost of reducing GWP-weighted emissions by 20%, relative to 1990, in both 2000 and 2010 is approximately $15 billion lower in the Discount Rate Sensitivity Case.

7.7 CONCLUSIONS

Two of the regulatory policy instruments studied were directed at electricity-generating facilities. The first policy, Reforestation, mandated the planting of trees to offset the lifetime carbon emissions of all newly constructed and life-extended fossil fuel-fired stationary combustion facilities. The Reforestation policy reduces carbon emissions in two ways: it imposes a cost penalty on new fossil fuel generating plants, which discourages their construction, and the trees planted for the fossil fuel plants that are still constructed act to sequester the carbon emitted from those plants. Reforestation proved to be the most powerful regulatory policy instrument in reducing GWP-weighted greenhouse gas emissions at a low relative cost, but there are several unaddressed issues and uncertainties associated with implementation and maintenance of the policy.

The second policy aimed at electricity-generating plants was the Powerplant Efficiency Standards. These standards were designed as cost penalties for the construction of new fossil fuel plants that did not employ the most efficient generating technology available. These standards were not as effective as reforestation because they allowed some types of fossil fuel-powered plants, although only the most efficient, to come into operation and emit carbon without suffering any penalties for doing so.

Two of the remaining regulatory instruments studied were standards imposed on energy end-use sectors. The first set of end-use standards were the Buildings Standards. These standards were not nearly as powerful in reducing greenhouse gas emissions beyond the levels achieved in the NES Actions Case as were the fiscal policies or the regulatory policies aimed at utilities. This does not mean that there are few opportunities for energy conservation in the buildings sector; the potential for cost-effective energy conservation in this sector is great. Rather, this result is indicative of the success the NES Actions have in affecting energy conservation. In general, there are only marginal additional gains to be obtained beyond NES Actions.

The second set of end-use standards were the Transportation Energy Efficiency Standards on gasoline-powered passenger vehicle fuel efficiency. The Transportation Energy Efficiency Standards had only a marginal effect on greenhouse gas emissions, relative to the NES Actions Case, due, in part, to the high market share of non-conventional vehicles that penetrate the market in the NES Actions Case.

In general, end-use energy standards that go beyond the NES Actions appear to be relatively expensive as individual strategies for reducing potential future greenhouse gas emissions. This does not mean that there is little opportunity for greenhouse gas emissions reductions in those sectors, relative to today's practices. The NES has simply been highly successful in effecting cost-effective end-use energy conservation, leaving few remaining opportunities.

To address the maximum market potential of currently available technologies for reducing the cost of achieving carbon emissions reductions targets, a Discount Rate Sensitivity Case was studied. As constructed, the Discount Rate Sensitivity Case was identical to the NES Actions Case except that the internal rate of return on capital by end-use activities was reduced to 5%.

In general, both the total and marginal costs of emissions reductions are lower in Discount Rate Sensitivity Case than in the NES Actions Case, but the amount by which costs are lower varies considerably as the degree of reduction sought varies. The lower costs reflect the fact that, at lower internal rates of return, investments in energy-efficient end-use technologies are greater at any carbon tax rate. This sensitivity provides an upper bound on the maximum market potential of currently available

technology. In this regard, three caveats are especially important. First, market potential may be overstated because consumer decisions regarding the technologies may actually reflect heterogeneity in applications or in other product attributes that are not incorporated in the modeling framework, rather than failures in capital markets. Second, there may not be any policies that can capture the technological potential. Finally, even if policies are available, they may present other problems, by failure to account for heterogeneity or other attributes, or by diverting investment resources for alternative opportunities that offer internal rates of return higher than 5%.

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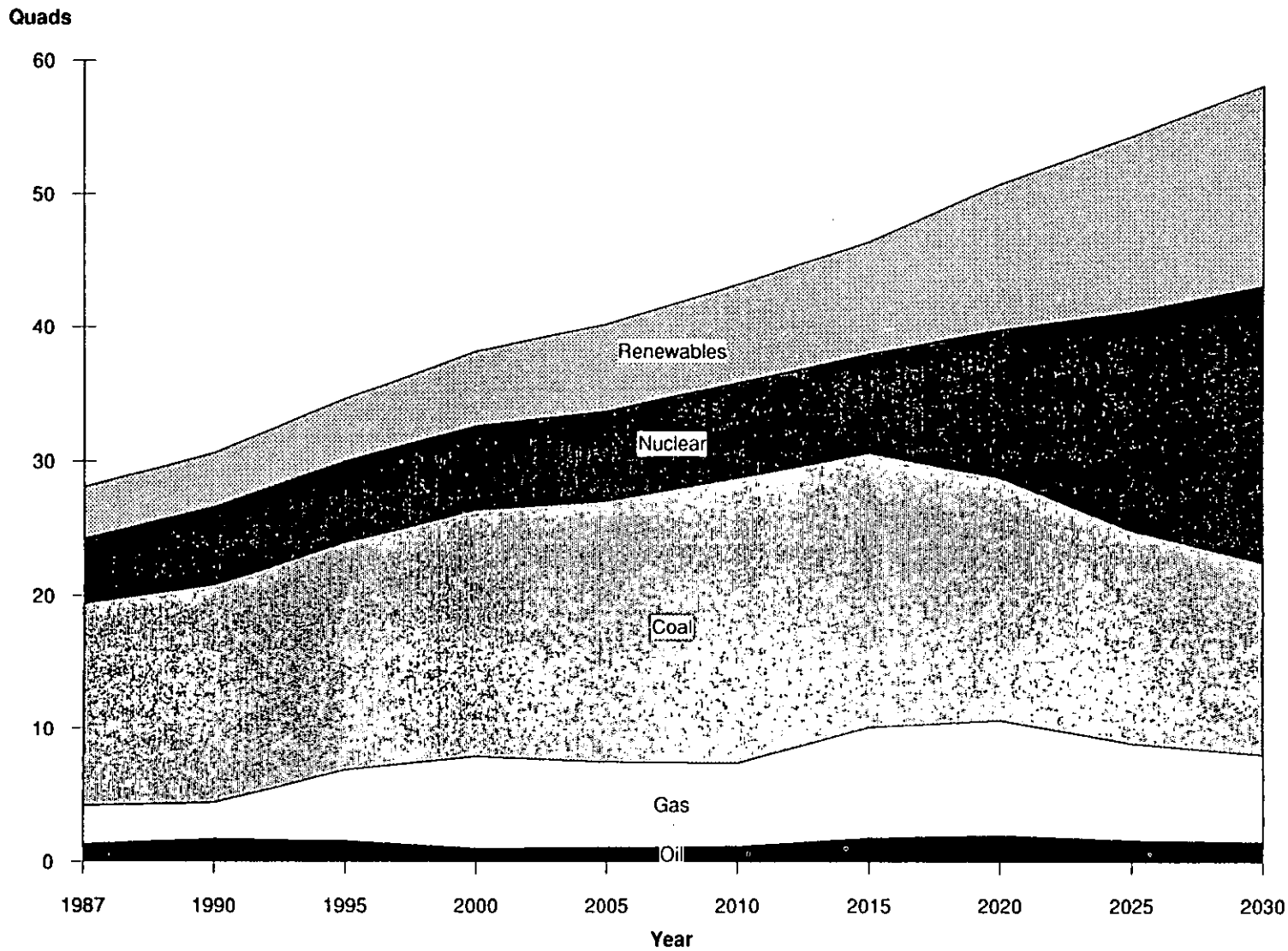

Figure 7.1. Reforestation with High-Cost Trees: Electric Utility Energy Consumption, by Fuel, 1987-2030

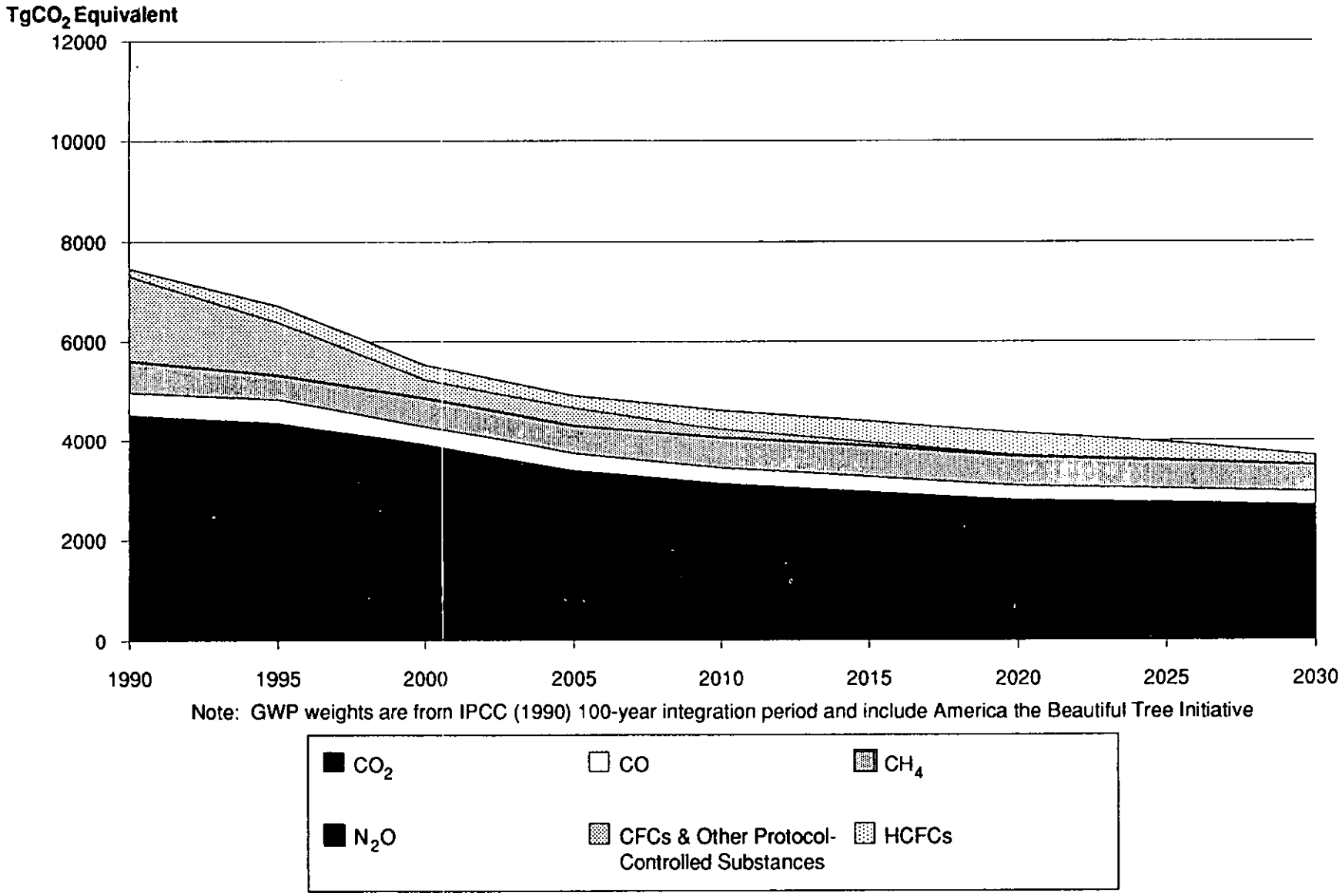

Figure 7.2. Reforestation with High-Cost Trees: GWP-Weighted Energy-Related Emissions by Gas and by Year

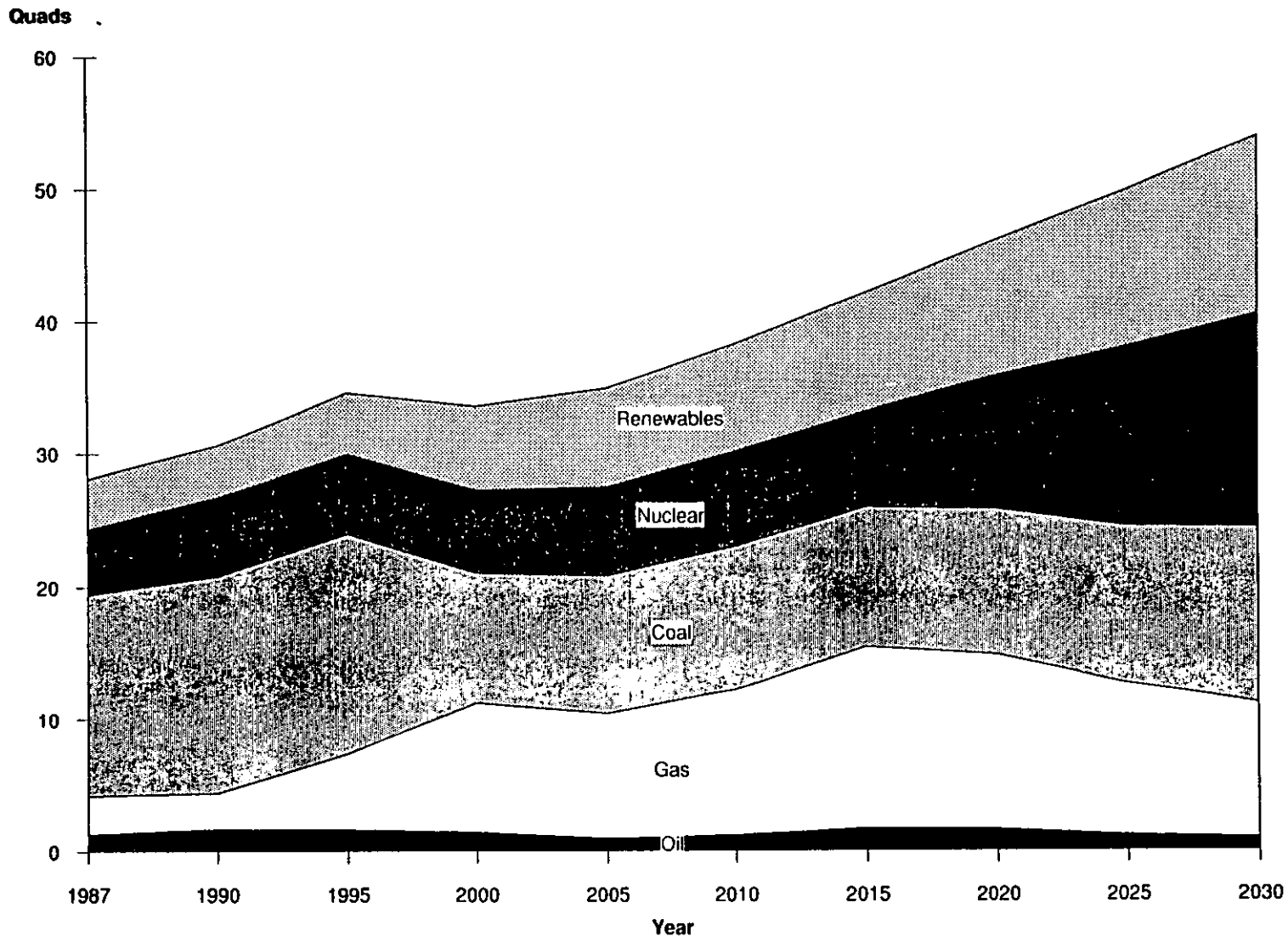

Figure 7.3. Powerplant Efficiency Standards: Electric Utility Energy Consumption, by Fuel, 1987-2030 (quads)

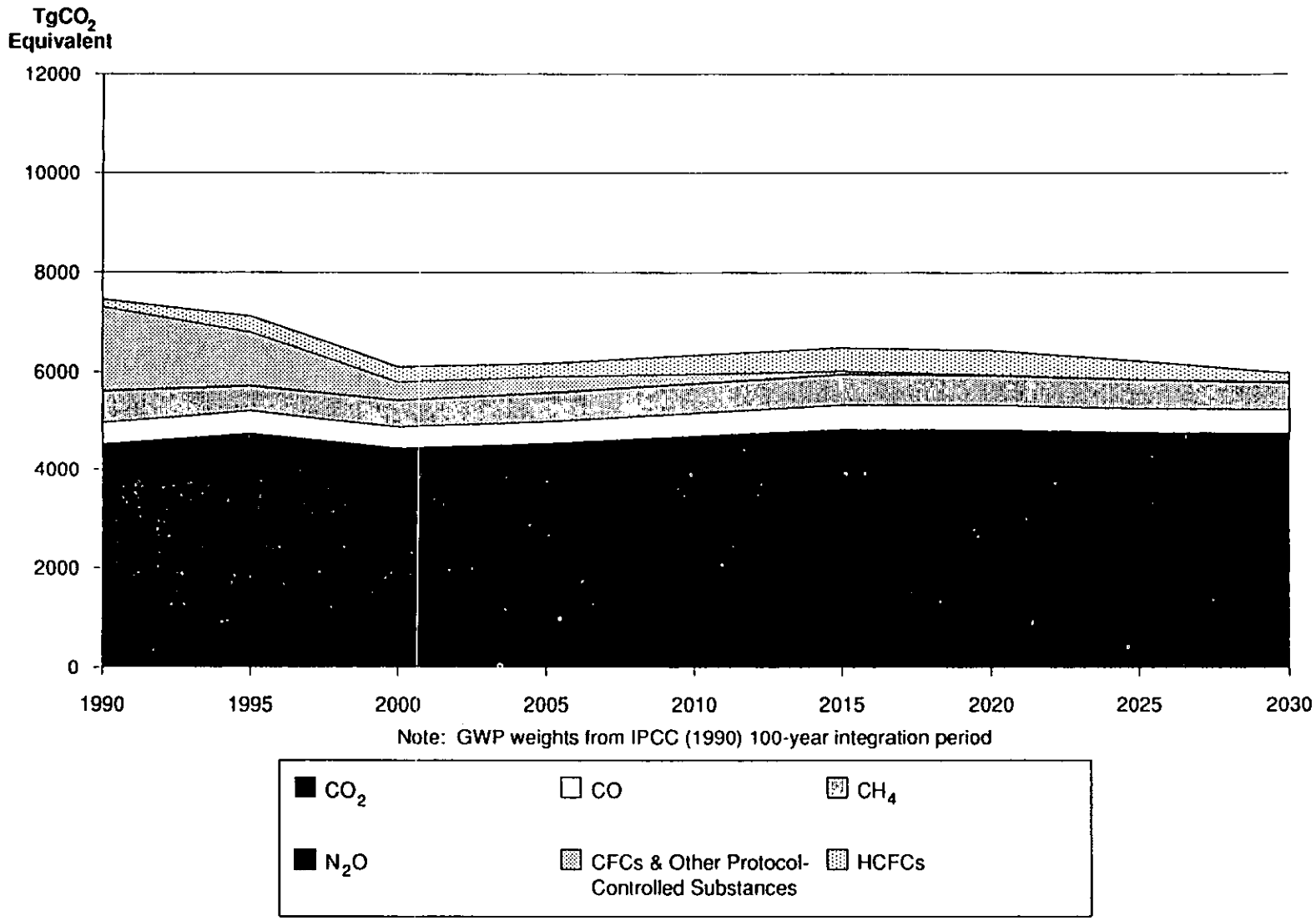

Figure 7.4.. Powerplant Efficiency Standards: GWP-Weighted Energy-Related Emissions by Gas and by Year

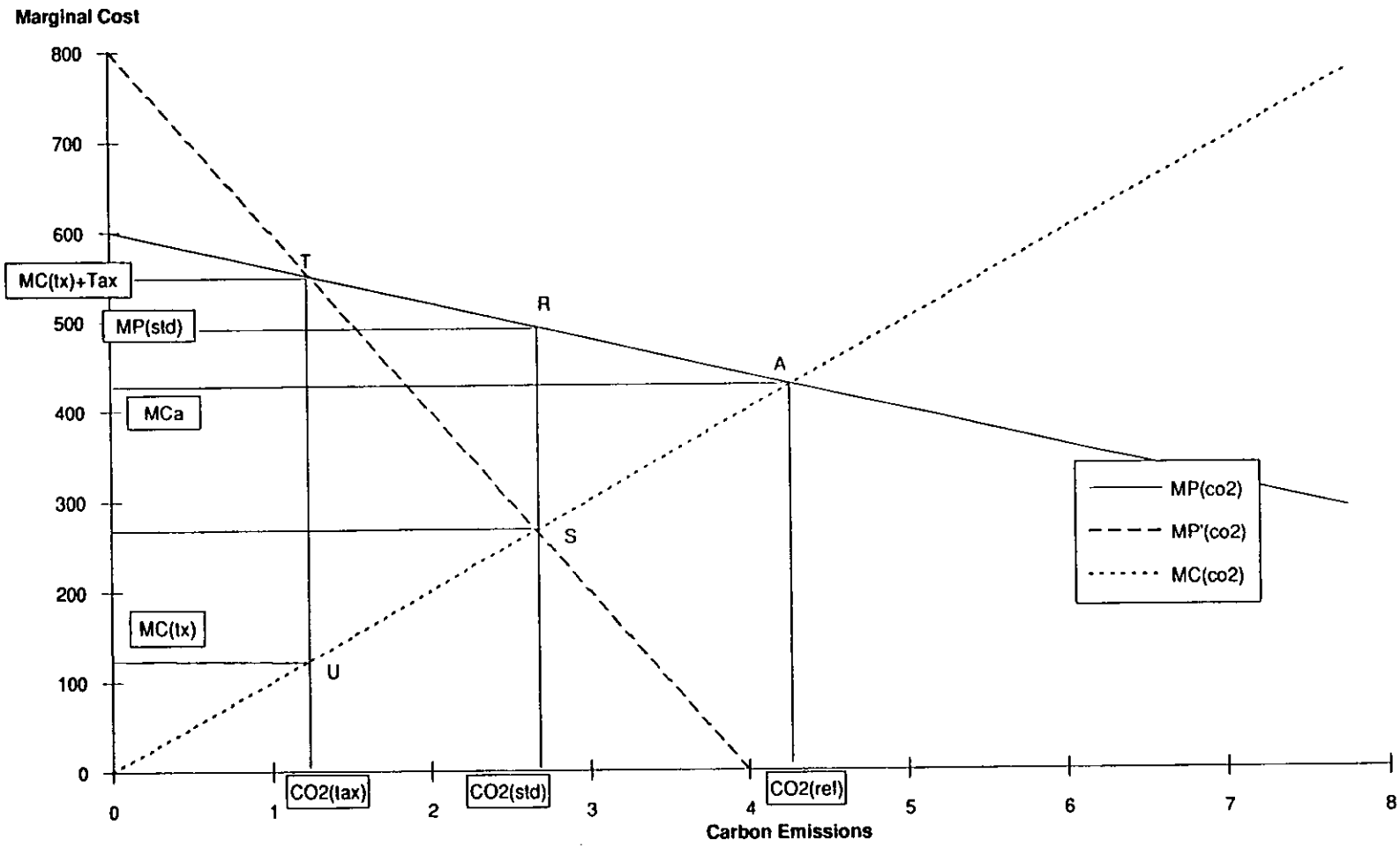

Figure 7.5. Computing the Total Cost of Efficient Buildings Standards

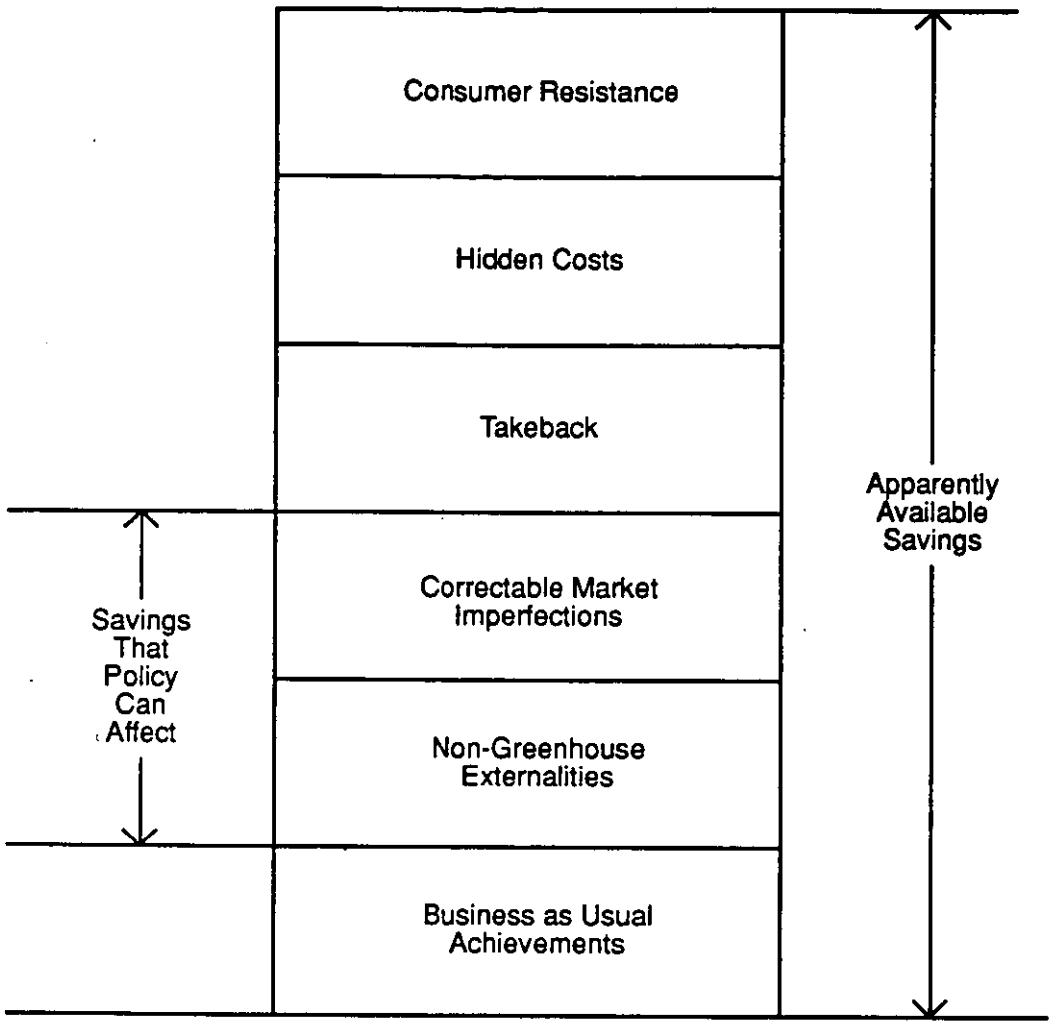

Figure 7.6. Decomposition of Apparently Available Carbon Emissions Reductions

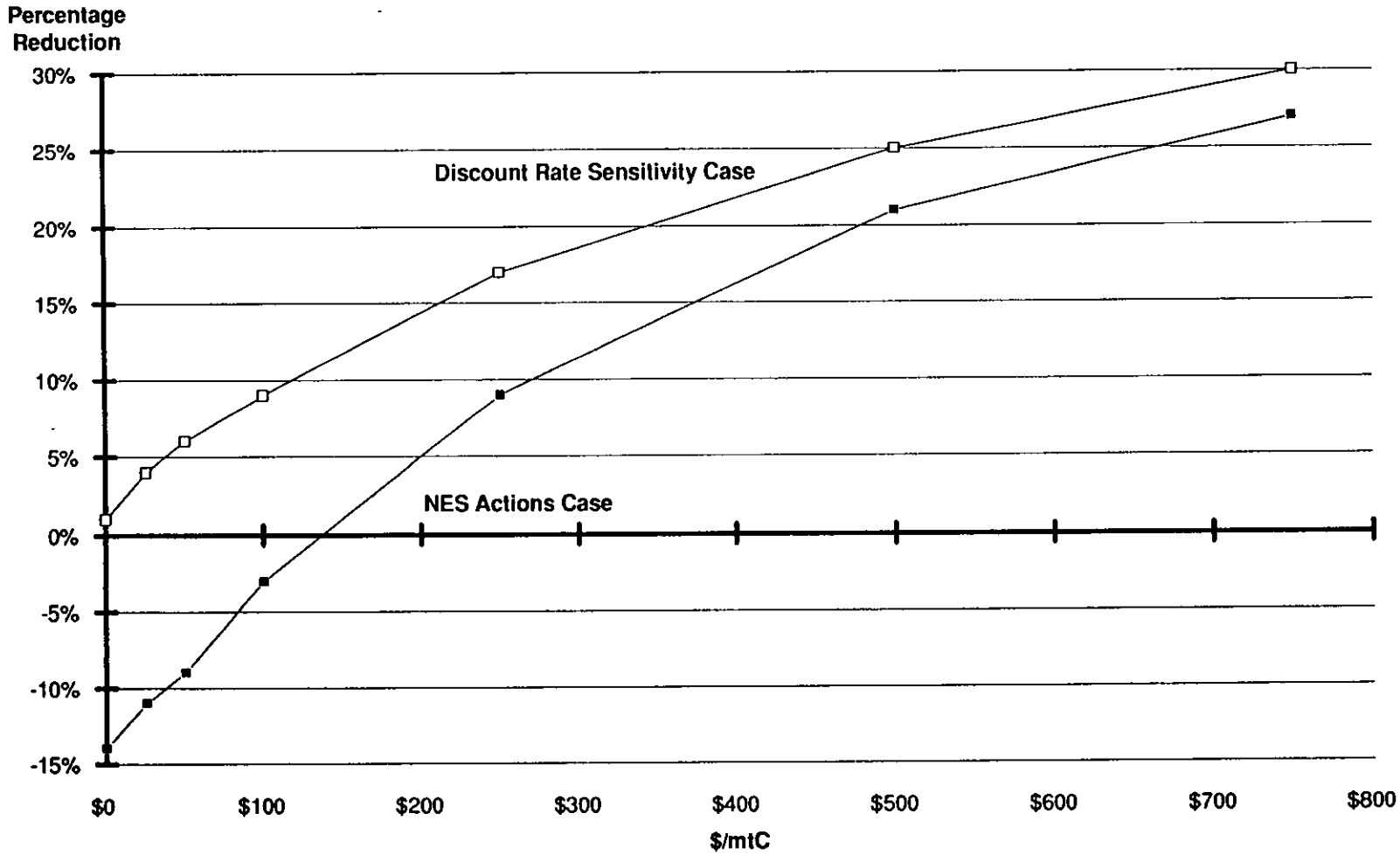

Figure 7.7. Year 2000 % Carbon Emissions Reduction Relative to 1990 vs. Marginal Cost ($/mtC)

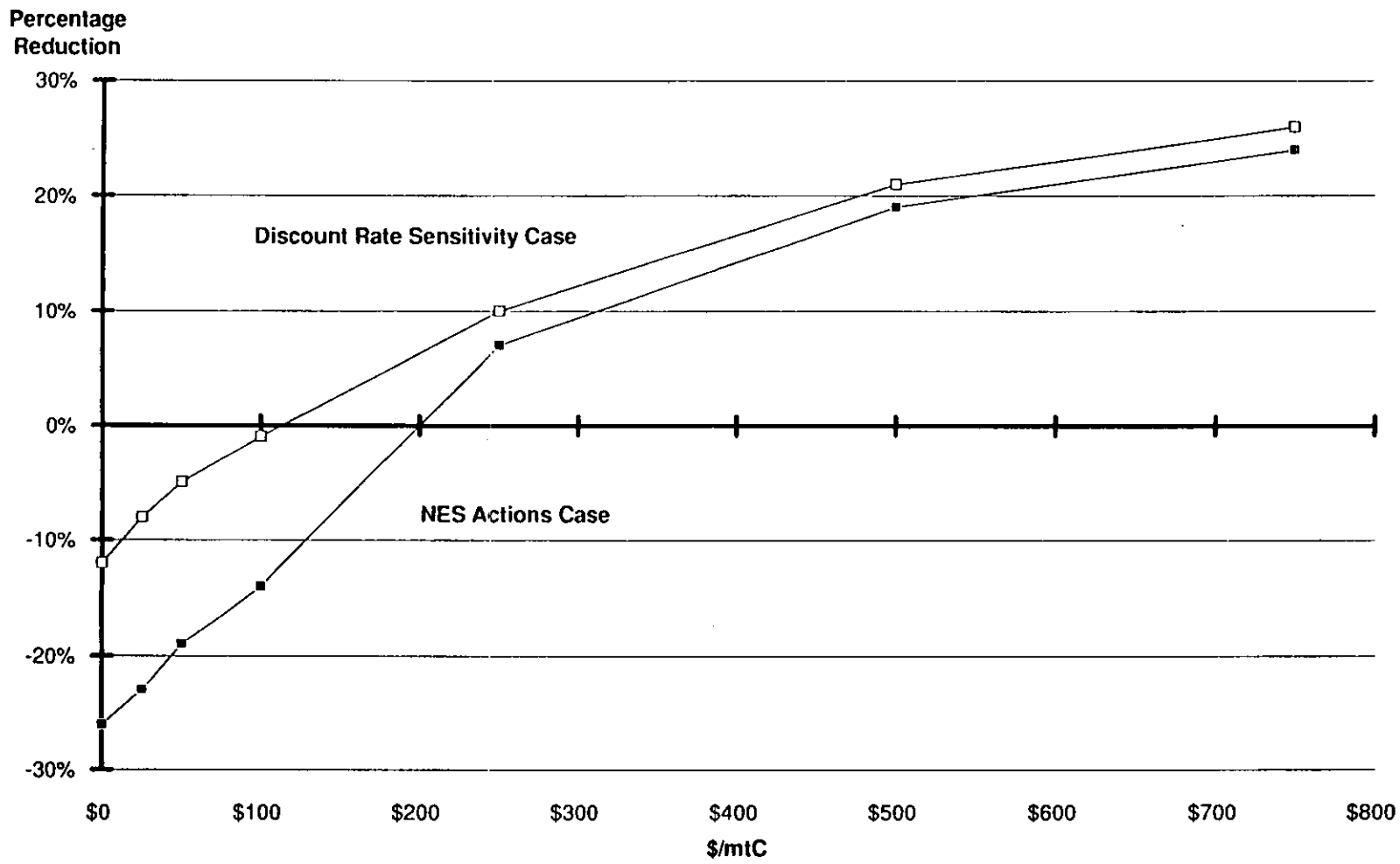

Figure 7.8. Year 2010 % Carbon Emissions Reduction Relative to 1990 vs. Marginal Cost ($/mtC)

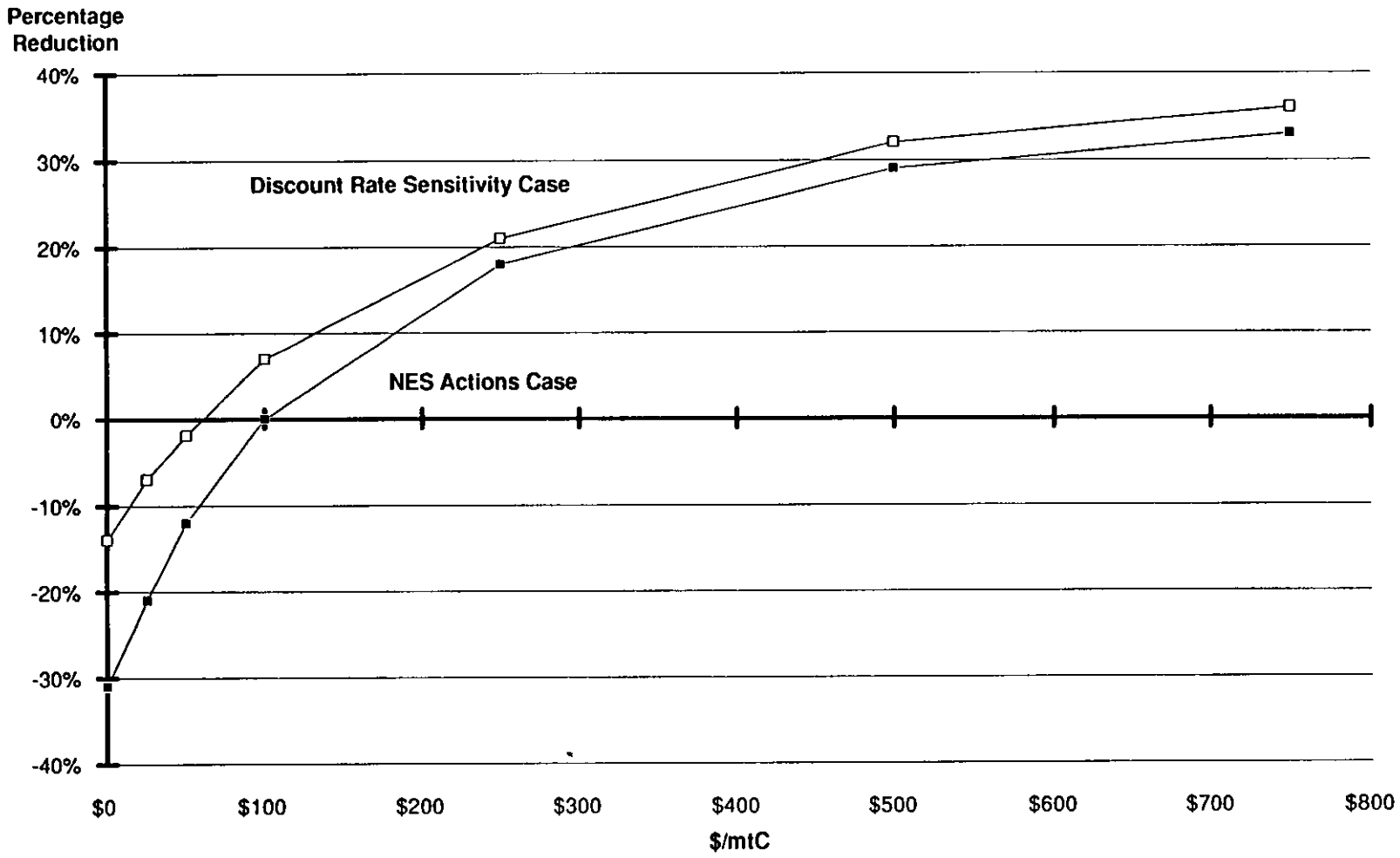

Figure 7.9. Year 2030 % Carbon Emissions Reduction Relative to 1990 vs. Marginal Cost ($/mtC)

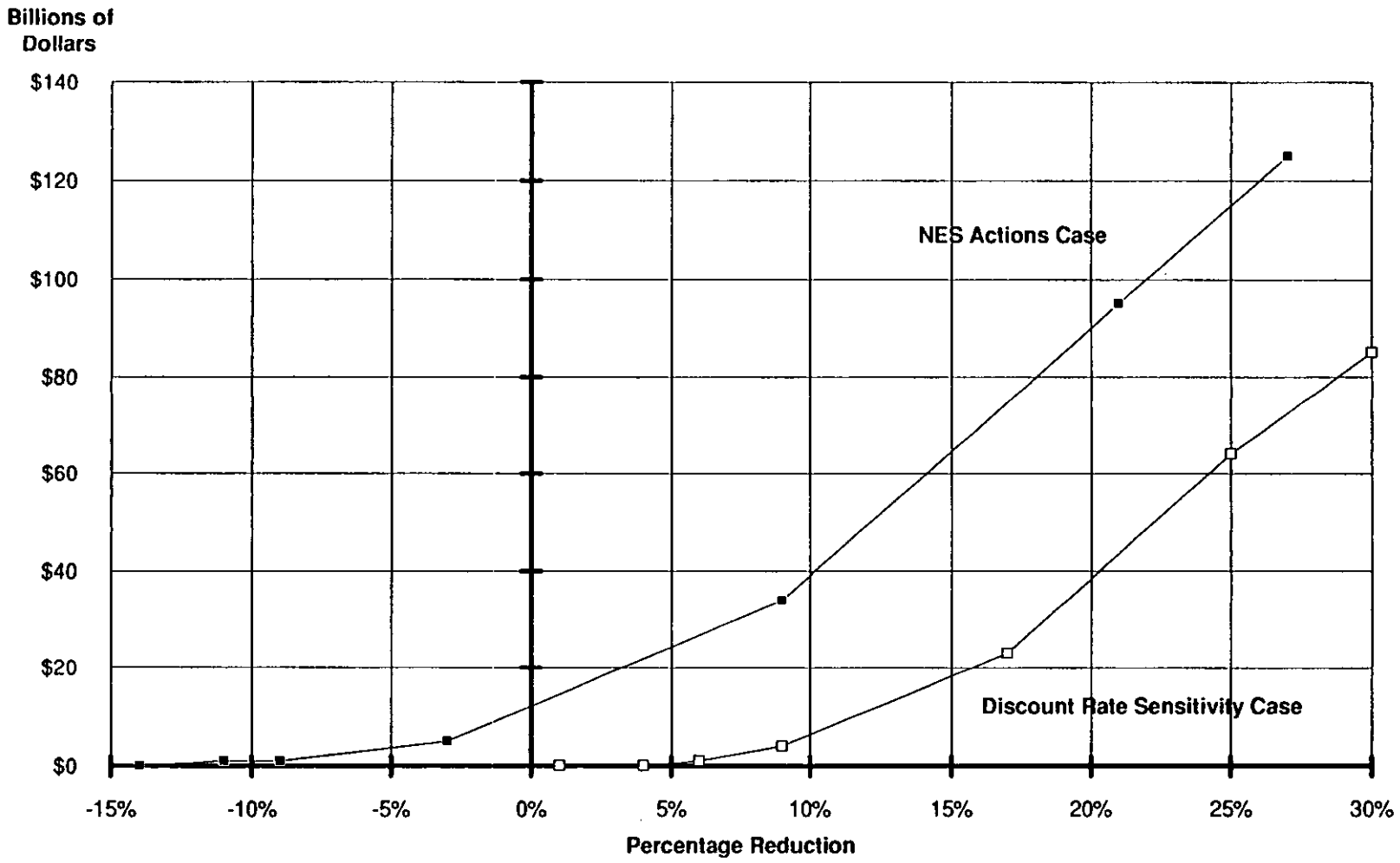

Figure 7.10. Year 2000 Total Cost (billions of dollars) vs. % Carbon Emissions Reduction Relative to 1990

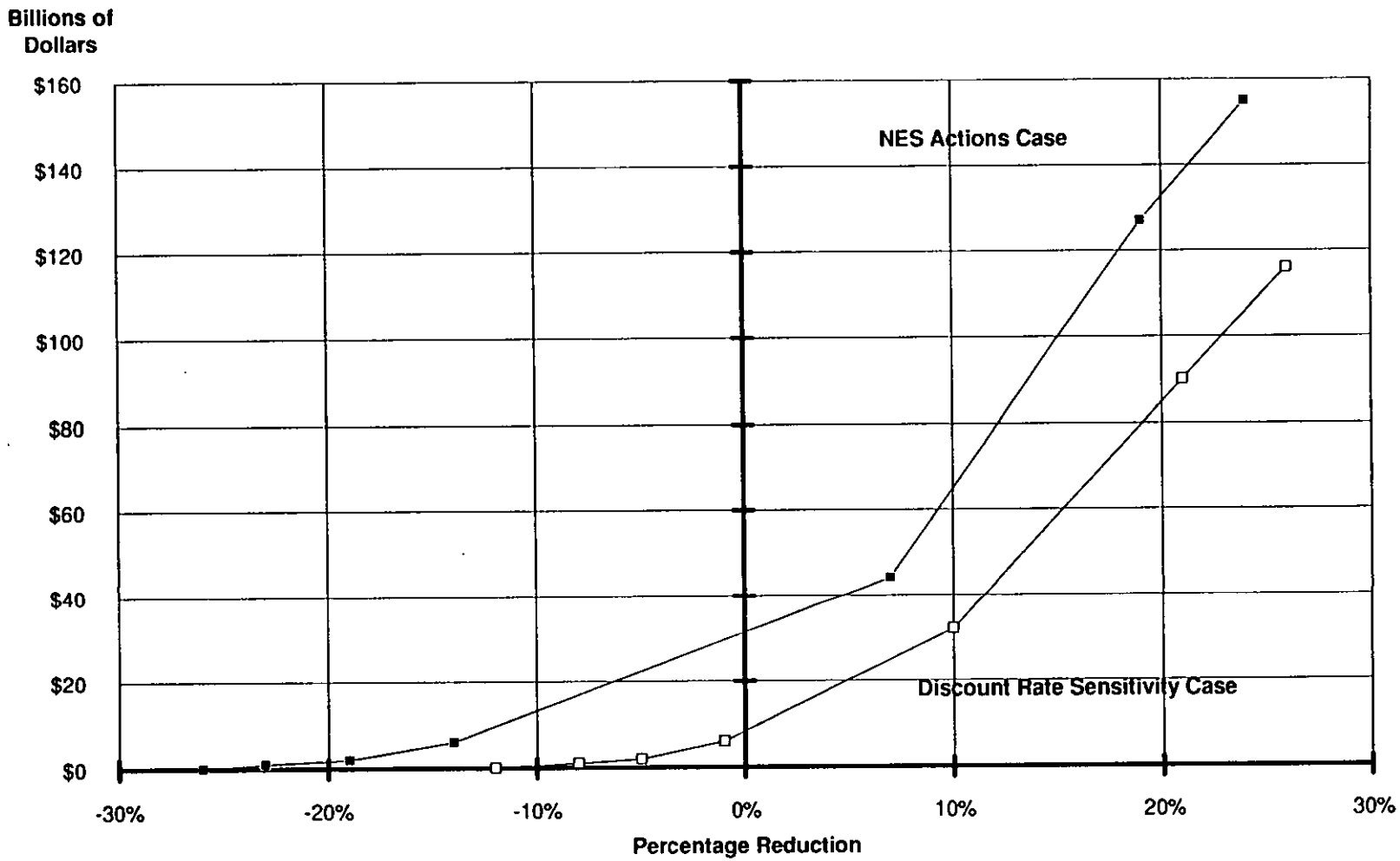

Figure 7.11. Year 2010 Total Cost (billions of dollars) vs. % Carbon Emissions Reduction Relative to 1990

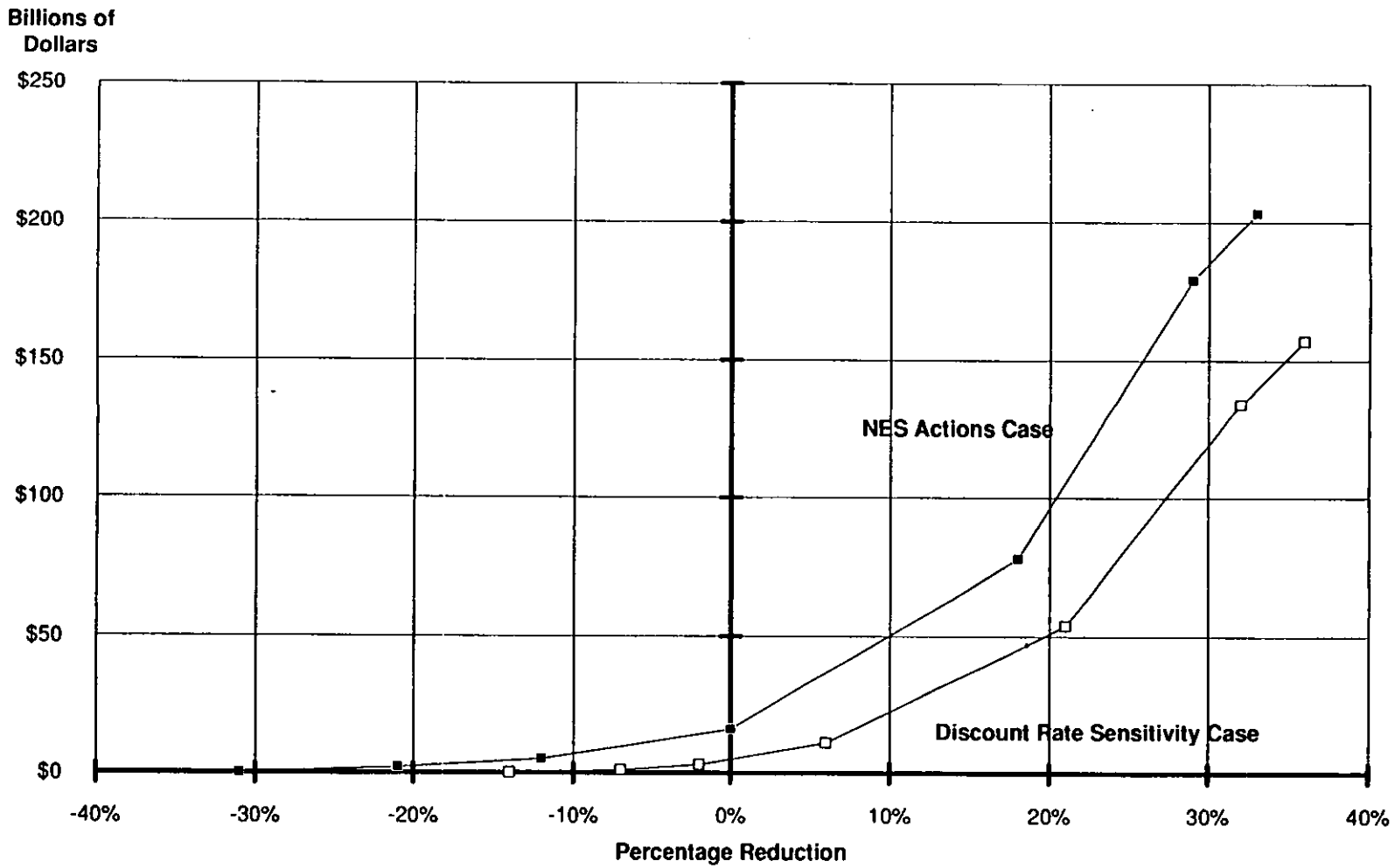

Figure 7.12. Year 2030 Total Cost (billions of dollars) vs. % Carbon Emissions Reduction Relative to 1990

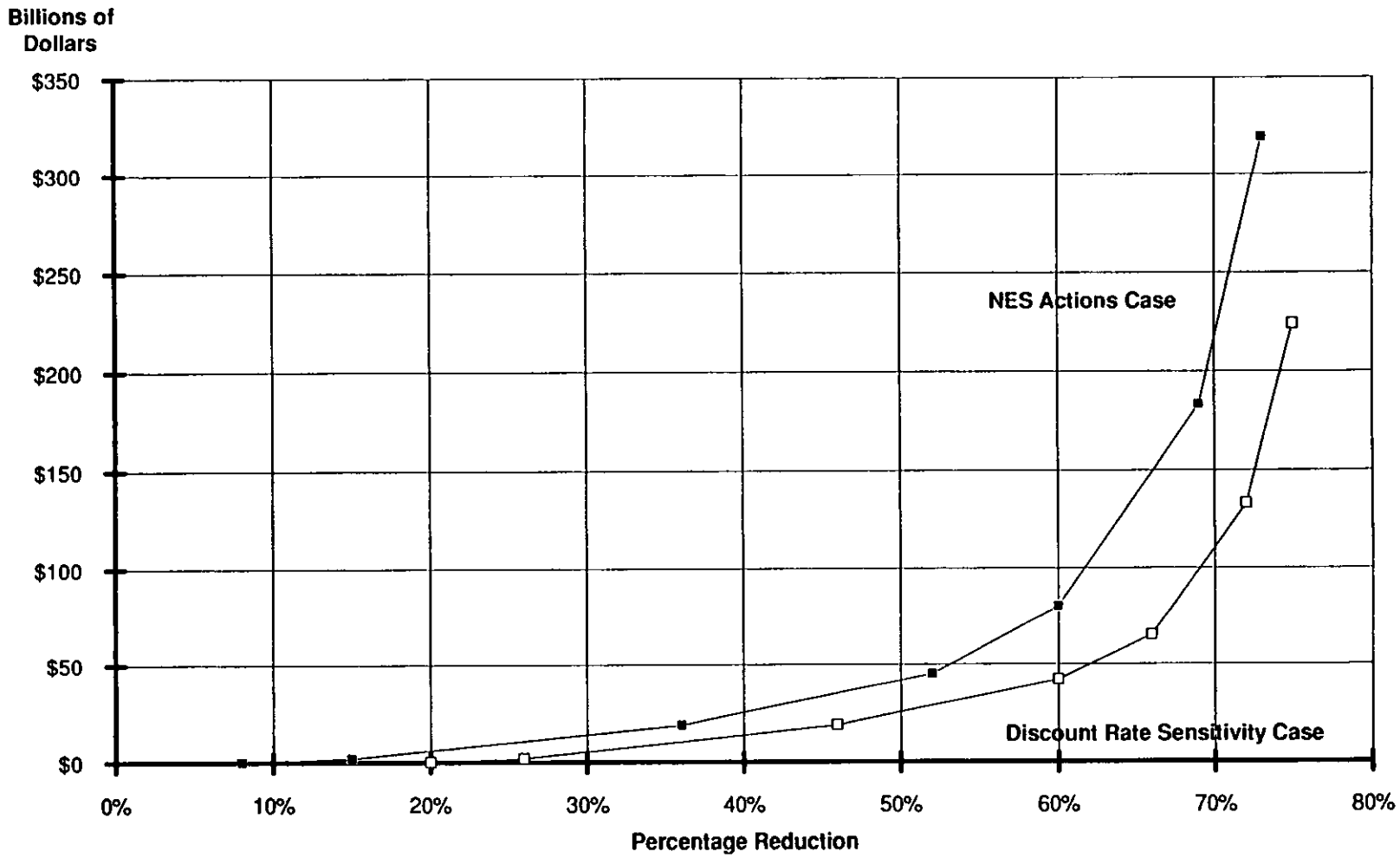

Figure 7.13. Year 2000 Total Cost (billions of dollars) vs. % GWP Emissions Reduction Relative to 1990

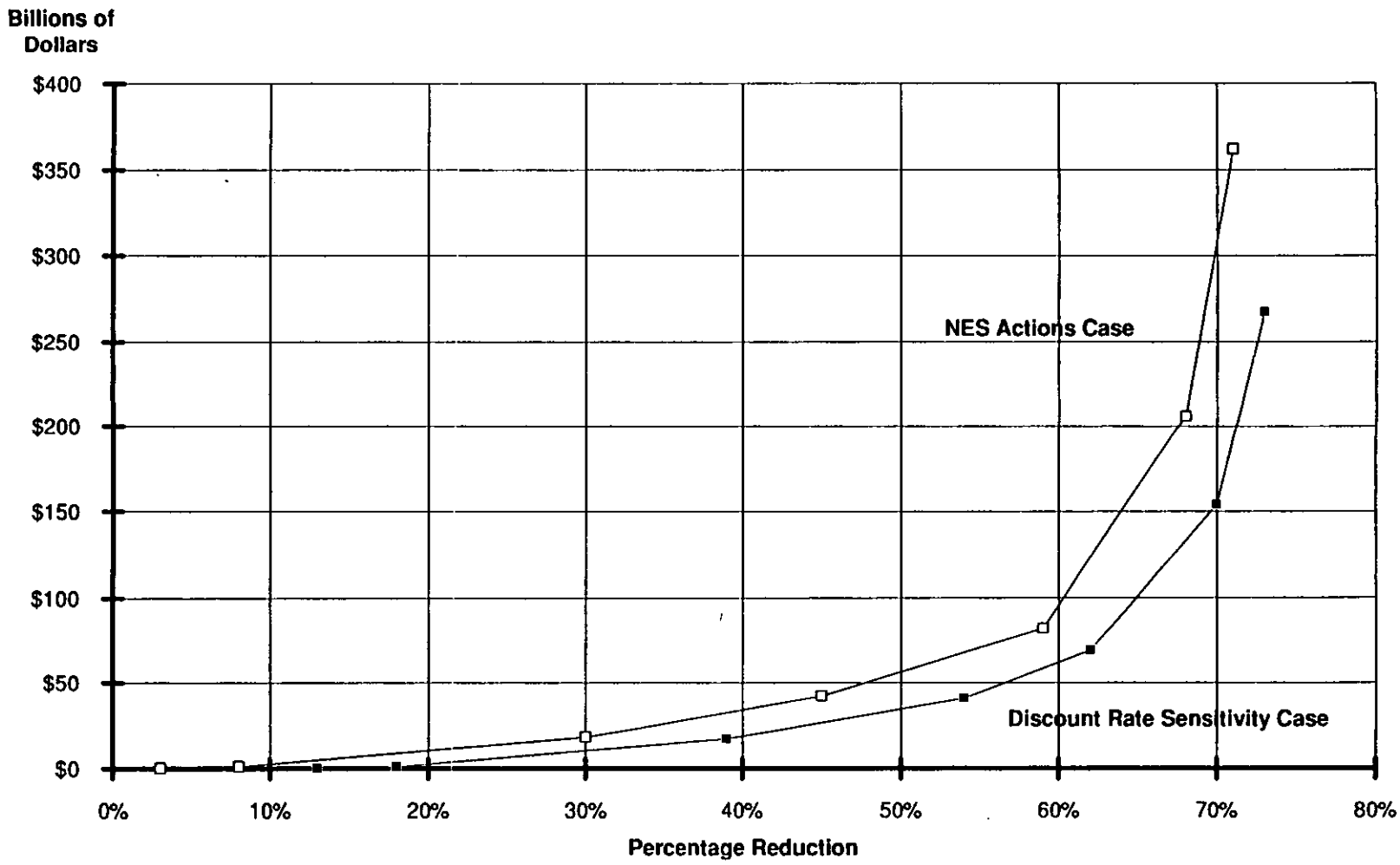

Figure 7.14. Year 2010 Total Cost (billions of dollars) vs. % GWP Emissions Reduction Relative to 1990

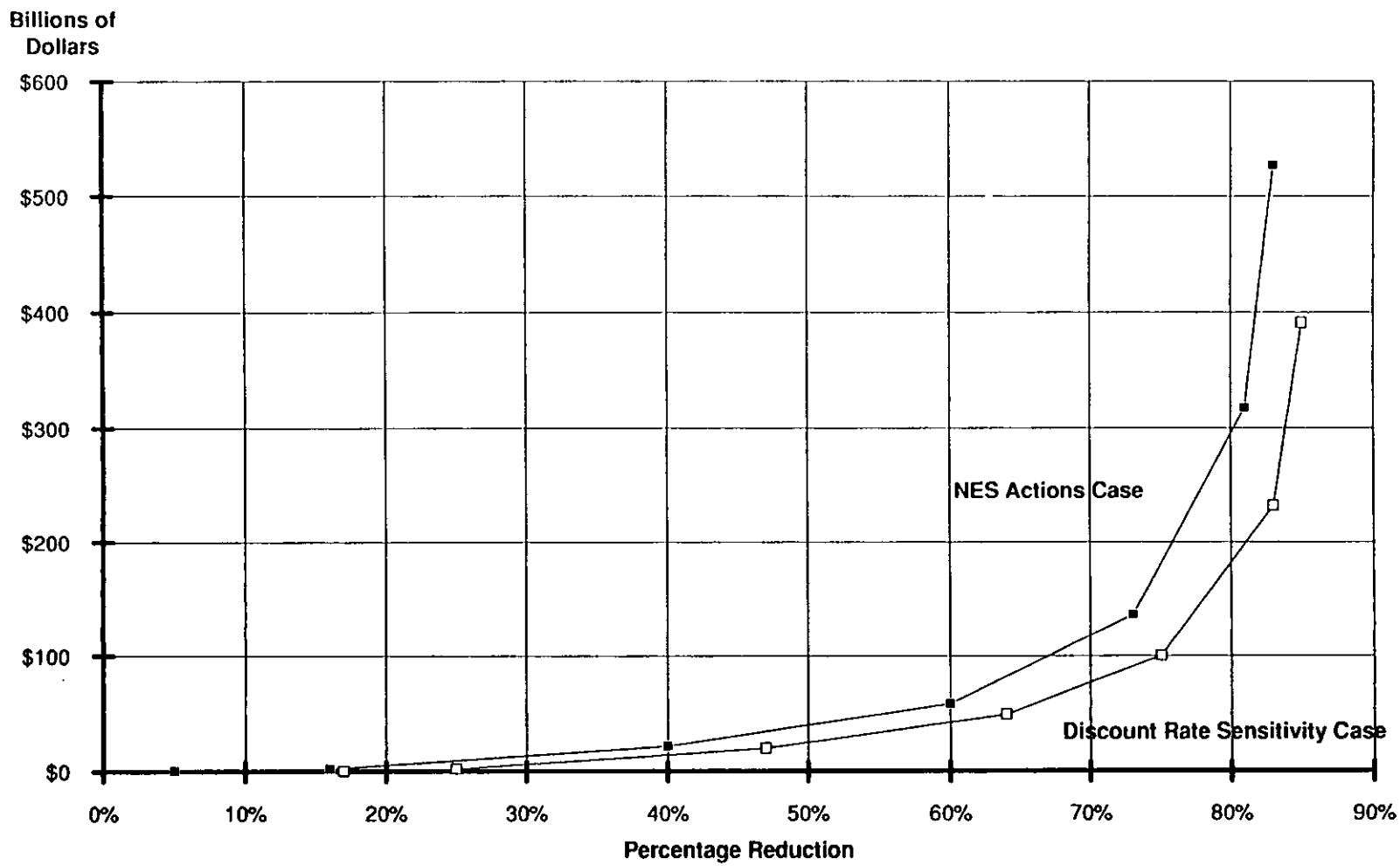

Figure 7.15. Year 2030 Total Cost (billions of dollars) vs. % GWP Emissions Reduction Relative to 1990

8.0 COMBINED STRATEGIES AND INSTRUMENTS

8.1 INTRODUCTION

In previous chapters, the effect of individual policy instruments on energy-related GWP emissions was examined. Here, the effect of a combination of policy instruments is investigated. It might be tempting to try to quantify the impact of combined strategies by simply adding the emissions reductions together. This only rarely provides a correct analysis. The problem is that policy instruments often interact with one another, in some instances reinforcing each other and in other instances counteracting each other. An obvious example is the imposition of a carbon tax and an end-use efficiency standard. If the tax rate is high and the standard set low, the carbon tax would change behavior such that no additional gains from the imposition of a standard would be observed, although there are instances, such as in the presence of a market failure, in which the imposition of both a standard and a carbon tax could provide greater emissions reductions at a given cost, than either policy instrument used alone.

In this chapter we examine three possible policy combinations. All include the concept of reforestation (tree planting). These policy combinations are:

- Case 1. Carbon and GWP taxes with refund for reforestation
- Case 2. Reforestation with buildings standards
- Case 3. Carbon caps with and without reforestation.

These three cases by no means exhaust the possible combinations of individual policies. They were selected because they showed promise of providing a maximum of carbon emissions reduction for any given cost, and/or because they shed light on the consequences of circumstances that might arise. Many other combinations are possible. The three combinations examined in this chapter are intended to be indicative of the kind of combinations that might occur, and of potential emissions reductions that might be achieved and their associated costs. Each of these policy combinations is described in more detail below.

As in the previous chapters, we also perform a sensitivity analysis on the costs and effectiveness of the combined strategy, using the NES Actions Case without new nuclear power as an alternative reference point.

8.2 CARBON AND GWP TAXES WITH REFUND FOR REFORESTATION

This case examines the potential for combining the carbon or GWP taxes with a policy to enhance carbon sinks. The carbon sink enhancement policy is effected by allowing for a deposit-refund for carbon sequestration in the form of reforestation. The combination of these two policies is more powerful in reducing GWP emissions than either of the individual policy instruments taken separately. The notion of linking the two strategies together through a market mechanism, the deposit-refund option, provides an efficient strategy for accessing carbon emissions reductions and carbon sink enhancement.

Briefly, the deposit-refund option allows anyone to obtain a payment for carbon sequestration achieved by the planting of new trees. A refund from carbon tax revenues is granted on the basis of the carbon uptake of the trees planted. Forest systems continue to absorb carbon over the lifetime of the trees, though the rate of absorption varies with the age of the tree and eventually becomes minimal. For the purpose of this analysis, trees in the program are not allowed to be harvested, but this need not be the case. As we discussed earlier in Chapter 7 in the Reforestation Case, several alternative options are open for the disposition of the mature trees. Anyone subject to a carbon tax can recover

the tax by planting trees whose sequestration of carbon is equal to the amount of the carbon emission. But unlike the reforestation option, there is not necessarily a match between the energy-related emission of carbon and the carbon captured. Since payments are associated with the program, the amount of tree planting could, in principle, be so great as to consume all of the tax revenues. This does not occur in any of the cases examined in this chapter. In all instances, the program generates significant net revenues.

8.2.1 Assumptions

The assumptions used in this case are the same as for the NES Actions *plus* either the carbon taxes or GWP taxes (see Chapter 6). In addition, the implementation of a deposit-refund option requires the construction of a supply schedule for carbon sequestration. That is, a relationship between the rate of carbon removal by new trees and the levelized cost of acquiring the land and planting and maintaining the trees. Significant uncertainty surrounds the supply schedule for enhanced carbon sequestration by trees. Because this is the case, we have constructed three alternative supply schedules. The first is based on Moulton and Richards (1990), and the second is based on more recent work by Richards (1990), specifically the "3X" Land Cost Case. These supply schedules are broadly consistent with the work of other researchers such as Marland (1988) and Sedjo and Solomon (1989). A third supply schedule is derived by halving the amount of carbon sequestered at each level of marginal and total cost associated with the "3X" Land Cost Case.

We will refer to the two sequestration supply schedules as Cases A ("high-cost trees") and B ("low-cost trees"), respectively. The amount of carbon sequestered at each tax level through reforestation for high-cost (Case A) and low-cost (Case B) trees is depicted in Figure 8.1a. The total cost of carbon sequestered appears in Figure 8.1b. We note that Case A is identical to the supply schedule used in Chapter 7 for the Reforestation Case.

Several simplifying assumptions were used in this analysis. Forest systems are assumed to absorb carbon at a constant rate over a 40-year period associated with the planting of trees, at which point carbon absorption ceases. Carbon is absorbed by the entire forest system. Carbon is accumulated in the tree both above and below ground, as well as in the forest floor and soils through the accumulation of debris. No allowance is made for a CO_2 fertilization effect.

It is worth noting that trees are not the only mechanism that could be employed to sequester carbon. Other mechanisms are also available, carbon scrubbing (Steinberg et al. 1984; Wolsky and Brooks 1987) for example, or the use of fossil fuels as a hydrogen feedstock with the systematic removal and sequestration of the associated carbon (see, for example, Steinberg and Grohse 1989 or MacCracken et al. 1990). We have made no attempt to examine such strategies here. The technical issues surrounding other sequestration strategies are different; nevertheless a similar analytical approach could be employed to examine such technology-policy options.

8.2.2 A Comparison to the NES Actions Case

Energy

The impact on the energy system (supply, demand, trade, etc.) is identical to that already described in the carbon tax and GWP tax sections of Chapter 6. This assumption is reasonable in that the energy system and forest sectors are fairly isolated from each other in terms of their demand for factors of production. The most important point of potential overlap occurs if the energy system were to develop a substantial biomass farms component. This does not occur in any of the cases examined here. To the extent that the energy system places demands on additional lands for energy use, they tend to be for non-biomass renewable energy sources such as wind or solar. Here, too, we assume that there are no conflicts in land use. This possibility cannot be completely excluded.

Greenhouse Gas Emissions

Carbon. Without considering "take-back" effects from refunds of taxes, which might result in higher energy purchases, gross carbon emissions from combustion of fossil fuels associated with each level of carbon and GWP tax are identical to those obtained in Chapter 6. However, net emissions differ substantially, due to carbon uptake by the trees. Net emissions are calculated by subtracting the amount of carbon sequestered at each tax level from gross energy-related emissions. Net carbon dioxide emissions are shown for carbon and GWP taxes with deposit refund in Figures 8.2a and 8.2b. These net emissions differ from those described in Chapter 6 by the amount of the carbon sink provided by the reforestation program (low- and high-cost trees); net carbon emissions for the GWP tax cases are slightly lower.

As can be seen from these figures, year 2030 carbon emissions are reduced substantially as compared with the NES Actions Case, particularly in the higher tax cases. Net emissions are also well below 1990 levels in the higher tax cases. In fact, with high-cost trees and a \$750/mtC (carbon tax) or \$750/mtC_e (GWP tax), net carbon emissions are only about one-third of 1990 levels. With low-cost trees, net carbon emissions are around 10% of 1990 levels.

Figures 8.3a through 8.3c show net carbon emissions and emissions reductions comparable to the NES Actions Case as attributable to taxes or carbon sequestration through either high- or low-cost trees. At low tax levels (e.g., \$50/mtC), there is a significant difference in the amount of carbon sequestered from low-cost versus high-cost trees (see Figures 8.3a and 8.3b). In both these cases, however, the relative contribution of trees (through carbon sequestration) to net carbon emissions reductions is substantial. At higher tax levels (e.g., \$750/mtC_e), the relative impact of trees diminishes as a share of total emissions reductions. The GWP tax would show similar results, although net carbon emissions would be somewhat smaller as a result of higher effective tax rates, as described in Chapter 6.

Methane. The reforestation program does not affect net energy-related methane emissions. These emissions are the same as those given in Chapter 6. However, total anthropogenic emissions of CH_4 may be affected as the reforestation program impacts alternative land uses.

GWP Emissions. The impact on total GWP emissions from taxes combined with a carbon sink (trees) is significant (see Figures 8.4a and 8.4b). Basically, these emissions scenarios are the same as those for carbon and GWP taxes shown in Chapter 6, except that CO_2 emissions are reduced by the carbon sink. The impact of carbon sequestration, and hence GWP emissions, through reforestation is substantial. For example, GWP emissions are about 80% lower than 1990 levels in the year 2030 with a \$750/mtC_e GWP tax. GWP reduction for carbon taxes are similar for the tax levels and tree-cost assumptions depicted in Figures 8.4a and 8.4b.

8.2.3 The Cost of Greenhouse Gas Emissions Reductions

Approach to Computing Cost

We have addressed the problem of computing the cost of net carbon emissions by computing carbon emissions reductions in a three-step process. First, we computed the relationship between fossil fuel carbon emissions reductions relative to the reference case and the tax rate. This provides a marginal cost schedule for energy-related carbon emissions reductions. From this, we computed the total cost associated with any rate of carbon emissions reduction as the integral over marginal costs (see Chapter 6 for a discussion of these procedures). Second, in a separate procedure, we computed the relationship between additional carbon sequestration from reforestation and marginal cost for Cases A and B. As noted earlier, these relationships are taken from Moulton and Richards (1990) and Richards (1990). Total annual costs are also supplied by these sources. Third, total net carbon emissions reductions relative to the reference case for any carbon tax rate under a deposit-refund option were computed as the horizontal summation

of the marginal cost schedules for carbon emissions reductions by the energy sector and carbon sink enhancement via reforestation. That is, at any marginal cost, total net carbon emissions reductions are the sum of emissions reductions resulting from the changes in the energy system plus additional carbon sequestration from reforestation that is profitable at that cost.

The total cost of emissions reductions at any marginal cost is simply the sum of the total cost of carbon emissions reductions by the energy sector and the cost of carbon sequestration from reforestation. The total emissions reductions associated with that total and marginal cost are the sum of emissions reductions by the energy sector and the annual carbon sequestration.

For the sake of brevity, only the cost schedules for taxes based on relative GWP are included in the following sections. The cost schedules for the carbon taxes are similar to those for GWP taxes, since the two tax levels are similar and the relative emissions reductions are close. In addition, costs are only stated in terms of reductions as compared with 1990 emissions (not the NES Actions Case). GWP emission levels associated with the NES Actions Case are always below and relatively close to 1990 levels, so a separate comparison to NES levels would be redundant.

Marginal Cost. The marginal cost schedules for net GWP emissions reductions relative to the 1990 levels with fossil fuel taxes based on relative GWP are shown in Figures 8.5a and 8.5b. This includes both the carbon sequestration from reforestation and energy sector emissions reductions under alternative tax assumptions for the period 1990 through 2030, for Cases A and B. We note that reforestation affects the shape of the marginal cost schedule for marginal costs below \$100/mtC or \$100/mtC_e, but this is not the case when the tax rate rises above \$100. All of the marginal lands available for forests are assumed to be employed at costs below \$100. As a consequence, higher tax rates produce no additional gains in emissions reductions. The emissions reductions from reforestation thereafter assume the character of a fixed addition to emissions reductions at marginal costs above \$100, and the shape of the marginal cost schedule is totally governed by energy sector responses.

These figures show that, even at zero tax levels, GWP emissions are never greater than 1990 levels (emissions reductions are always positive). The reason for this is that emissions of other components (such as CFCs) of GWP emissions are being reduced, keeping total GWP emissions below 1990 levels. The percentage reduction in emissions levels, as compared with 1990, is similar to that achieved under the NES Actions Case, since GWP emissions associated with the NES tend to stay below, but close to 1990 levels in out years.

Total Cost. The total cost of emissions reductions relative to 1990 for the GWP taxes and a deposit-refund option for reforestation is given in Figures 8.6a and 8.6b. As can be seen from these charts, the cost of stabilization is zero. That is, the NES Actions have already stabilized GWP emissions through 2030. A 20% reduction by 2000 could be reached at a total cost of between \$4 billion and \$6 billion, depending upon the true cost of trees, in that year. A 50% emissions reduction by 2010 would cost \$38 billion per year in 2010 with low-cost trees, rising to \$56 billion with high-cost trees.

Two trends are clearly evident. First, marginal costs--that is, tax rates--rise with increases in net carbon emissions reductions for any individual year. Second, total costs rise more rapidly than emissions are reduced. This is the effect of increasing marginal costs. The difference between high-cost and low-cost trees can be seen when examining these figures. For instance, when comparing Figure 8.6a with 8.6b, with every year and for every level of total cost, the curves shift right for low-cost trees as compared to high-cost trees. In other words, there is greater net GWP emissions reduction at any given total cost level with low-cost trees than with high-cost trees, or conversely, the total cost of any level of emissions reduction is less with low-cost trees than with high-cost trees.

Average Cost. As we have noted in earlier chapters, average costs are generally lower than marginal costs. The average cost is the total cost of emissions reductions divided by the total emissions reduction, in this case relative to 1990 (see Figures 8.7a and 8.7b). As with marginal costs, the same amount of emissions reduction can be achieved for less with low-cost versus high-cost trees. For instance, with low-cost trees, GWP emissions can be reduced as much as about 60%, compared with 1990 at an average cost of less than \$20/ $mtCO_2e$ for most years (see Figure 8.7b). However, with high-cost trees, an emissions reduction of this magnitude can only be achieved in the most distant years (2025 and 2030) at comparable average costs (see Figure 8.7a).

8.2.4 Tax Revenue

Significant revenues are generated in these cases (see Figures 8.8a and 8.8b). In contrast to the case of the simple carbon tax, however, there are both tax revenues and costs to this program. Revenues are raised by the tax on fossil fuel-related emissions. Payments are refunded for carbon sequestration. Both Cases A and B generate identical amounts of gross revenue and nearly identical net revenues, except at low tax rates. With a tax rate of \$750/mtC_e, net revenues exceed \$250 billion per year in the years 2005 to 2015. Net revenues are higher in the GWP tax cases because the effective tax is somewhat higher on carbon emissions and because more sources of energy-related emissions are being taxed (see Chapter 6). The gap between net revenues at the various tax levels narrows substantially in the later years. This is because the difference in net emissions of carbon between the cases has diminished.

8.2.5 Limitations

The same limitations discussed in Chapter 6 apply to the energy system analysis described here. Likewise, the discussion in Section 7.2.7, "Limitations of the Reforestation Analysis" apply. We will not repeat these limitations here; we merely note that they still apply.

8.2.6 Sensitivity Analysis: Reduced Land Availability

Due to the uncertainties associated with a reforestation program of this magnitude, we have conducted a sensitivity analysis, similar to that in Chapter 7 for the Reforestation Case, for the GWP Tax with Deposit Refund Case. As in Chapter 7, we have studied an alternative scenario with the assumption that only one-half of the carbon sequestration potential is available at each level of cost from the supply of trees from the Moulton and Richards high-cost estimate. The effect of this land availability constraint is much simpler to quantify in this case, since the effect of the land constraint is simply a smaller pool of carbon sequestration from which the GWP taxes can be offset. Beyond the point at which the maximum carbon sequestration from trees has been exhausted, the consumers must pay the GWP tax.

With the reduced land constraint, the total cost of reducing GWP-weighted emissions by 20% of 1990 levels in the year 2000 is \$13 billion (versus \$6 billion in the high-cost trees case with full land availability). The total cost of reducing GWP-weighted emissions by 50% of 1990 levels in the year 2010 becomes \$204 billion (versus \$56 billion in original case). The constraint on available land has a greater relative effect on the cost of meeting the 50% reduction target than on the 20% reduction target. The difference is due in part to the fact that, even with the assumption of reduced land, there is still a sufficient carbon sink from reforestation to reduce emissions by 20%. For the 50% reduction target, however, more of the reduction must be gained by the GWP tax alone, since the supply of sequestration from trees is exhausted earlier than under the original assumptions.

8.3 REFORESTATION WITH BUILDINGS STANDARDS

8.3.1 Assumptions

In this strategy, an end-use policy (buildings standards) is applied in conjunction with a policy directed at electric powerplants (reforestation) to assess the potential of employing combined strategies across sectors for reducing greenhouse gas emissions. The buildings standards are the $250/mtC Case presented in Section 7.5, and the reforestation policy is that discussed in Section 7.3. The two policies are modeled directly in Fossil2 as a single, combined strategy by applying the buildings standards on the appropriate conservation supply curves while specifying the reforestation mandate on new electric capacity. As before, the assumptions of the NES Actions Case are used as the baseline.

8.3.2 A Comparison to the NES Actions Case

Because the impacts of the reforestation policy dominate this combined strategy, only the major differences in results between this case and the single Reforestation Case of Section 7.3 are presented in detail here.

Energy Prices

The improved efficiency under the buildings standards reduces the demand for natural gas, which has the effect of lowering its price compared to the Reforestation Case. In the combined strategy, natural gas at the wellhead is $8.04/mBtu in 2030. Without the buildings standards, the price in 2030 reaches $8.27/mBtu. However, the price in the combined strategy is still 10% higher than in the NES Actions Case. The price of gas in the residential sector is also somewhat lower than in the Reforestation Case at $11.80/mBtu (versus $12.00/mBtu) in 2030.

Energy Consumption

The total primary energy consumption in the Combined Strategy Case of 122.5 quads in 2030 is a 1.0 quad reduction compared to the Reforestation Case. This difference is attributable, in part, to the difference in nuclear energy consumption, which is 20.3 quads here and 20.6 quads in the Reforestation Case. The decrease in nuclear energy consumption indicates a decrease in the demand for electricity, which results from the efficiency imposed by the buildings standards. Total primary energy consumption is less than 1% below the NES value in 2030.

Energy Transformation

The differences in energy transformation results between the Combined Strategy and the Reforestation Case are basically the same as the differences in energy consumption results. Total electricity fuel consumption in 2030 is 57.6 quads for the combined strategy and 58.3 quads under reforestation alone. The difference in the total is comprised of a 0.3-quad reduction in nuclear energy and a 0.9-quad reduction in coal. Relative to the NES Actions Case, total electricity fuel consumption in the combined strategy is 5% lower in the year 2015, but rebounds to just 1% lower in 2030.

End-Use Energy Consumption

Although the buildings standards apply to buildings and appliances in both the residential and commercial sectors, the only pronounced changes from the Reforestation Case occur in the residential sector. Table 8.1 gives the energy consumption by fuel for the residential sector under the combined strategy. Natural gas shows the largest relative decrease from the Reforestation Case, with a difference of 0.5 quad in 2030. Total residential energy consumption, at 11.5 quads in 2030, is 5% less than in the NES Actions Case.

Table 8.1. Residential Energy Consumption (quads)

Year	Oil	Gas	Coal	Rnew	Elec	Total
1990	1.6	4.9	0.1	0.9	3.2	10.7
1995	1.2	4.2	0.1	1.0	3.4	9.9
2000	1.0	4.1	0.1	1.1	3.6	10.0
2005	0.9	4.1	0.1	1.1	3.9	10.1
2010	0.8	4.2	0.1	1.2	4.1	10.4
2015	0.8	4.1	0.1	1.3	4.4	10.7
2020	0.7	4.1	0.1	1.4	4.7	11.0
2025	0.7	4.2	0.1	1.4	4.9	11.2
2030	0.7	4.2	0.1	1.5	5.1	11.5

Table 8.2. Carbon Emissions by Fuel (TgC/yr)

Year	Oil	Gas	Coal	Geothermal	Total
1990	546	274	477	2	1299
1995	534	284	448	3	1269
2000	537	278	331	4	1150
2005	556	247	209	7	1018
2010	565	230	159	8	962
2015	568	219	117	11	916
2020	564	204	78	21	866
2025	555	205	67	24	851
2030	547	199	63	25	833

Greenhouse Gas Emissions

Chapter 7 reported that the Reforestation Case was the single most effective regulatory policy of those studied for reducing carbon emissions. The effect of multiple policies used in combination cannot be considered mathematically additive because of the interrelationships between sectors. In the case here of combining reforestation with buildings standards, the incremental benefit of imposing building standards is diminished when the reforestation policy is also in effect. The Reforestation Case by itself results in greater conservation in buildings than does the NES Actions Case, through increases in the prices of electricity and end-use fuels, so there is less potential conservation for the buildings standards to invoke. Table 8.2 shows net carbon emissions for the combined strategy. Note that the value in 2030 of 833 TgC is only 8 TgC less than the value in the Reforestation Case. The GWP results for the Combined Case, which again differ only slightly from the Reforestation Case, are shown as Figure 8.9.

8.3.3 The Cost Of Greenhouse Gas Emission Reductions

Approach to Computing Cost

The cost of the combined strategy is calculated in two steps. The first step is obtaining the cost of reforestation alone, which has been done in Section 7.3. The second step involves computing the cost of the buildings standards, given that the reforestation policy is in effect. The total cost of the combined strategy in each year is then the sum of costs from these two steps.

The method employed to compute the cost of the buildings standards with reforestation is the same as that used for buildings standards alone, detailed in Section 7.5, with some modifications.[a] For the combined strategy, a series of carbon taxes up to $250/mtC is applied, with the Reforestation Case instead of the NES Actions Case as the basis. The same series of carbon taxes is applied with the combined reforestation and buildings standards as the base. The total cost of the buildings standards, given that reforestation is in effect, is then computed as the difference between the total cost of the $250/mtC carbon tax with reforestation and the total cost of the $250/mtC tax with both reforestation and the buildings standards in effect.

Table 8.3 shows the total and average costs for the combined strategy of reforestation with buildings standards. Only in 1995 are the costs significantly different from the Reforestation Case. The imposition of the buildings standards accelerates the gains in efficiency that eventually occur due to

(a) Refer to the discussions of cost calculations for taxes in Chapter 6 and for building standards in Chapter 7.

Table 8.3. Total Cost of Carbon Emissions Reductions from the Combined Reforestation Plus Buildings Standards Case

Year	Carbon Emissions Reduction (TgC/yr)	GWP-Weighted Emissions Reduction ($TgCO_2e$/yr)	Total Cost (bil$/yr)	Average Cost ($/mtC)
1990	0	0	0	0
1995	107	392	4	37
2000	337	1216	9	27
2005	555	1987	17	31
2010	678	2384	24	35
2015	780	2774	31	40
2020	843	3028	35	42
2025	859	3098	31	36
2030	874	3164	30	34

reforestation, so in the earlier years, the buildings standards make more of a difference in carbon dioxide emissions. In 1995, the combined strategy reduces emissions by 107 TgC, relative to the NES Actions Case at a total cost of $4 billion. In the same year, the Reforestation Case reduces emissions by 75 TgC at a cost of $3 billion. In all years, the average costs for the combined strategy exceed those of the Reforestation Case, indicating that the incremental reductions in emissions achieved by the buildings standards are more costly than the reductions achieved through reforestation alone.

8.4 CAPS ON FOSSIL FUEL CARBON EMISSIONS AND GLOBAL WARMING POTENTIAL

This section evaluates the impact of imposing carbon and GWP caps on the U.S. energy economy. The concept of caps is discussed with reference to carbon in the DOE Report to Congress *A Compendium of Options for Government Policy to Encourage Private Sector Responses to Potential Climate Change* (DOE 1989). Conceptually, a GWP cap does not differ from a carbon cap. Both types of caps have what economists call a "dual" relationship to carbon emissions-based or GWP-based taxes. This means that a carbon (or GWP) tax fixes the price of carbon at the tax rate and allows the market to determine the extent to which carbon emissions are reduced, while the carbon (or GWP) cap program establishes the level of carbon emissions (or GWP equivalent) and allows the market to determine the price of carbon (or of the GWP level). For example, in the case of a carbon tax, a tax of $25/mtC will cause firms to reduce their emissions such that the marginal cost of reducing the last unit of carbon emissions is $25/mtC. At that tax level, firms produce Q tonnes of carbon. If, in the case of a carbon cap, the level of carbon emissions were set at Q, firms cutting back their carbon emissions to this level would find that the marginal cost of doing so is $25/mtC. We thus act as if the transaction costs of a tradeable permit program are zero.[a]

There is no unique way of implementing a carbon cap. Nevertheless, all schemes begin with the government determining an overall amount or rate of emissions it will allow. The emission of this quantity or rate becomes a right, the total of which is allocated to members of the economy either by assignment or by sale. One mechanism that has received an increasing amount of attention among both economists and regulators involves creating tradable permits that would allow individual firms to release some given amount of carbon into the atmosphere. The total number of permits would be set such that a given level of emissions reductions could be achieved. Since the permits would be tradable, their price would be bid up to a level equivalent to a carbon tax, in the sense that it would be equal to the marginal cost of the emission reductions. Such an approach allows regulators to determine the total level of emissions, but it enjoys the flexibility and efficiency of market-oriented schemes, while at the same time providing regulators with a "feedback" price signal they can use to adjust the size of the cap if warranted. If, instead, the government reserves the right to distribute the permits periodically through auctions, then the revenues generated by the auctions would tend to

(a) This is analogous to the way we proceed with a carbon or GWP tax. In none of these cases is this assumption in fact true. Transactions costs are of course never zero. In some cases, these costs may be substantial.

converge over time on an amount equal to the tax revenues that could be collected from the (equivalent) tax. There are a multitude of mechanisms for allocating and selling these rights, all of which have income distribution and macroeconomic implications. These issues are discussed in detail in DOE 1989.

The remainder of this report focuses on the methods for computing emission impacts and the cost associated with carbon and GWP caps and presenting the cost results. Because of the dual relationship between emission-based taxes and emission caps, the energy impacts of the two types of caps are not presented here. Rather, the reader is referred to the information presented in Chapter 6 on the energy impacts of carbon and GWP taxes.

8.4.1 Assumptions and Approach

The carbon and GWP cap levels chosen for this analysis are those equivalent to stabilization of emissions at 1990 levels, a 20% reduction from 1990 levels by 2000, and a 50% reduction from 1990 levels by 2010. The absolute levels are contained in Table 8.4. Marginal, total, and average costs are calculated for each of these cap levels, given carbon or GWP taxes with and without a reforestation program for carbon sequestration. The marginal cost, in this analysis, is equivalent to the auction price that emitters would be willing to pay for the right to emit the next tonne of carbon or CO_2-equivalent of greenhouse gases. Costs for both high- and low-cost trees, as described earlier in this chapter, are presented. Costs associated with carbon caps are those that would result from a series of carbon taxes. Likewise, costs associated with a GWP cap are derived from GWP taxes. For more information on the difference in application between carbon and GWP taxes, see Chapter 6.

Table 8.4 Carbon and GWP Cap Levels

	Stabilization	20% Reduction	50% Reduction
CO_2 Cap	1300	1040	650
GWP Cap	7450	6000	3725

Marginal, total, and average costs were calculated for the CO_2 cap and GWP cap levels. The method used to compute these costs was identical in both cases. Following the dual relationship between taxes and caps, the marginal cost of a specific cap in a given year is simply the lowest corresponding tax required to achieve that level of emissions or total GWP. This marginal value was interpolated from the tax-emissions level information produced for Chapter 6. Marginal values were interpolated for each year and for each cap. Once the marginal cost associated with a specific cap was determined, the total cost of a specific cap in a given year was calculated as the total cost associated with the cap level and marginal cost (tax) from the previous step. This value was interpolated, year by year, from the tax-total cost information in the tax analysis. Computing the average costs associated with each type of cap required computing the annual emissions difference between the NES Actions Case and the specific cap. These differences were, of course, systematically related to the differences between the cap levels. Finally, the average cost of emissions (or total GWP) for a specific cap in a given year was calculated by dividing the corresponding total cost by the corresponding carbon emission or GWP difference.

The linear interpolations used to derive marginal costs for the cap analysis are based on the results of the application of constant tax levels through time, as employed in Chapter 6. Therefore, in this analysis, it is not possible to talk about a "time-path" of marginal costs (tax levels) that result in either stabilization or reduction in emissions to some level in a year and then hold at that level from that time forward. Instead, the interpolated marginal cost is equivalent to the tax or auction price that would have to applied in every year up to and including the year for which the cap is being applied. This cost is, in turn, consistent with a series

of unique caps for each of the previous years, which eventually result in obtaining the cap level in the year desired.

For instance, if a tax rate of $100/mtC is required for stabilization of carbon emissions at 1990 levels by 2030, then, through linear interpolation, that is the tax rate that would need to be applied in every prior year up to and including 2030. **This does not mean that carbon emissions would also be stabilized in earlier years (e.g., 1995 through 2025). Nor does it mean that this tax level is necessary and sufficient to stabilize emissions beyond that date.** In fact, in order to stabilize or reduce emissions in earlier years, higher tax levels are typically required. However, higher tax levels in earlier years would also typically result in lowering the required tax levels in later years, since infrastructure developed during that higher-tax period would be less energy-intensive.

Therefore, some care should be exercised in interpreting the results of the tables presented in these sections. Although data for several years and cap levels are presented, it is only appropriate to talk in terms of "the cap level" in "the year chosen" and not follow that cap through time. It would be incorrect to follow "a cap level" through the years and deduce that the marginal, total, and average costs required to maintain that cap would vary as might seem indicated by the tables.

8.4.2 The Cost of Greenhouse Emission Gas Emissions Reductions

The marginal, total, and average costs of the carbon and GWP cap levels used in the analysis are presented here. As stated above, these results are based on the carbon and GWP tax cases shown in Chapter 6, although the information is presented in slightly different form and the results are interpolated.

Marginal Cost

Tables 8.5 and 8.6 show the marginal costs or tax rates that would be required to stabilize or reduce emissions in the years 2000, 2010, and 2030. As can be seen from these tables, the marginal cost (auction price) required to meet these cap levels is reduced substantially with a reforestation program. For instance, in order to meet a 20% reduction in carbon emissions in 2010, a marginal cost of $495/mtC would be required with no reforestation program beyond the President's America the Beautiful Tree Initiative. However, if a reforestation program for carbon sequestration with refund of taxes is implemented, the rate required falls by over 90%. To further illustrate the importance of a reforestation program, notice that a 50% reduction in carbon emissions from 1990 levels is not possible, even at the highest marginal rates employed in this analysis ($1000/mtC), unless a reforestation program is

Table 8.5. Marginal Costs ($/mtC) of Carbon Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High- and Low-Cost Trees

	Stabilization			20% Reduction			50% Reduction		
	No	High	Low	No	High	Low	No	High	Low
2000	$140	$27	$12	$495	$42	$28	NA	$ 94	$ 72
2010	202	35	21	539	52	37	NA	156	156
2030	102	33	21	296	46	34	NA	90	75

Note: NA = "Not Achievable".

Table 8.6. Marginal Costs ($/mtC$_e$) of GWP Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High- and Low-Cost Trees

	Stabilization			20% Reduction			50% Reduction		
	No	High	Low	No	High	Low	No	High	Low
2000	0	0	0	$149	$30	$15	NA	$ 95	$ 82
2010	0	0	0	180	38	24	NA	153	153
2030	0	0	0	53	29	16	$710	74	48

Note: NA = "Not Achievable".

implemented. On the other hand, Table 8.6 shows that GWP-weighted emissions can be stabilized by the NES Actions at a net benefit to the nation, though we will treat costs as zero. In addition, 20% to 50% reductions can be achieved (in most cases) at costs lower than for simple carbon caps.

Total Costs

Total costs associated with carbon and GWP caps are presented in Tables 8.7 and 8.8. As with marginal costs, total costs tend to be higher, the lower the cap level imposed. For instance, if stabilization of carbon emissions would cost $13 billion, a 20% reduction would cost about $90 billion in 2000, without a reforestation program. Total costs drop dramatically with a reforestation program, and only through reforestation is it possible to reach a 50% reduction in carbon emissions.

As with marginal costs, the total cost of stabilizing GWP emissions is zero. This is because the NES Actions Case, which is the reference case for this analysis, already stabilizes these emissions. Total costs are also substantially lower than those required for similar cap levels for carbon. Once again, this is due to the nature of GWP-weighted emissions, which included all radiatively important greenhouse gases. Some of these gases, particularly CFCs, decline during this period, due to policies outside this analysis; hence, the reduction in GWP-weighted emissions is "free" in this analysis.

Average Costs

Average costs for carbon and GWP caps are reported in Tables 8.9 and 8.10. The interpretation of these costs is similar to that for marginal and total costs. However, the units for average costs differ

Table 8.7. Total Costs (billions of 1989$) of Carbon Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High- and Low-Cost Trees

	Stabilization			20% Reduction			50% Reduction		
	No	High	Low	No	High	Low	No	High	Low
2000	$ 13	$ 4	$ 3	$ 90	$14	$ 9	NA	$ 42	$ 24
2010	32	9	6	128	20	14	NA	62	44
2030	17	9	6	97	20	14	NA	53	34

Note: NA = "Not Achievable".

Table 8.8. Total Costs ($ billions) of GWP Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High- and Low-Cost Trees

	Stabilization			20% Reduction			50% Reduction		
	No	High	Low	No	High	Low	No	High	Low
2000	0	0	0	$ 17	$ 6	$ 4	NA	$ 4	$ 42
2010	0	0	0	30	10	6	NA	56	32
2030	0	0	0	6	6	5	$199	40	23

Note: NA = "Not Achievable".

Table 8.9. Average Costs ($/mtC) of Carbon Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High- and Low-Cost Trees

	Stabilization			20% Reduction			50% Reduction		
	No	High	Low	No	High	Low	No	High	Low
2000	$ 70	$19	$18	$ 90	$32	$20	NA	$ 50	$ 28
2010	93	27	17	128	34	23	NA	63	44
2030	42	23	16	97	31	21	NA	50	32

Note: NA = "Not Achievable".

Table 8.10. Average Costs ($/mt$CO_2$e) of GWP Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High- and Low-Cost Trees

	Stabilization			20% Reduction			50% Reduction		
	No	High	Low	No	High	Low	No	High	Low
2000	0	0	0	$ 20	$ 7	$ 5	NA	$ 14	$ 12
2010	0	0	0	24	8	5	NA	16	10
2030	0	0	0	6	5	4	$ 59	12	7

Note: NA = "Not Achievable".

between carbon and GWP caps. While average costs for carbon caps are in dollars per metric tonne of carbon ($/mtC), average costs for GWP caps are in dollars per metric tonne of CO2 equivalent ($/ mt$CO_2$e), which are about 3.5 times larger. This is because GWP-weighted emissions are expressed in units of CO_2 equivalent, while carbon emissions are simply expressed in tonnes of carbon.

8.4.3 Emissions Reduction

The amount of emissions reduction in net carbon and net GWP-weighted emissions necessary to reach each of the cap levels is shown in Tables 8.11 and 8.12. These tables show the amount that net emissions would have to be reduced from NES Actions Case levels for each out-year in order to

Table 8.11. Net Carbon Emissions Reductions Required to Meet Cap Levels (TgC)

	Stabilization		20% Reduction		50% Reduction	
	Carbon Reduction	%	Carbon Reduction	%	Carbon Reduction	%
2000	187	13%	447	30%	837	56%
2010	340	21	600	37	990	60
2030	407	24	667	39	1057	62

Table 8.12. Net GWP Emissions Reductions Required to Meet Cap Levels ($TgCO_2$)

	Stabilization		20% Reduction		50% Reduction	
	Carbon Reduction	%	Carbon Reduction	%	Carbon Reduction	%
2000	0	0%	843	12%	3118	46%
2010	0	0	1233	17	3508	48
2030	0	0	1082	15	3357	47

stabilize or reduce emissions compared to 1990 levels. Gross carbon emissions for the reforestation cases could actually be higher (reductions lower), since the carbon uptake by trees offsets these higher emissions levels, resulting in equivalent net emissions reductions levels.

8.4.4 Limitations of the Emissions Cap Analysis

The way in which an emissions cap is implemented can alter the results of the analysis. We have acted as if the government retains ownership of the emissions permit and auctions the right annually. This does not deal with questions that arise regarding futures markets, enforcement, or the effects of the income transfers on energy markets. These transfers will be substantial and will have substantial consequences, as the discussion in Chapter 9 regarding the macroeconomic effects of carbon taxation implies. Auction revenues would be so immense that they would substantially alter important macroeconomic variables. Alternative systems of allocating permits are also available. A system of tradeable emissions allowances could be set in motion by any number of mechanisms such as distributing the desired number of allowances free of charge to existing emitters in proportion to their previous emissions and then allowing free trade in the allowances between any buyer or seller. We have not attempted to explicitly model the consequences of the different income distributions associated with alternative permit allocations, but further research in this area is clearly warranted.

In a world of perfect certainty, taxes and permits would have a dual relationship with each other. But the real world is uncertain, and these two alternative policy instruments provide greater and lesser certainties in different domains. Ignoring for the moment the problem of emissions measurement and verification, the emissions cap with emissions permits provides policymakers with better control over the rate of emission. However, the marginal cost, that is the price of a permit, is determined by the market and is therefore relatively uncertain. In contrast, the emissions tax fixes the marginal cost, tax rate, but leaves to the market the job of determining the emissions reduction.

8.5 SENSITIVITY ANALYSIS: CARBON AND GWP CAPS, NES ACTIONS WITOUT NUCLEAR

As in the carbon and GWP tax cases presented in Chapter 6, the effect using the alternative baseline scenario--the NES Actions with no new nuclear orders or life-extensions--would have on the costs of caps on carbon and GWP-weighted emissions is studied as a sensitivity analysis. As in the straight tax cases in Chapter 6, the implications of the assumption about the availability of nuclear power are greatest in the later years of the study.

8.5.1 Marginal Costs

Tables 8.13 and 8.14 show the marginal costs necessary to achieve certain emissions targets or caps on carbon emissions and GWP-weighted emissions without new nuclear power. Note that, under the NES Actions Case assumptions, stabilization in GWP-weighted emissions was achieved at no additional cost. In the NES Actions Without Nuclear Case, this is no longer true. From Table 8.14, a marginal cost of $31/mtC$_e$ is required through the year 2030 in order to achieve stabilization.

Total Costs

Total costs associated with carbon and GWP caps under the NES Actions Without Nuclear Case assumptions are presented in Tables 8.15 and 8.16. Again, the total costs for meeting targets are considerably higher for the later years, compared to the NES Actions Case assumptions. As in the tax cases, this result reflects the fact that the growth in nuclear energy due to the NES Actions becomes significant sometime after the year 2010.

Table 8.13. Marginal Costs ($/mtC) of Carbon Caps for No Reforestation Program Beyond the President's Tree Initiative and for High-Cost Trees under the NES Actions Without Nuclear Case

	Stabilization		20% Reduction		50% Reduction	
	No	High	No	High	No	High
2000	$144	$27	$495	$42	NA	$ 94
2010	267	36	571	53	NA	191
2030	229	47	428	72	NA	183

Note: NA = "Not Achievable".

Table 8.14. Marginal Costs ($/mtC$_e$) of GWP Caps for No Reforestation Program Beyond the President's Tree Initiative and for High-Cost Trees under the NES Actions Without Nuclear Case

	Stabilization		20% Reduction		50% Reduction	
	No	High	No	High	No	High
2000	0	0	$151	$30	NA	$ 95
2010	0	0	218	39	NA	180
2030	31	22	135	44	NA	111

Note: NA = "Not Achievable".

8.6 SUMMARY

The combination of carbon or GWP taxes with a program of reforestation for carbon sequestration

Table 8.15. Total Costs (billions of 1989$) of Carbon Caps for No Reforestation Program Beyond the President's Tree Initiative and for High-Cost Trees under the NES Actions Without Nuclear Case

	Stabilization		20% Reduction		50% Reduction	
	No	High	No	High	No	High
2000	$ 13	$ 4	$ 90	$14	NA	$ 42
2010	43	10	116	21	NA	69
2030	72	20	172	39	NA	104

Note: NA = "Not Achievable".

Table 8.16. Total Costs (billions of 1989$) of GWP Caps for No Reforestation Program Beyond the President's Tree Initiative, and for High-Cost Trees

	Stabilization		20% Reduction		50% Reduction	
	No	High	No	High	No	High
2000	$ 0	$ 0	$ 17	$6	NA	$ 42
2010	0	0	36	10	NA	61
2030	2	2	36	16	NA	63

Note: NA = "Not Achievable".

with tax refund is the most potent policy combination for stabilizing and reducing carbon and GWP-weighted greenhouse gas emissions. In fact, a 50% reduction in carbon emissions is not achievable without such a combination of policies. If the goal is to stabilize or reduce GWP-weighted greenhouse gases (which includes gases other than CO_2), this goal can be met more comfortably and at lower costs than similar levels of constraints on just carbon emissions.

A policy of reforestation bundled with building standards is nearly as effective in reducing carbon and GWP-weighted emissions for a similar marginal cost (tax) combined with reforestation. However, this policy combination alone is insufficient to meet reduction levels of 20% in 2000 and/or reductions of 50% by 2030. In fact, this policy combination is only marginally more effective than a single policy of reforestation without building standards (see Chapter 7).

In lieu of taxes, a system of carbon or GWP caps could be instituted, with auctionable permits for the right to emit carbon or GWP-weighted greenhouse gases. Due to the dual nature of prices and quantities, the auction price that emitters would be willing to pay for the right to emit these gases is equivalent to the tax level that would induce similar reductions in these gases. Therefore, the cost and impact of a cap program would be identical to the carbon or GWP tax cases. The choice of one policy (taxes) over the other (emissions caps with tradeable permits) would depend upon the relative cost of administering such a policy and the ability to measure and verify its impact.

A sensitivity analysis shows that, as in the case of carbon and GWP taxes discussed in Chapter 6, the assumption concerning the availability of nuclear power has a limited impact on costs of meeting carbon emissions targets in the short term. However, the costs of emissions targets in the long term rises significantly without the growth in nuclear power expected under the NES Actions.

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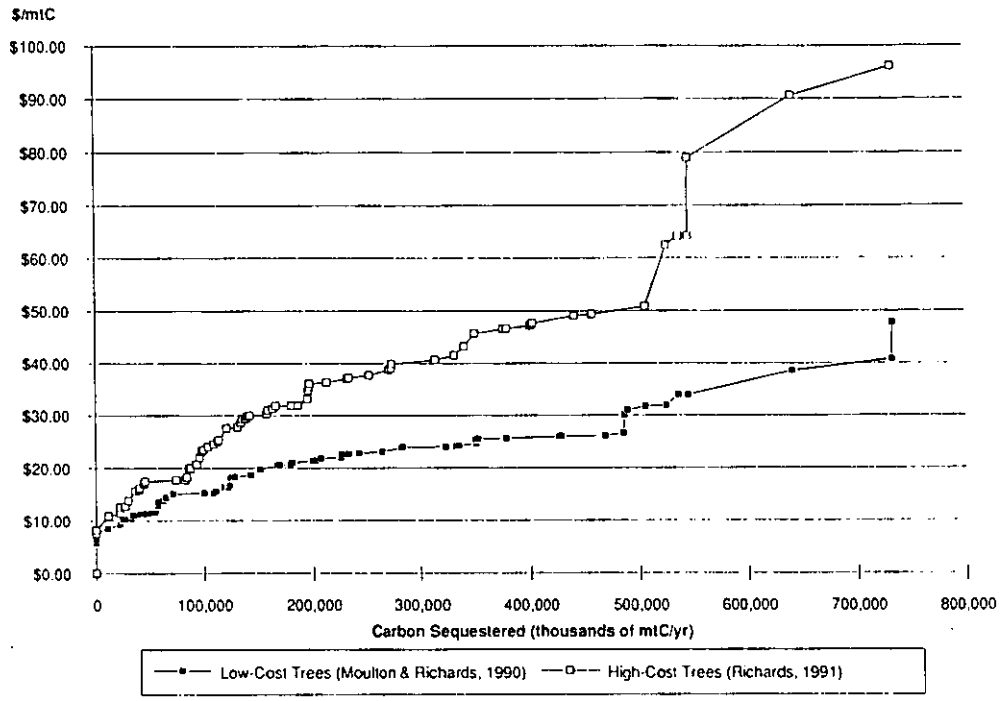


Figure 8.1a. Marginal Cost of Carbon Sequestration from Reforestation

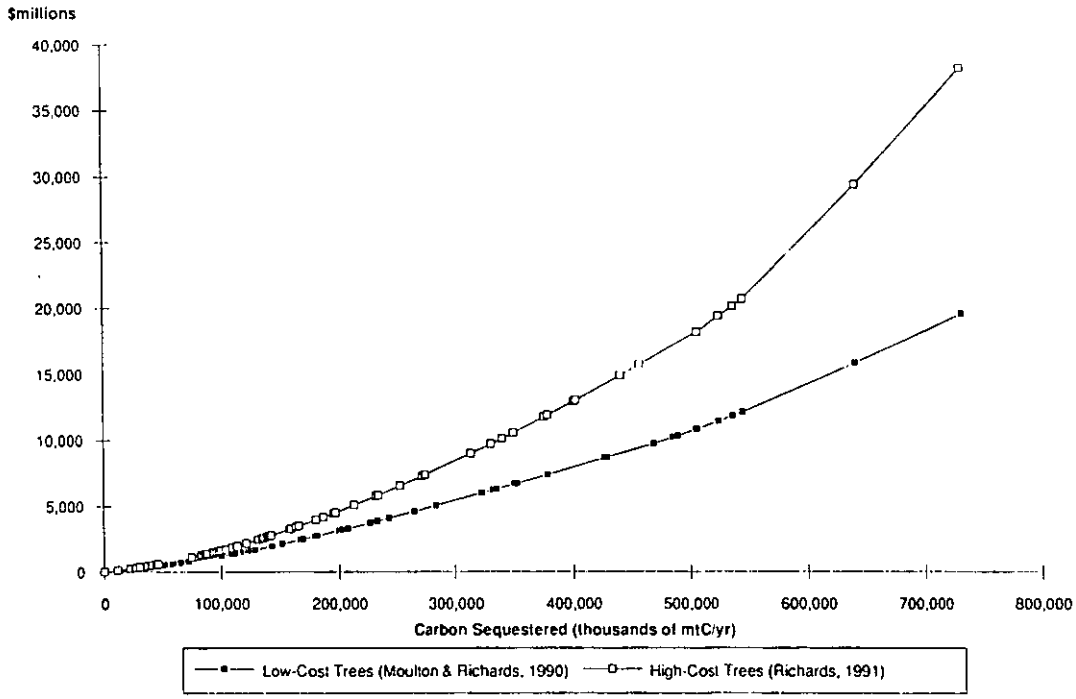


Figure 8.1b. Total Cost of Carbon Sequestration from Reforestation

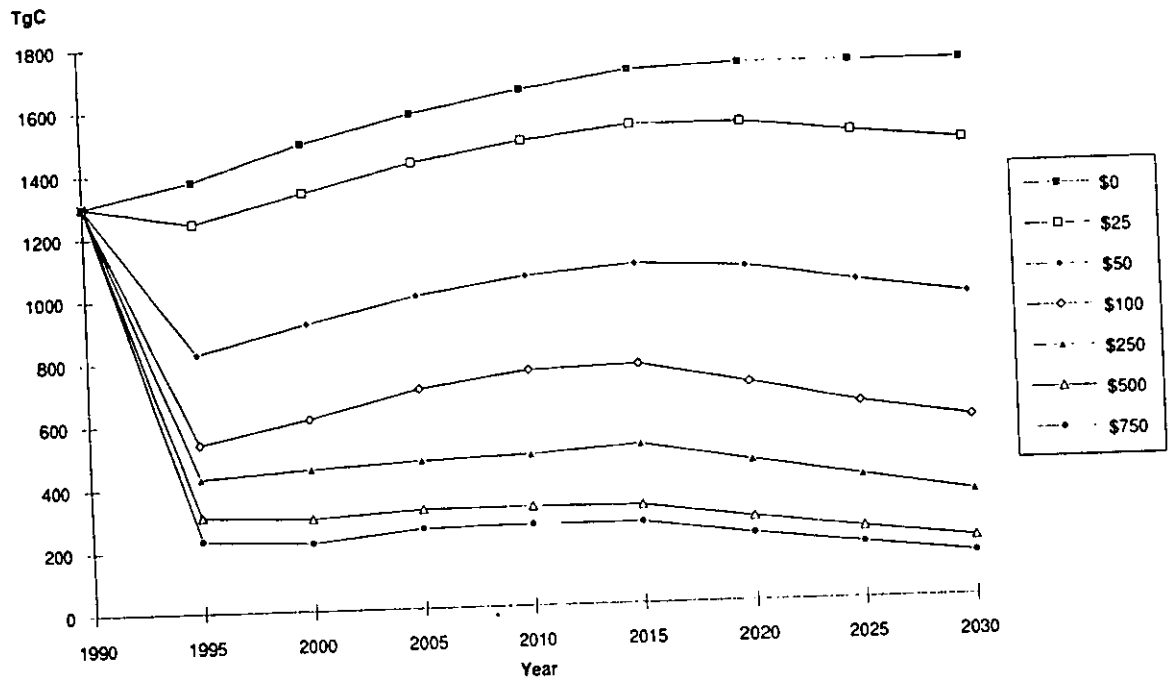


Figure 8.2a. Carbon Tax Deposit Refund, Case A (High-Cost Trees): Net U.S. Carbon Emissions (TgC/yr)

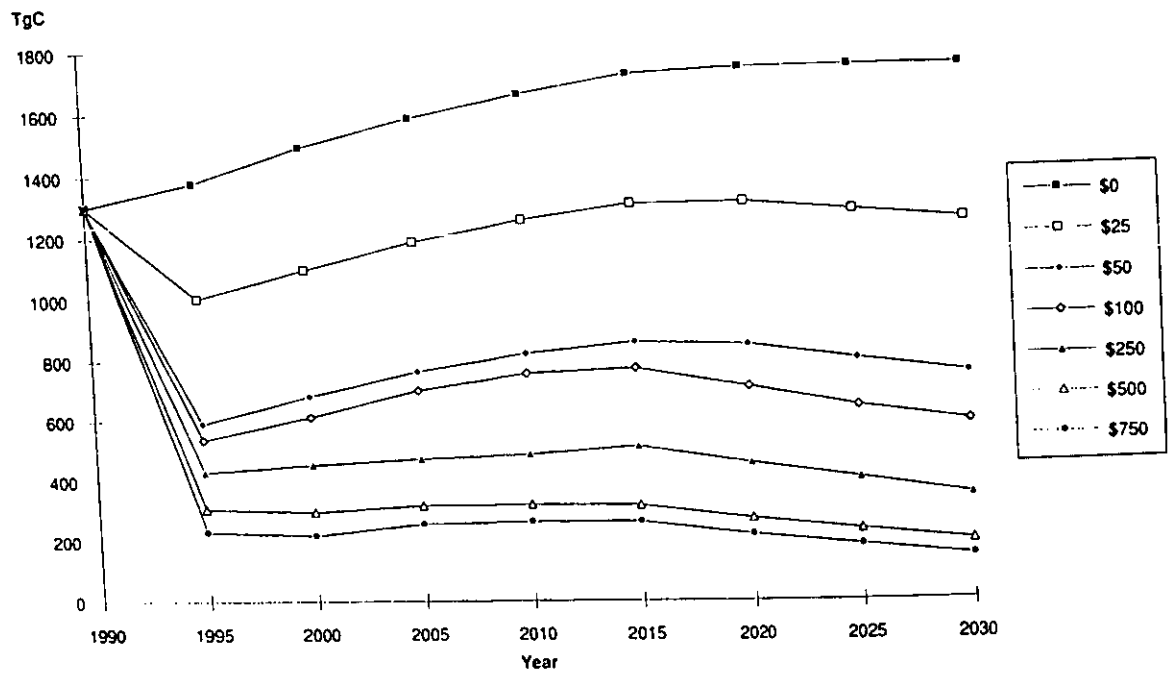


Figure 8.2b. Carbon Tax Deposit Refund, Case B (Low-Cost Trees): Net U.S. Carbon Emissions (TgC/yr)

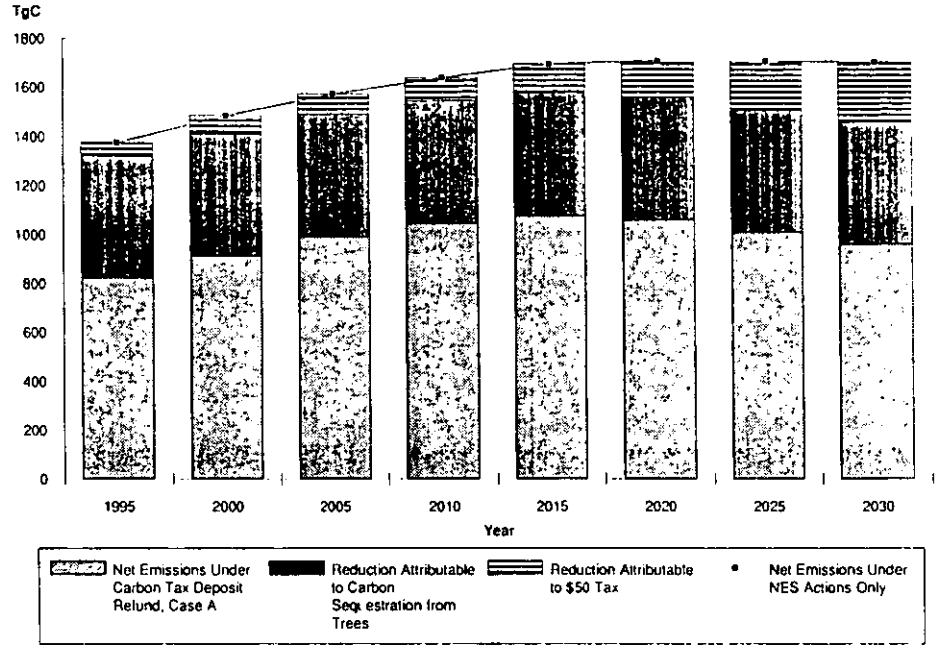


Figure 8.3a. Carbon Tax Deposit Refund, Case A (High-Cost Trees): Carbon Emissions Reductions Attributable to $50 Tax and to Trees

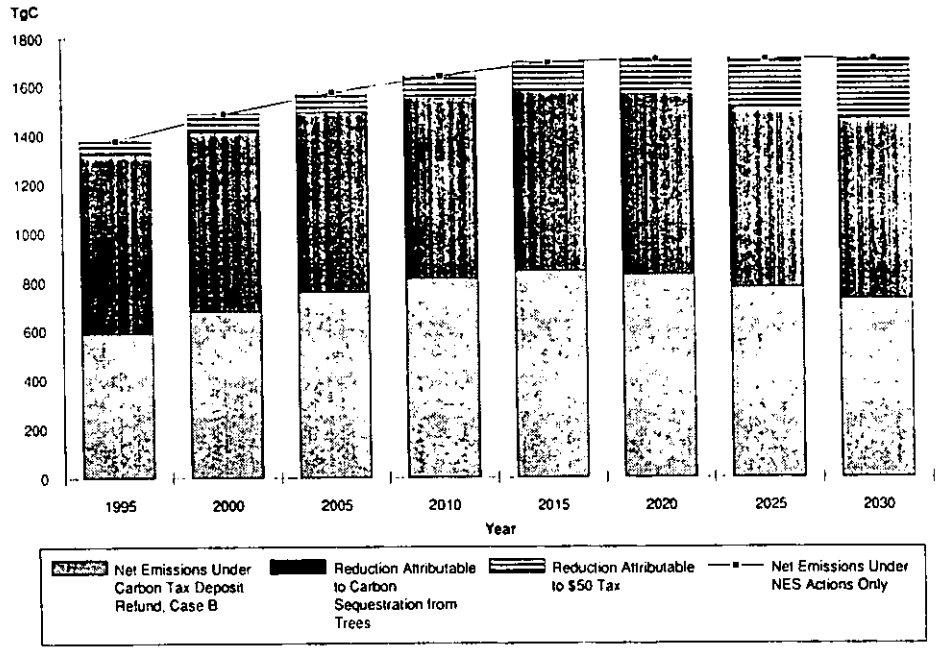


Figure 8.3b. Carbon Tax Deposit Refund, Case B (Low-Cost Trees): Carbon Emissions Reductions Attributable to $50 Tax and to Trees

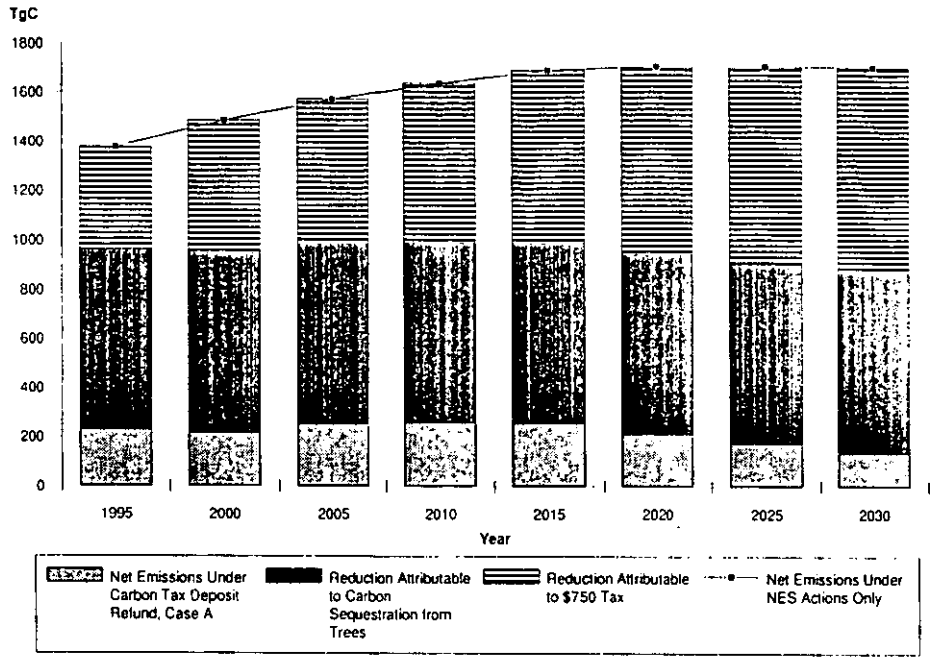


Figure 8.3c. Carbon Tax Deposit Refund, Case A (High-Cost Trees): Carbon Emissions Reductions Attributable to $750 Tax and to Trees

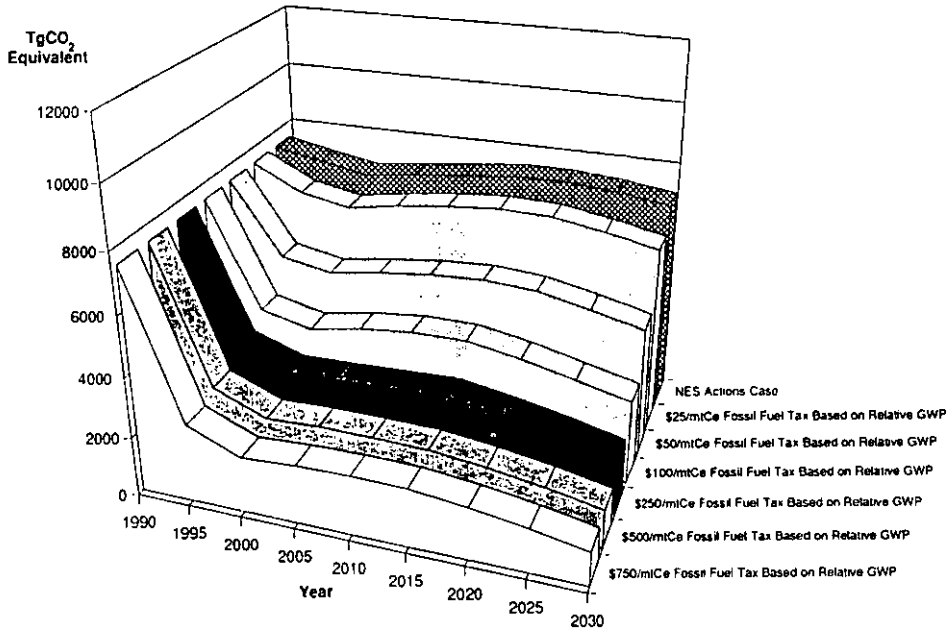


Figure 8.4a. Fossil Fuel Taxes Based on GWP Weights and Carbon Tax Refund with High-Cost Trees: GWP-Weighted Emissions by Year

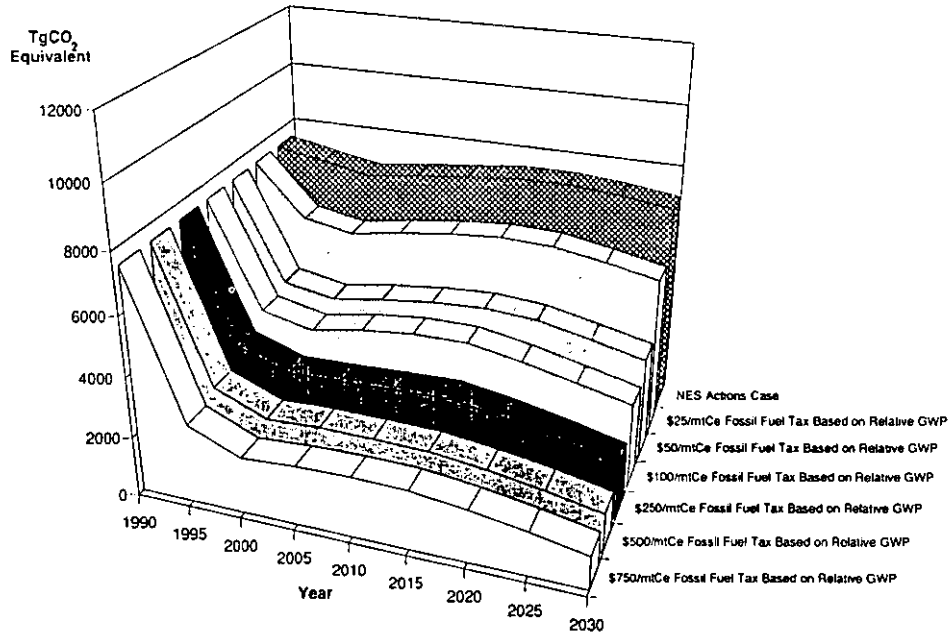


Figure 8.4b. Fossil Fuel Taxes Based on GWP Weights and Carbon Tax Refund with Low-Cost Trees: GWP-Weighted Emissions by Year

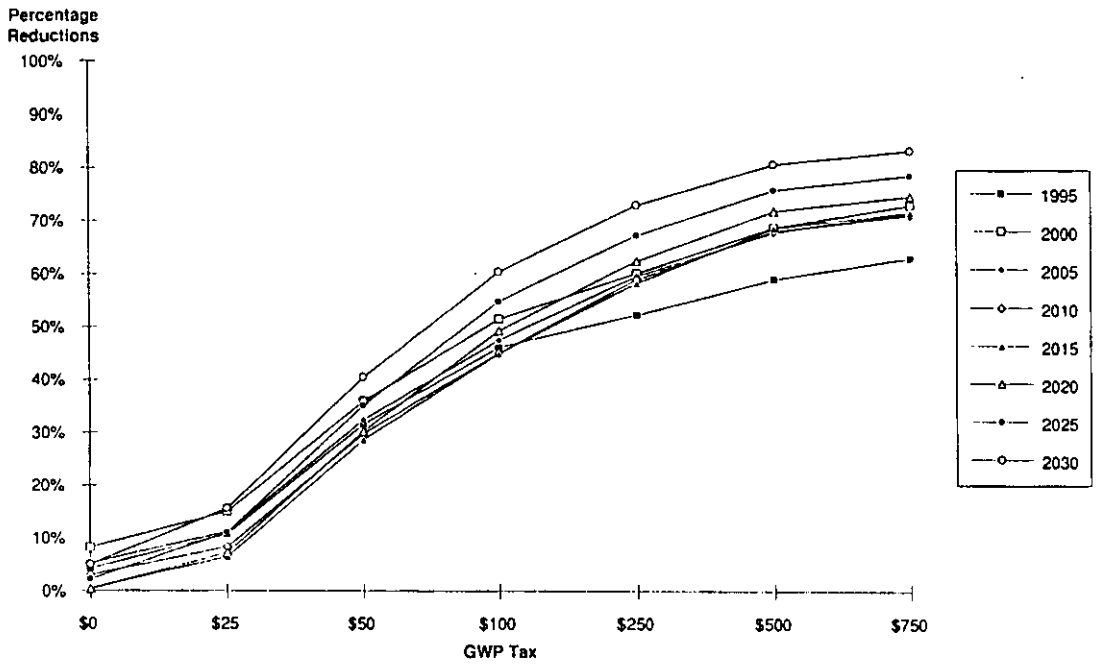


Figure 8.5a. GWP Taxes and High-Cost Trees: % Net GWP Emissions Reductions Relative to 1990 vs. GWP Tax by Year

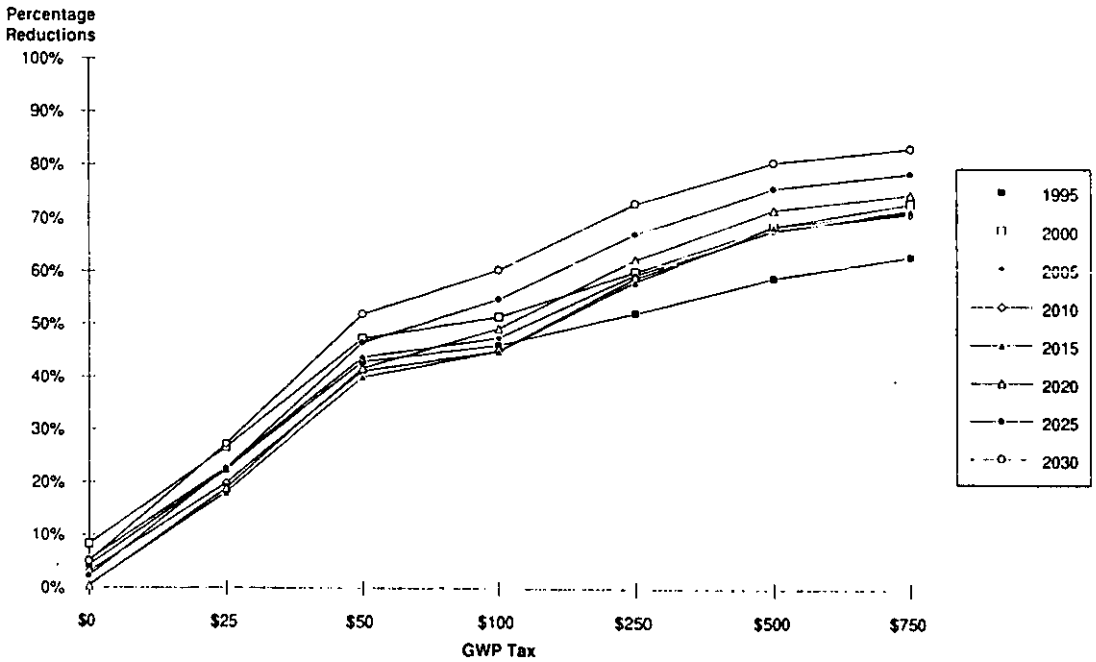


Figure 8.5b. GWP Taxes and Low-Cost Trees: % Net GWP Emissions Reductions Relative to 1990 vs. GWP Tax by Year

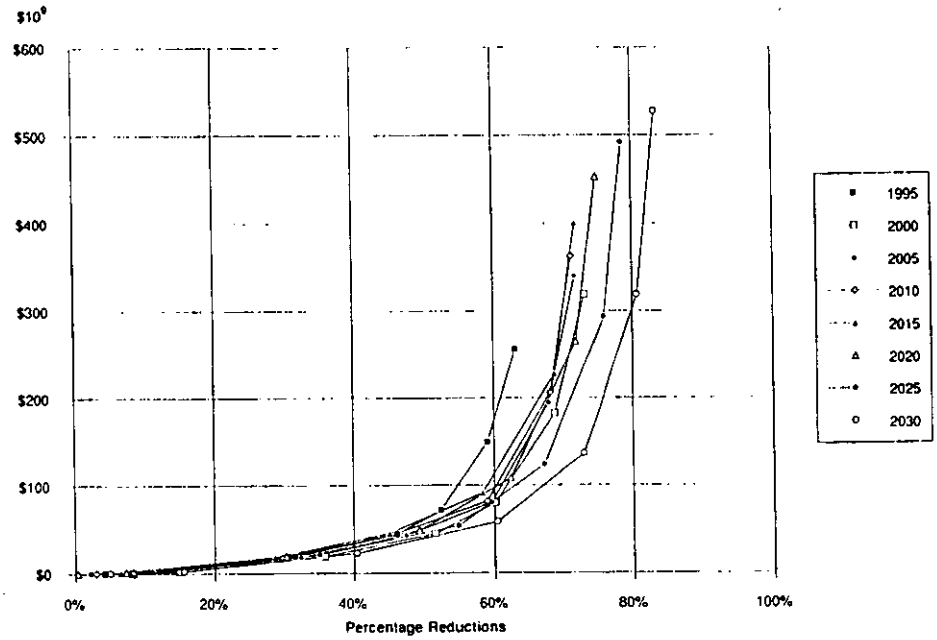


Figure 8.6a. GWP Taxes and High-Cost Trees: Total Cost vs. % Net GWP Emissions Reductions Relative to 1990

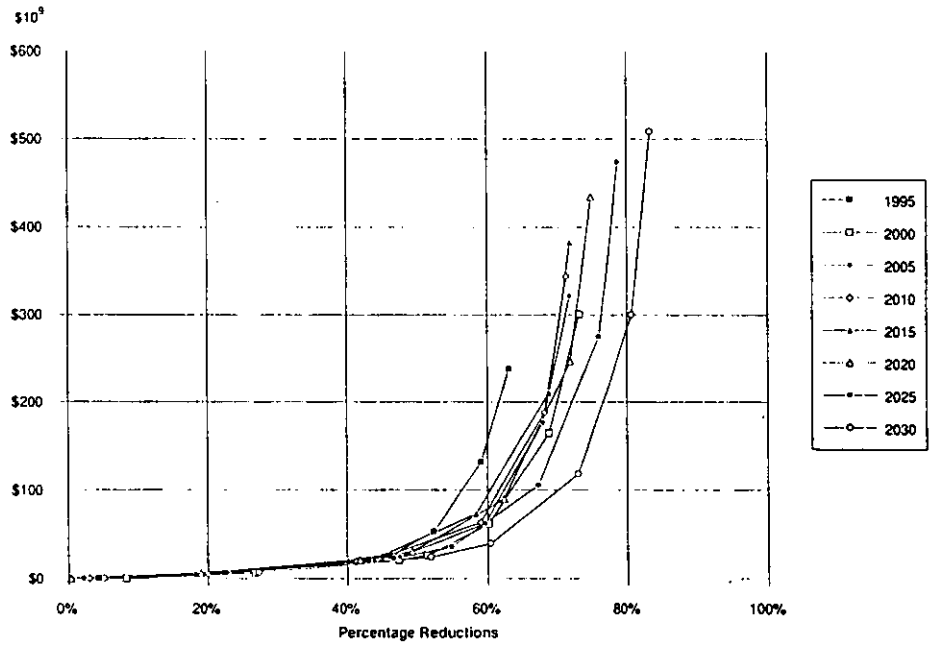


Figure 8.6b. GWP Taxes and Low-Cost Trees: Total Cost vs. % Net GWP Emissions Reductions Relative to 1990

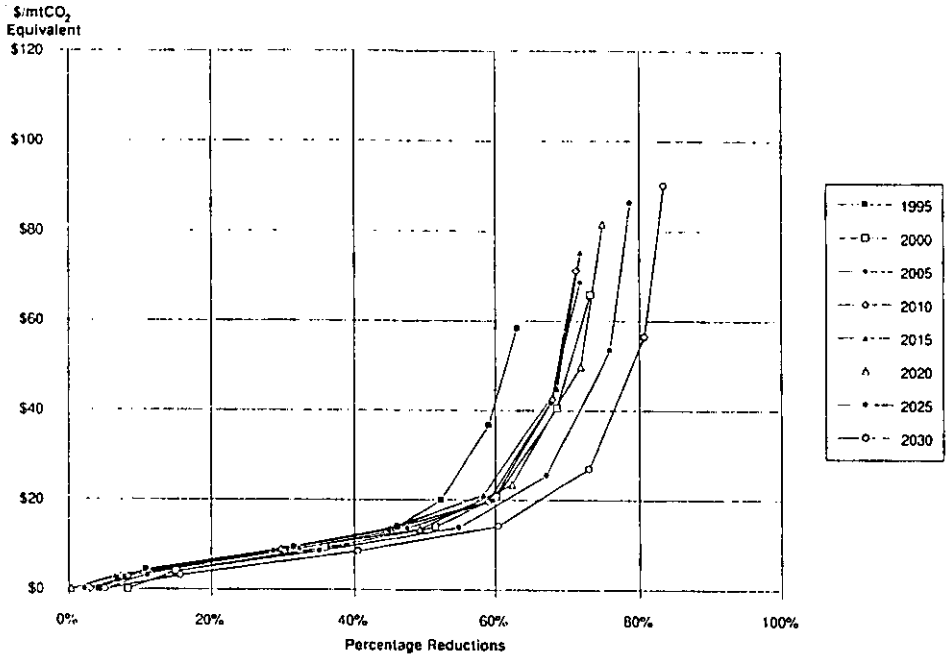


Figure 8.7a. GWP Taxes and High-Cost Trees: Average Cost vs. % Net GWP Emissions Reductions Relative to 1990 by Year

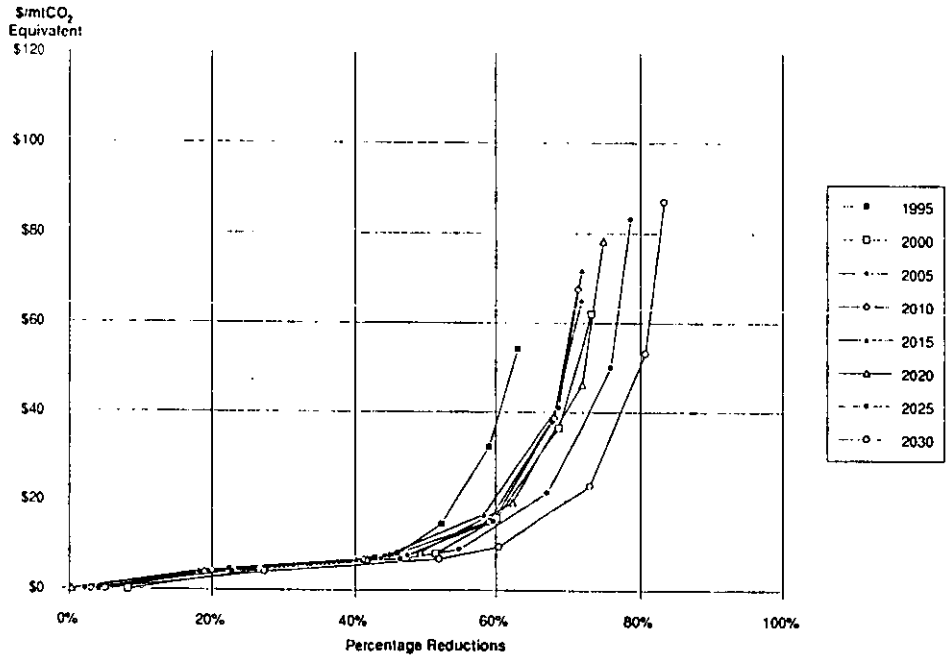


Figure 8.7b. GWP Taxes and Low-Cost Trees: Average Cost vs. % Net GWP Emissions Reductions Relative to 1990 by Year

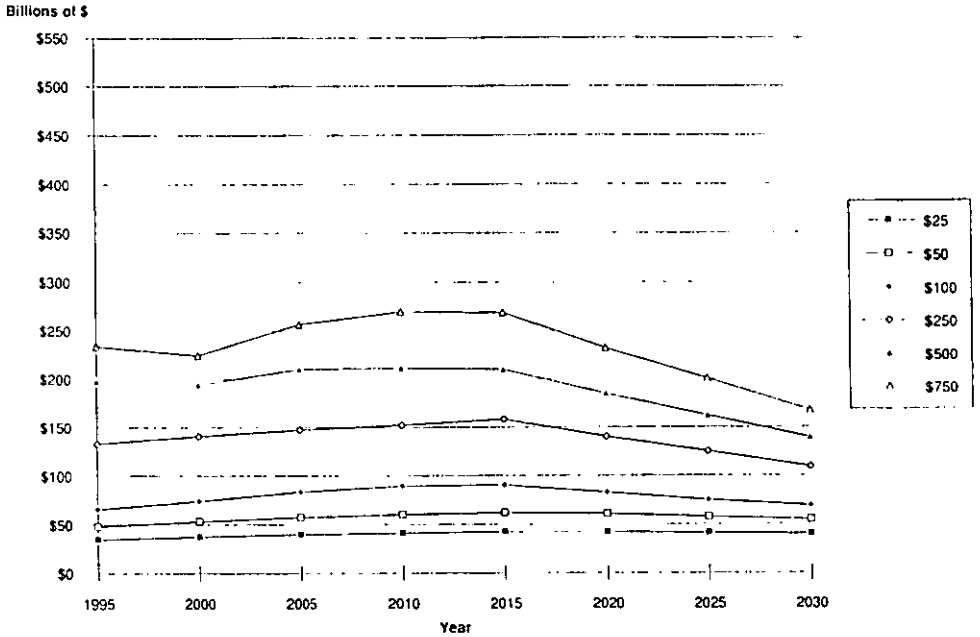


Figure 8.8a. GWP Taxes and High-Cost Trees: Net Revenue from GWP Tax Less Carbon Sink Enhancement Refund, by Year and GWP Tax Rate

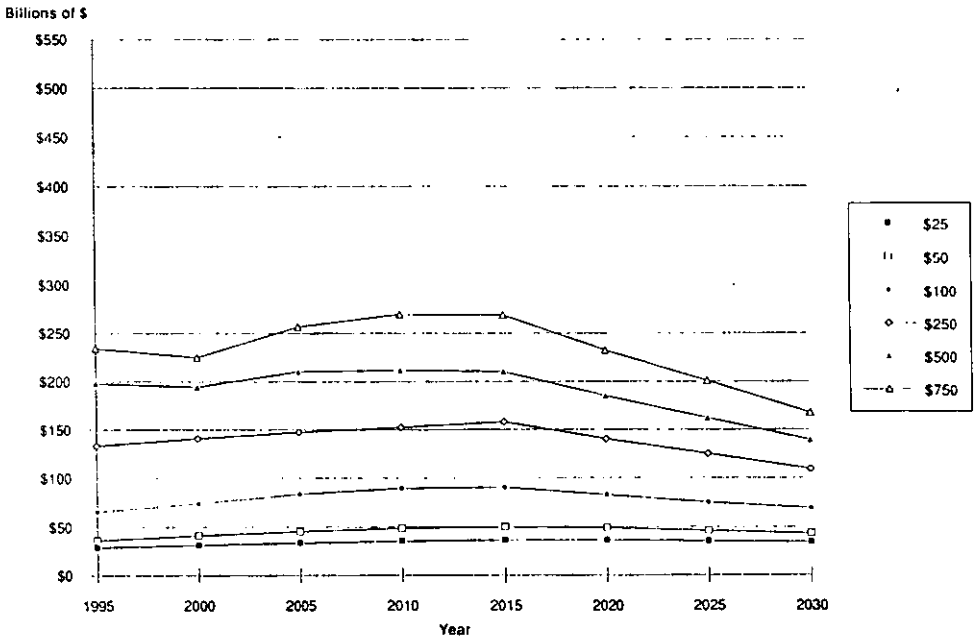


Figure 8.8b. GWP Taxes and Low-Cost Trees: Net Revenue from GWP Tax Less Carbon Sink Enhancement Refund, by Year and GWP Tax Rate

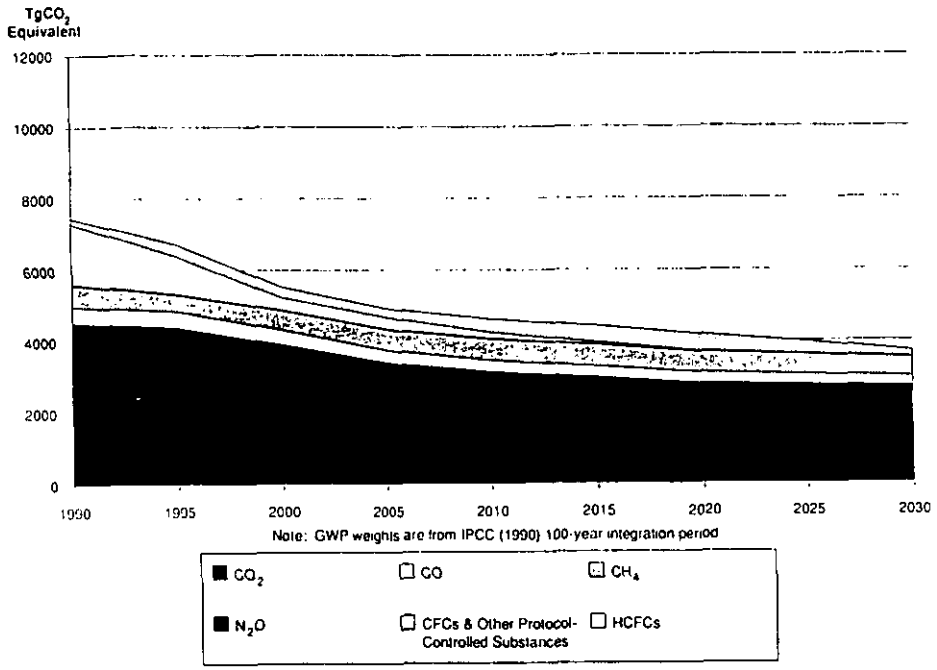


Figure 8.9. Reforestation with High-Cost Trees and $250/mtC Buildings Standards: GWP-Weighted Energy-Related Emissions by Gas and by Year

9.0 MACROECONOMIC IMPACTS

9.1 INTRODUCTION

Estimating macroeconomic impacts of policies intended to reduce greenhouse gas emissions is a difficult and uncertain endeavor. Direct and indirect policy effects are potentially large, but difficult to quantify. The focus of this chapter is on a policy's indirect effects as they spread through the many markets and sectors of the economy.

Most potential greenhouse gas control policies would increase expenditures on end-use energy consumption and/or energy conservation. Other policies, such as reforestation, would also require additional expenditures, but these would not be primarily related to the energy sector. Major macroeffects channels are identified here as follows:

1. *Price and Interest Rate Effects.* Energy price increases raise production and labor costs throughout the economy and lead to higher inflation rates. Interaction of the increased inflation with money supply, credit available in real dollars, and demand for financial assets leads to higher interest rates. Higher interest rates, in turn, lead to reductions in interest-sensitive spending such as business investment, housing, and consumer durable goods, which are components of the GNP.[a]

2. *Substitution Effects.* Households shift purchase patterns toward less energy-carbon intensive goods and increase the amount of conservation-related investment. Firms also substitute capital and labor for energy for producing goods and services. The structural impacts these substitutions have on the overall economy can influence macroeconomic performance.

3. *Import Bill Effects.* Changes in world oil prices have an income (or wealth) transfer effect. This channel is an external benefit of a policy that promotes energy conservation and lowers the import demand for oil. Lower world oil demand is expected to result in lower oil prices on average over time, potentially saving the United States and other importing nations billions of dollars on import bills.

9.2 POLICY INSTRUMENTS

This chapter considers two specific policies that were discussed in Chapters 6 and 8:

- A $100 real carbon tax
- A program of reforestation and building standards.

The level of tax apportioned to each major fossil fuel depends upon the carbon content of the fuel. Based on 1990 prices of these fuels, the largest proportionate increase would be for coal. Without considering the eventual market price after supply and demand interactions, the initial price increase for coal would be over 200%. In the same manner, percentage increases in oil and gas prices would be 65% and 84%, respectively.

The combined reforestation/building standards policy was described in Section 8.3. The reforestation policy mandates the planting of trees to fix or sequester the lifetime carbon emissions of all new fossil fuel powerplants. The direct impact on the economy is sharply higher electricity prices as utilities incorporate the cost of the tree planting into their rate bases. The second part of the policy deals with a program to apply stringent energy efficiency standards to residential and commercial buildings. As discussed in Section 7.5, the building standards are set at the $250/mtC level.

(a) We note, however, that the experience of the early eighties shows that high interest rates impact not only business investment, housing and consumer durables, but also interest income. Furthermore, historically, the availability of credit tends to be as important to business as its cost.

9.3 MODELS AND METHODS

As mentioned at the outset of this chapter, estimating macroeconomic impacts of policies intended to reduce greenhouse gas emissions is a difficult and uncertain task. For instance, a carbon tax would in many ways affect the economy like the energy shocks of the 1970s. Literally dozens of econometric studies have been undertaken to attempt to measure the exact impacts those shocks had on macroeconomic indicators, with a wide range of results.

Several major factors contribute to the uncertainty in measuring the macroeconomic impacts of energy price shocks and policies:

1. Most macroeconomic models don't distinguish between energy consumption and energy service; accordingly, they do not embody long-term energy conservation potentials.

2. Long-term constraints and balance sheet effects are often omitted or are incorporated in only a rudimentary way. As an example, the long-term fiscal effects of such policies on the government debt may not be realistic.

3. Differences of opinion exist as to what stabilization targets should be used and how they should be set. Thus, how interest rates, money growth, government deficits, or exchange rates are targeted within the model makes a considerable difference in the impact of a particular energy policy.

Other issues further complicate the estimation of the quantitative impact of specific policies. The economy changes and grows through complex adjustment processes relying primarily on private decisionmakers and market forces. These complex adjustment processes suggest that the response to any policy change is not likely to be uniform over time or across sectors; rather, there may be periods of larger impacts and overshooting and periods of lesser impacts, relative to an identical economy in the absence of a policy. Often the impact is small, relative to natural fluctuations in the economy, so that estimating average impacts over some period may be an acceptable measure of impact.

It would be a mistake to think of the forecasted impact from a macroeconomic model simulation as an accurate estimate; it is better to think of it as a quantitative illustration of the channels through which impacts in energy markets are translated into impacts on economic aggregates. The quantitative impact estimates will be sensitive to the hundreds of price, income, and interest rate elasticities in the macro model and the rate adjustment parameters, all of which have been estimated econometrically with limited data and under uncontrolled conditions.

If these impacts are highly uncertain, why are probability methods not used more often? The principal reason is the tractability of such analyses. The specification of economic relationships is interdependent--in the models, A affects B and B simultaneously affects A. While the solution to these models can be found routinely with a deterministic specification, it is very difficult to calculate probability distributions that are consistent with the hundreds of behavioral equations and identities in a macro model.

A final note on the meaning of macroeconomic impacts is appropriate. The concepts of costs and welfare losses as derived in microeconomic models such as Fossil2 can only be loosely applied to macroeconomic simulations such as the DRI Quarterly Model. The DRI Models are designed to forecast the components of the National Income and Product Accounts (NIPA), with the GNP being the measure of national income and also the value of final goods produced. But those familiar with the GNP accounts recognize that they have deficiencies. GNP accounts require aggregation and index number manipulation, and the accounts must deal with changing product mixes, product quality, and technical change. They exclude benefits of improved environmental quality. Pollution abatement

expenditures may be captured as inflation in product price indices rather than as improved product quality.

With these caveats in mind, the remainder of this chapter will discuss and attempt to quantify macroeconomic impacts of the two alternative policies for reducing greenhouse gas emissions.

9.3.1 Models Used in this Study

Two efforts were undertaken to estimate the effects of these policies on the overall performance of the economy. The first involved a group within the Energy Information Administration (EIA) using the large-scale version of the quarterly econometric model of the United States maintained by DRI. The full-size DRI Model contains about 1200 variables and contains considerable detail of the NIPA.

A second effort was conducted at Argonne National Laboratory and used the compact version of the DRI Macroeconomic Model. The compact version of the model contains about 400 variables, with fewer breakdowns within the NIPA.

As with other complicated modeling evaluations, the assumptions of the user can play an important role in determining the overall results. Although the full-size and compact models incorporate the same general model structure, a large number of assumptions and adjustments are required to realistically model the two greenhouse gas policies cited above. The degree of disaggregation will distinguish the model results; differences in the way the models are used will also play a role. The two efforts help to provide a range of estimates derived from equally plausible sets of assumptions by experienced teams of economic analysts.

The next two sections describe how the two models were used by the two different groups.

9.3.2 EIA Approach Using the DRI Full-Scale Model

During the NES process, the DRI Model was used to satisfy two fundamental system requirements:

- Develop baseline and alternative economic growth projections as inputs into the energy market analysis
- Evaluate detailed macroeconomic impacts associated with energy policies and events.

The focus here is on the how the model was used to evaluate the tax and reforestation/building standard policy options.

Linkage to the Energy Market Variables

The variables pertaining to energy markets and production contained in the macroeconomic model were calibrated to the energy results coming from DOE Fossil2 runs. The following 20 energy variables in the DRI Model were linked to DOE energy model results: primary energy consumption; domestic production of oil and natural gas; domestic production of coal, renewables, nuclear, and hydroelectricity; generation of electricity; highway consumption of gasoline and diesel fuel; wholesale prices of coal, natural gas, electricity, and refined petroleum products; implicit price deflators of electricity, fuel oil and coal, gasoline and oil, and natural gas; consumer spending for electricity, fuel oil and coal, gasoline and oil, and natural gas; industrial production indices for mining; and world oil prices.

To estimate the macroeconomic effects of the two cases, the 20 DRI variables described above were set up to match the percentage change from base of the DOE energy model variables. The

macroeconomic model was then used to estimate the GNP change that results from changes in energy variables. A solution technique was applied that calculated add-factors to achieve the desired percent change *without* oxygenizing the variable in question. The model was then solved three and sometimes four times to ensure that the final percent changes in the energy variables closely matched the target percent changes. This solution procedure permits the evaluation of accommodating policy actions in conjunction with the initial simulation without having a simulation that is frozen on energy variables.

Efficiency in Supply Potential of the Economy

The Quarterly Model was solved using two assumptions regarding the effect of decreased energy consumption on the supply potential of the economy, defined as potential GNP in the model. Potential GNP is a measure of the output potential of the economy when all resources in the economy are fully employed--the unemployment rate is low, capacity use is high, and there are no destabilizing events occurring in the economy.

Potential GNP is a representation of the supply-side dynamics of the economy. This is modeled as a Cobb-Douglas production function featuring labor, capital, and energy as key factors of production. Labor contributes the most effect on the production function, having a weight of approximately 62%; capital has a weight of 33%, and energy has a weight of 5%. With an observed decline in energy consumption, potential GNP would experience a decline, even though energy might be used more efficiently (resulting in no decline in energy services). The model captures little of the economic benefits of energy conservation resulting from a more efficient use of energy.

In order to sort through the dynamic effects on the economy, the simulations were performed in two stages:

- Only the 20 energy variables were calibrated using DOE energy model runs
- Adjustments were incorporated to reflect changes in the productive efficiency of the economy.

Three adjustments were made to derive the latter case. The potential GNP was adjusted to reflect no change in energy services, adjustments were made to reflect incremental energy investments, and an oil import bill adjustment was made.

Potential GNP was adjusted by the amount that energy consumption declined in the first case (multiplied by its share), so that potential GNP would not fall as a result of the decline in energy consumption alone. Substitution of other factors of production--labor and capital--for energy maintains the productive efficiency of the economy. This change implicitly assumes that there is no decline in energy services accompanying a reduction in primary energy use.

A second adjustment was made to reflect the terms of trade effect of a change in the oil import bill. The oil import bill in each case is calculated as the total expenditures for oil imports, expressed in constant 1982 dollars. Potential GNP is adjusted by the difference in this constant dollar expenditure level. When the price of imported oil declines, more of U.S. production is left for domestic consumption and the real welfare of U.S. consumers increases. In general, living standards have increased even though production (GNP) is not greatly affected. This adjustment corrects for this terms of trade effect.

Finally, an adjustment was made to both residential and non-residential investment to reflect the increased investment in more energy-efficient equipment resulting from higher energy prices.[a]

In total, these adjustments reflected the judgment that, although the economy must still adjust to shocks imposed by these policies, in the long

(a) These values were derived by Argonne National Laboratory from the energy model simulations provided by Pacific Northwest Laboratory.

term, the greater changes in production relationships would tend to lessen the aggregate impact of the imposed policies.

The Role of Monetary and Fiscal Policy

During the course of the development of the NES, a debate ensued about the proper set of monetary and fiscal policies that should accompany any proposed energy policy. This is particularly important in the current analysis where, in the Carbon Tax Case, there are large sums of collections from this tax. From that discussion, the following assumptions were made for the current study:

- There is no accommodating monetary policy accompanying either of the policy cases considered
- Compensating fiscal policy is considered only as a mechanism to return collected revenues back to the economy. Therefore, fiscal policy is applied only to the Carbon Tax Case and not to the Reforestation Case.

For the carbon tax, the simulations were carried out in two modes. In the *deficit reduction* mode, the gross collections from the imposition of the tax raise federal indirect business tax revenues, and these additional revenues are assumed to be used to reduce the deficit. In the *deficit neutrality* mode, the gross revenues are *not* used to reduce the federal deficit. The simulation explicitly targets the "full employment federal deficit" to remain at baseline throughout the forecast period. The Economic Policy Council on Energy Taxes advocates the deficit neutrality approach for the assessment of energy tax policy options.

Two mechanisms for targeting deficit neutrality were investigated--a cut in the effective social security tax rate and a reduction in the effective personal income tax rate. Changing the effective social security tax rate in the model implies changing both the employee and employer tax rates. The deficit reduction simulations were fully tuned to the DOE energy model runs. The model was then targeted to achieve deficit neutrality by allowing the tax rates to change endogenously until neutrality was achieved.

9.3.3 Argonne Approach Using the DRI Compact Model

In general, the Argonne approach was similar to that taken by EIA. Three types of information from the Fossil2 Energy Model were employed in the DRI Compact Model: 1) prices and quantities of fuels, 2) conservation-related investment, and 3) the oil import bill. The Argonne team made similar adjustments to the DRI Model to reflect increased energy efficiency in the long term.

Prices and Quantities

The prices of energy commodities are an important input driver in the DRI Compact Macro Model. The prices are provided to the macro model in the form of wholesale price indices. The wholesale price indices are obtained from Fossil2 runs and are matched to industrial sector energy prices.

Energy consumption quantities included residential household real consumption of electricity, natural gas, oil fuels, and gasoline. From a microeconomic perspective of individual households, these represent energy demands as a function of energy prices with the demand curves embedded in Fossil2. From the macroeconomic perspective, these terms are components of the consumption of final goods in real terms and hence are components of real aggregate demand.

Conservation-Related Investment and Other Expenditures

Both fiscal and regulatory policies tend to have expenditures associated with them that enter the DRI Model as an exogenous shift in aggregate demand. For the Carbon Tax Case, these expenditures are conservation-related investments in the residential building sector and the non-residential buildings and manufacturing sectors. These conservation investments are based on the conservation

supply curves in Fossil2. For each energy service in Fossil2 and for each possible fuel that can provide that service, there exists a conservation supply curve in Fossil2.

For the Reforestation/Building Standards Policy Case, there is also residential and non-residential conservation investment, due to higher electricity prices in this case. There is also additional residential building conservation expenditure, due to the building standards themselves. Finally, there is expenditure in this case for the reforestation program. It was assumed that the expenditures on reforestation are equal to the revenue collected from the tax on electricity. This expenditure was entered into the DRI Model as a component of government spending. Table 9.1 shows these exogenous expenditures for both policy cases.

Oil Import Bill

A consequence of lower demand for oil is a slightly lower world oil price as forecast by Fossil2. Fossil2 also projects lower oil imports. Hence, the total bill for oil imports decreases, and since GNP is identified with national income, this change in import bill represents a change in national income. Viewed in another way, since GNP is also the value of final goods less the net purchase of material inputs, a change in the oil import bill will change GNP by the same amount. These statements are true of actual GNP based on aggregate demand and also true of potential GNP based on aggregate supply capacity. This change in the oil import bill was therefore entered in the DRI Model as an add factor in potential GNP (it is automatically accounted for in the calculation of actual GNP).

9.4 MACROECONOMIC IMPACTS OF CARBON TAXES

Both versions of the DRI Model display the expected dynamics of change from the carbon tax policy. The imposition of the tax has a direct impact on consumer spending and on the aggregate price level of the economy, with a complex time-profile of impacts on aggregate output. From the point of view of the consumer, two issues prevail. First, households will be faced with higher prices for energy and will adjust their amount of energy consumed. Nonetheless, nominal expenditures will likely rise, taking a larger share of the family budget. Consumers can be expected to reduce their expenditures on other goods and services. Second, higher energy prices effectively reduce real disposable income. Workers will attempt to bargain for higher wages. To the extent they are successful, this represents a cost increase in the production of all goods and services.

Energy services also represent a key intermediate input in the production of all goods and services. After energy prices increase, substitution away from energy is limited, and the prices of other inputs do not fall. This raises the production costs per unit of output for firms. Higher wage costs and spillover price effects on other variable costs further escalate production costs throughout the economy. This process places upward pressure on the nominal prices of all intermediate goods and final goods and services in the economy.

The effect on interest rates is subject to uncertainty, depending on the reaction of the monetary authorities. Lowering federal government

Table 9.1. Expenditure Categories for the DRI Compact Model Runs

Carbon Taxes	Investment Per Year	Reforestation/Buildings Standards	Investment Per Year
Residential investment	$3 billion	Residential investment	$5.5 billion
Non-residential investment	$6 billion	Non-residential investment	$3 billion
		Reforestation program	$2 billion

borrowing will place downward pressure on interest rates. However, if there is no change in the level of non-borrowed reserves, the higher aggregate price level effectively reduces the real supply of money. This will place significant upward pressure on interest rates.

On balance, the effect of the higher price level in the economy should dominate in the near-term, forcing both nominal and real interest rates above baseline. The rise in interest rates discourages investment and interest-sensitive components of consumer expenditures such as automobiles, housing and other durable purchases. In the long term, as price inflation in the economy abates, the continuing reduction in federal government borrowing serves to ultimately lower interest rates, relative to the baseline.

9.4.1 EIA Modeling Results

As described in Section 9.3.2, the EIA team made separate model runs with and without adjustments to account for increased energy efficiency. Before making the efficiency adjustments, EIA summarized the results of tracking only the direct energy price and quantity impacts on the economy. For the carbon tax, the assessment was first carried out under the assumption that the gross collections from the tax are used to reduce the federal deficit. Accommodating fiscal policy (defined as deficit neutrality) is then applied to investigate the short- and long-term effects of returning a portion of the collected revenues to business and consumers.

A second set of simulations focuses on the resiliency of the economy in the face of these energy market impacts, through supply-side adjustments to the potential output. This is accomplished using the methodology discussed in Section 9.3.2. These alternative sets of results are intended to help define the range of impacts that may be expected from these policies.

Economic Impacts - Energy Market Effects Alone

Relative to the baseline projection, the path of real GNP in the Deficit Reduction Case is shown in Figure 9.1. GNP falls by more than $100 billion during the latter part of the 1990s. In the longer term, the increased rate of national savings engendered by the reduction in government debt spurs investment and increases overall productive capacity. By around 2010, the level of GNP returns to match its baseline level and subsequently increases to more than $100 billion over the baseline by the terminal year of the simulation, 2020.

The top portion of Table 9.2 summarizes these impacts that consider only energy market price and quantity changes. The values shown are the discounted (at 10% per year) values of the GNP losses from baseline over various time horizons.

Alternative Accommodating Fiscal Policies

The pattern of collections relative to reductions in the federal deficit is important to consider in defining a Deficit Neutrality Case. In essence, "deficit neutrality" is not "fiscal neutrality." To achieve deficit neutrality through 2006, less money is returned to consumers or business than is actually collected. This is because the improvement in the deficit in the case discussed above was less than collections. In the post-2006 period, more is returned than collected. In this way, the federal deficit is maintained at essentially baseline levels.

Two separate approaches to achieving deficit neutrality were analyzed by EIA: 1) a personal income tax reduction, and 2) a reduction in the payroll (social security) tax. As Figure 9.1 indicates, the return of collected tax revenues to consumers and business has the effect of moderating the GNP losses through the year 2000. From 1990 to 2000, the personal income tax cut reduces the net present

Table 9.2. Economic Impacts of Carbon Tax from EIA Analysis

	Net Present Value of Real GNP Loss (billions of 1982$) (Percentage Change from Baseline)		
	1990-2000	1990-2010	1990-2020
Energy Market Effects Alone			
Deficit Reduction	-378 (-1.2)	-514 (-1.1)	-444 (-0.9)
Personal Tax Cut	-275 (-0.9)	-583 (-1.3)	-634 (-1.2)
Payroll Tax Cut	-46 (-0.1)	-263 (-0.6)	-345 (-0.7)
Efficiency Effects on Supply Potential			
Deficit Reduction	-317 (-1.0)	-341 (-0.8)	-228 (-0.4)
Personal Tax Cut	-210 (-0.7)	-415 (-0.9)	-431 (-0.8)
Payroll Tax Cut	+28 (0.1)	-77 (-0.2)	-128 (-0.2)

value of the real GNP loss from the loss of $378 billion in the Deficit Reduction Case to $275 billion (see Table 9.2). The personal income tax cut spurs consumption by increasing disposable income, but does nothing to lessen the underlying inflationary pressures set in place by the carbon tax. By cutting business costs, the payroll tax helps to control inflation. As a result, it is even more effective, reducing the GNP loss to a net present value of $46 billion.

However, if a longer time horizon is considered, the effectiveness of the deficit neutrality cases changes appreciably relative to the Deficit Reduction Case. The personal income tax cut case actually yields higher GNP losses than the Deficit Reduction Case when measured from 1990 through 2010 and through 2020. The aggregate price level remains above baseline (Figure 9.2). The improvement in consumption experienced in the first ten years begins to wane. Worse, investment activity remains weak, particularly with interest rates remaining above baseline. The payroll tax cut significantly lessens the GNP impacts early in the forecast period. However, by the year 2020, the economy still has not returned to baseline GNP levels, primarily because of higher sustained costs. Nevertheless, when measured over the entire 30-year period, this case also shows the smallest GNP loss of all the carbon tax cases.

Economic Impacts - Energy Efficiency and Supply Potential

The discussion above focused on the dynamic effects on the economy, principally from a demand perspective. The ability of the economy to supply goods and services is equally important. As mentioned in the methodology section, potential GNP is forecast through an aggregate production function, with labor, the capital stock, energy, and research and development as key factors. Primary energy use goes down with the two policy measures under consideration. What does this imply for the supply potential of the economy? Two views exist, with time a linking element.

- Reducing energy consumption alone does not necessarily improve the productive efficiency of the economy. The economy may be more efficient in its use of energy, but the lower level of energy use can adversely affect the productivity of other factors of production in the economy, thus lowering the potential output of the economy. This is particularly true in the near-term, when the capital resource base is largely unaltered.

- However, in the longer term, higher energy costs would reduce the use of energy by shifting production toward less energy-intensive sectors, by replacing energy with labor and capital in

specific production processes, and by encouraging energy conservation. There may be little or no sacrifice in the energy services rendered.

Accounting for Efficiency Effects

The assessment of the GNP impacts thus far essentially adheres to the first view. As a direct result of a decline in primary energy use, the potential output of the economy declines. The following discussion considers the premise that, in the long-term, there is no reduction in energy services, even though primary energy use is down. Essentially, the economy does not need to drop to a lower potential supply path simply because energy use is lower.

When these efficiency effects are taken into account, the economy is more resilient than when energy market price and quantity effects alone are considered. When faced with the same percentage changes in energy prices and quantities, the dynamic effects on the economy are altered. First, labor productivity does not decrease by as much and labor costs do not increase, compared to the Unadjusted Case. This, in turn caused total prices to increase less, leading to lower interest rates. As a result, adjusting the supply potential of the economy has a substantial effect on the level of the real GNP impacts.

The lower portion of Table 9.2 highlights the impacts on the economy after explicitly adjusting for improved energy efficiency. The difference in the two views is substantial. For the carbon tax, assuming deficit reduction, the price and quantity effects alone result in a net present value loss of $444 billion through 2020; if efficiency gains are incorporated, the net loss to the economy is $228 billion, an improvement of $216 billion.

The effect of alternative fiscal accommodation policies for the carbon tax is similar to that found under deficit reduction. Using the personal tax cut to rebate revenues, the Adjusted Efficiency Case shows GNP losses to be $431 billion, an improvement of $203 billion compared to the Unadjusted Case. The payroll tax cut reduces the impact from $345 billion to $128 billion, an improvement of $217 billion (see Figures 9.3 and 9.4).

The overall result in judging the comparative GNP losses using different accommodating fiscal policies is unaffected by the inclusion of adjustments to potential GNP. As Figures 9.1 and 9.3 show, the ordering of the GNP losses does not change, even though the GNP losses are smaller in absolute terms in the adjusted cases. The payroll tax still fares better than the personal income tax cut over the entire 30-year forecast period.

9.4.2 Argonne Modeling Results

The Argonne team conducted a more limited set of simulations. All of their simulations incorporated adjustments for increased energy efficiency similar to those used by EIA; they did not conduct any analyses that considered only the price and quantity impacts. They examined a single accommodating fiscal policy--the reduction in the payroll tax. However, in contrast to EIA, they analyzed an accommodating monetary policy in the form of a constant short-term interest rate policy.

Four alternative cases were run by Argonne:

1. Case 1 was a fixed (6.25%) federal funds interest rate with a reduced deficit from the carbon tax

2. Case 2 was a fixed federal funds interest rate and was made deficit neutral with payroll tax reduction

3. Case 3 maintained money reserves at base levels and a reduced deficit due to the carbon tax

4. Case 4 maintained money reserves at base levels and was made deficit neutral by reducing the payroll tax.

The Argonne team focused on Cases 1 and 2, which hold the short-term interest rate (federal funds rate) constant. They judged the long-term

properties of the DRI Compact Model to be more reasonable under the assumption of a fixed short-term interest rate. As shown below, whether the money supply is fixed or endogenous makes very little difference to the short-term properties of the model. Cases 3 and 4 were performed to allow more direct comparison with the EIA results.

As in the EIA simulations, the Argonne results show that the macroeconomic impacts are very different when a deficit reduction from the carbon tax is compared with a Neutral Deficit Case achieved by reducing payroll taxes. The Deficit Reduction Case (Case 1) shows the expected pattern, in which higher energy prices are amplified, resulting in a higher price level, higher long-term interest rates, lower investment spending, lower GNP and, through a Keynesian multiplier, lower real consumption. In the longer term, the reduced federal deficit lowers long-term interest rates and is a stimulative factor, reversing the near-term pattern.

The Argonne results for real GNP for the four cases are shown in Figure 9.5. The Deficit Reduction Case results in lower GNP for a decade or longer. Through 1995, it makes little difference how monetary policy is treated. After that, the assumption of a constant money supply (Case 3) allows interest rates to fall and thus increases GNP by more than in Case 1 (with fixed interest rates).

The deficit neutral cases (Cases 2 and 4), in which the payroll taxes are reduced, show the reverse pattern. The lower payroll taxes reduce product prices and inflation, stimulating aggregate demand and initially raising GNP. Due to the cyclical character of the model, the initial increase in aggregate demand and higher price level is reversed, leading to a reduction in GNP in the longer term. As in the Deficit Neutral Case, the alternative assumptions regarding monetary policy make little difference in the first four to five years.

9.4.3 Comparison and Summary of Results

Table 9.3 compares the GNP results of the EIA and Argonne studies for four specific years. The years 1993 and 1995 were chosen to represent a very short-term perspective; 2000, an intermediate-term perspective; and 2015, a long-term perspective.

Table 9.3. Comparison of GNP Impact Results for Carbon Tax Policy

	(Percentage Change from Baseline)			
	1993	1995	2000	2015
EIA Results				
A. Prices and Quantities Alone				
Deficit Reduction	-1.1	-2.0	-2.0	+1.1
Deficit Neutral (Payroll Tax)	+0.9	-0.7	-1.1	-1.2
B. Energy Efficiency Gain				
Deficit Reduction	-0.9	-1.8	-1.4	+1.7
Deficit Neutral (Payroll Tax)	+1.0	-0.5	-0.4	-0.8
Argonne Results				
C. Energy Efficiency Gain and Fixed Money Stock				
CASE 3: Deficit Reduction	-0.5	-2.3	-2.8	3.8
CASE 4: Deficit Neutral (Payroll Tax)	+0.9	1.4	-0.7	0.5
D. Energy Efficiency Gain and Fixed Short-Term Interest Rate				
CASE 1: Deficit Reduction	-0.3	-1.9	-3.5	+7.7
CASE 2: Deficit Neutral (Payroll Tax)	+1.3	+2.0	0.2	-6.4

Some key points concerning the results shown in Table 9.3 follow.

1. The separate set of EIA simulations is intended to bound the range of uncertainty associated with induced changes in energy efficiency over the long run. Through 1995, the different

modeling approaches yield generally similar results. The cumulative impacts of the differences in the assumptions about changes in energy efficiency on potential output naturally lead to greater improvements in output by the end of the forecast period. More efficient use of energy leads to increases in GNP of 0.4% to 0.6%, relative to the base case, depending on the type of fiscal policy.[a]

2. In the near term (through 1995) alternative treatment of monetary policy makes little difference (panels C and D). The overall patterns are similar in the longer term, although the magnitude of the results are different.

3. The most direct comparison of the EIA and Argonne results is between panels B and C. Both approaches show the same general pattern. In the Deficit Reduction Case, reductions in output through 2000 are later reversed to show gains relative to baseline in the very long term. The Deficit Neutral Case, considered as a reduction in the payroll tax, has the opposite pattern.

4. Although the two models display similar time-varying responses to the carbon tax policy, the Argonne results with the DRI Compact Model suggest significantly higher cyclical sensitivity to such a policy. For example, in 1995, the implementation of a payroll tax ameliorates the GNP impacts of EIA and Argonne analyses, but the offsetting effect of the payroll tax on GNP is relatively greater in the Argonne analysis. This result is largely due to the different sensitivities of the two models; however, slight differences between the models in the implementation schedule of the tax changes may also explain part of this variance.

5. The greater amplitudes of cyclical variations may be responsible for the EIA-Argonne differences shown for GNP in the very long term--2015. This result should also caution us about making very strong statements about the long-term effects of these policies.

The principal conclusion to draw from this analysis is that the scale of fiscal transactions generated by a carbon tax of the magnitude discussed here is so large as to require a general reassessment of fiscal policies. Carbon tax revenues do not represent a minor change in the existing structure. Such taxes have potentially significant consequences. We note, for example, that depending upon the treatment of the tax revenues, GNP can either increase or decrease in the long term. The fact that the long-term GNP in a deficit reduction carbon tax case is larger than the reference case seems initially to be counterintuitive. This result is the consequence of the fact that, in the macroeconomic models used here, tax revenues used to reduce the deficit have the effect of increasing national savings, and thereby making additional funds available for investment in new plant and equipment throughout the rest of the economy. This fiscal option is, of course, always available to the federal government; there is nothing unique about the carbon tax in that regard. The analysis of the carbon tax simply serves to highlight this phenomenon. We also note here that the eventual dominance of the "government savings" effect in raising GNP over other GNP-reducing effects in the deficit reduction case may or may not be observed in other models. Further research is required to establish a quantitative relationship. We note also that while GNP was greater in the year 2030 in the deficit reduction case than in the reference case, personal consumption was not. Personal consumption never recovers to reference case levels during the course of the analysis.

(a) The results for "price and quantity alone" simulation compare closely with a recent study by the Congressional Budget Office (CBO) of a $100 carbon tax (CBO 1990). Using a deficit reduction assumption, the CBO estimated GNP losses of 1% for 1993, rising to 2% by 1995 through 2000. However, the CBO's results apply to a phased-in tax rising in a linear fashion to $100 by 2000. Presumably, the impacts for 1993 and 1995 would have been higher if the CBO had introduced the full tax in 1991, as in this study.

9.5 MACROECONOMIC IMPACTS OF REFORESTATION/BUILDINGS STANDARDS

The Carbon Tax and Reforestation Cases differ in two fundamental ways. First, the price shock to the economy is both greater and faster for the carbon tax, relative to the Reforestation Case. Second, the carbon tax generates a large stream of revenues, which have negative impacts on disposable income and corporate profits.

9.5.1 EIA Modeling Results

As mentioned above, energy prices rise much higher in the Carbon Tax Case than in the Reforestation Case. For the carbon tax, the wholesale price index for fuel and power goes up immediately. By 1995, it is 45% above base and remains about 20% above baseline levels for most of the remaining forecast period. This difference in energy prices feeds through to overall inflation.

By contrast, in the Reforestation Case, only electricity prices increase, compared to the base. They reach 5% above base by 2005 and increase gradually to 8% above the base by 2020. The rate of price increase is relatively steady. The impact of the building standards leads to falling natural gas prices until 2000; gas prices then rebound such that, by 2015, they are 5% above base. As a result, overall energy prices remain around baseline levels until 2010; after 2010, they rise to roughly 2% above baseline levels. In the reforestation scenario, consumer prices are slightly below baseline until 2010, following the path of overall energy prices. After 2005, the wholesale price index for energy begins to increase, compared to baseline levels. This increase in energy prices feeds through to overall prices, leading consumer prices to increase by 1% above baseline by 2020.

The difference in the price stocks leads to much lower losses in real GNP. Figures 9.1 through 9.4 show the time profile of impacts from the Reforestation Case in bold lines. In the Price and Quantity Case, real GNP shows a gradual decline throughout the forecast period. When the energy efficiency adjustments are made, the decline is not as severe in the first 15 years of the forecast period.

Table 9.4 summarizes the results of the EIA analysis under the two cases. Using the different assumptions about reforestation policy, the next present value of the loss in GNP is $93 billion in the first case and $18 billion when efficiency changes are incorporated, a difference of $55 billion over the 1990 to 2020 timeframe.

Table 9.4. Economic Impacts of Reforestation from EIA Analysis

	Net Present Value of Real GNP Loss (billions of 1982$) (Percentage Change from Baseline)		
	1990-2000	1990-2010	1990-2020
Price and Quantity Effects	-48	-72	-93
Alone	(-0.2)	(-0.2)	(-0.2)
Energy Efficiency Effects	-8	+0.2	-18
on Supply Potential	(0.0)	(0.0)	(0.0)

9.5.2 Argonne Modeling Results

The Compact DRI Model predicts a very slow and gradual decline in real GNP through 2005, followed by a steeper decline for about another five years. The reduction in energy consumption, prompted by the more energy-efficient building practices, is responsible for the behavior in the first fifteen years. In the latter part of the simulation, the accelerated decline stems primarily from the electricity surcharge increases. The increases in electricity prices lead to a cascading set of impacts: the overall price level rises, the relative price of U.S. exports rises, exports decrease, and GNP decreases. The lower GNP leads, in turn, to lower investment spending, capital stock, and potential GNP.

9.5.3 Comparison and Summary of Results

Similar to the carbon tax discussion, Table 9.5 compares the GNP results for the EIA and Argonne studies for four specific years. The years

Table 9.5. Comparison of GNP Impact Results for Reforestation Policy

	(Percentage Change from Baseline)			
	1993	1995	2000	2015
EIA Results				
A. Prices and Quantities Alone	-0.2	-0.2	-0.3	-0.3
B. Energy Efficiency Gain	0.0	0.0	0.0	0.3
Argonne Results				
C. (Energy Efficiency Gain and Fixed Short-Term Interest Rate)	0.1	-0.1	0.6	-1.5

1993 and 1995 were again chosen to represent a very short-term perspective; 2000, an intermediate-term perspective; and 2015, a long-term perspective.

In terms of aggregate output, both models suggest that the reforestation policy would have small negative effects. The very slight declines in real GNP through 2000, before substantial electricity price increases are projected, may be due to difficulties in adequately mapping the building standards through the NIPA categories within the models.

The differences between the EIA and Argonne results after that period may be traced to the alternative treatment of monetary policy. The money supply (non-borrowed reserves), which is unchanged from base in the Full-Size Model, allows interest rates to be more responsive to changes in economic activity. Falling interest rates (relative to the baseline scenario) in the Full-Size Model (see Figure 9.4) promote additional productive capacity in the long term. The Argonne simulation holds short-term rates constant. The electricity price increases in the Argonne approach appear to have a greater impact on reducing investment (via rises in long rates) and export demands in the latter portion of the projection period. This behavior within the Compact Model causes the relatively sharper decline in GNP by 2015.

9.6 CONCLUSIONS

Given the complexity of reactions that would occur upon implementation of either of the policies analyzed in this chapter, it is not surprising that quantitative estimates of the overall impact would be sensitive to alternative modeling approaches. However, the estimates are sufficiently consistent to warrant some general conclusions.

A $100 carbon tax in which revenues are used to reduce the federal deficit would depress overall output for a decade or longer. The models suggest that the imposition of a $100 carbon tax will create a loss of GNP in 2000 ranging from 1% to 3% of GNP. Over the longer term, such a tax could have very beneficial results. The increased level of national savings would lead to additional capital formation and higher living standards. After a 25-year period, around 2015, GNP could be from 1% to 4% higher, relative to the baseline.

If the revenues from the tax were returned by the government in some fashion, the pattern of effects would be quite different. In the short run, up to 3 years, the rebating of tax revenues by either reducing the personal income tax or the payroll tax rate would lead to a short-term expansion in the activity. By 1993, GNP is estimated to be from 1% to 4% higher than it would be otherwise. The high end of this range would give pause to policymakers wishing to avoid overheating the economy. After this immediate boost, however, the models all share the view that the long-term effects of such a policy would be detrimental to growth. By 2000, real GNP might be reduced by 1% to 2%, with further deterioration in subsequent years.

As stated earlier, the principal conclusion to draw from this analysis is that the scale of fiscal

transactions generated by a carbon tax of the magnitude discussed here is so large as to require a general reassessment of fiscal policies. Carbon tax revenues do not represent a minor change in the existing structure. Such taxes have potentially significant consequences. We reiterate that, at this time, no reliable, precise, quantitative measure of the impacts of carbon taxes is possible. We present these results as evidence of the potential magnitude of macroeconomic consequences of carbon taxes and as evidence of the importance of further analysis.

The estimated macroeconomic impacts from the combined reforestation/building standards policy are considerably less than those from the tax. By 2000, GNP losses range from 0% to 1.0%. In the long term, there is more uncertainty about the direction and magnitude, as the results in this study are sensitive to choice of assumptions and selection of model.

In spite of the lower cost in terms of foregone national output from the second policy, this analysis does not capture the efficiency advantages of the economic incentives (carbon tax) policy relative to the standards approach. The major point is that under the tax policy, each energy service will be provided at the least social cost. Prices of all goods and services, faced by producers and consumers, will eventually reflect the social cost of the carbon emissions as embodied by the tax. While addressing some very real market imperfections in the building sector, building standards provide no incentives for efficiency improvements beyond the standards, nor do they provide any penalty for inefficient operation of the buildings after construction.

Finally, it is important to understand that the deficit reduction approach to carbon taxation has quite different implications for the structure of GNP than do the deficit neutrality approaches. When the tax revenues generated by the carbon tax are used to reduce the federal deficit, investment and savings increase relative to consumption. When the tax revenues are rebated to consumers, the opposite is true. Consumption is stimulated at the expense of savings and investment. By 2030, the tradeoffs between these two approaches are very clear. The deficit reduction approach produces an investment-oriented economy in which higher GNP is purchased at the expense of lower consumption, not unlike contemporary Japan, while the deficit neutrality approaches produce a consumption-driven economy with lagging GNP. The fiscal policy option to use taxes as a mechanism to create additional national savings and thereby increase investment in new plant and equipment throughout the economy is, of course, always available to the government; this option is not created by the carbon tax. Nevertheless, the analysis of the carbon tax, which generates large annual revenues, serves to focus attention on these important fiscal options.

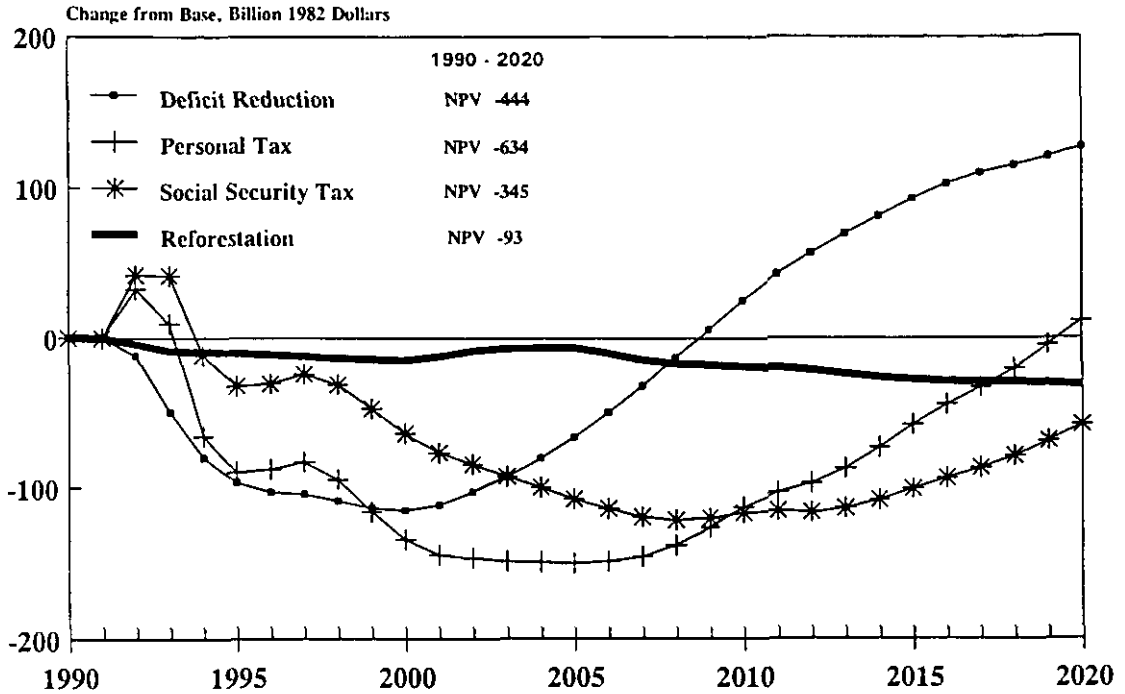
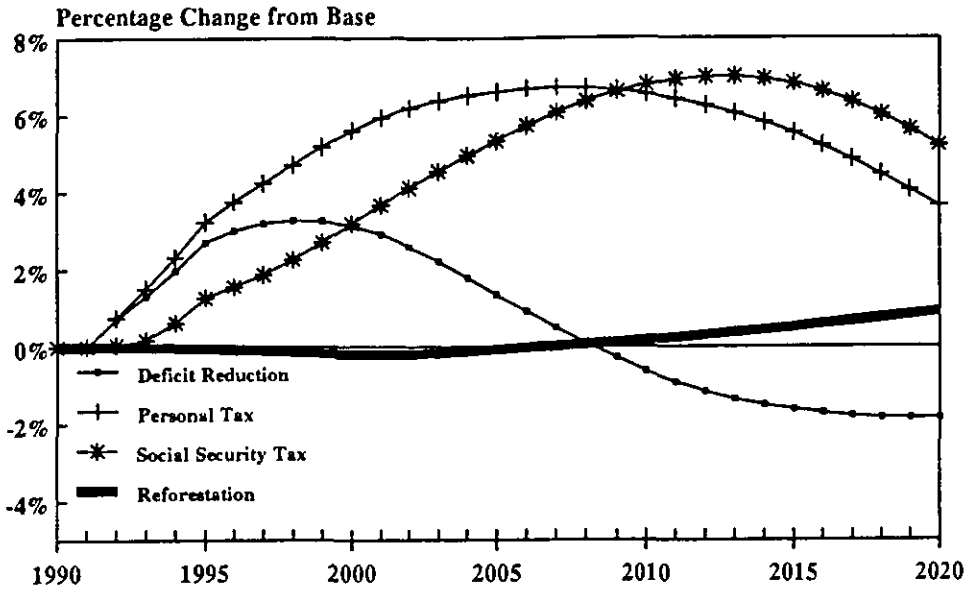
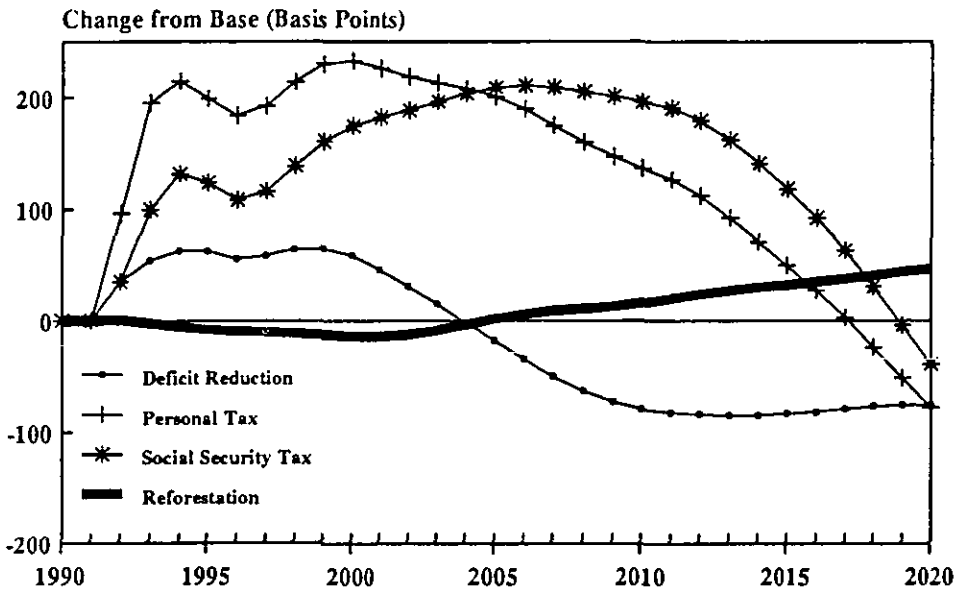


Figure 9.1. Price and Quantity Effects Case: Carbon Tax and Reforestation Cases--Real GNP



Consumer Prices



3 Month Treasury Bill

Figure 9.2. Price and Quantity Effects Case: Carbon Tax and Reforestation Cases

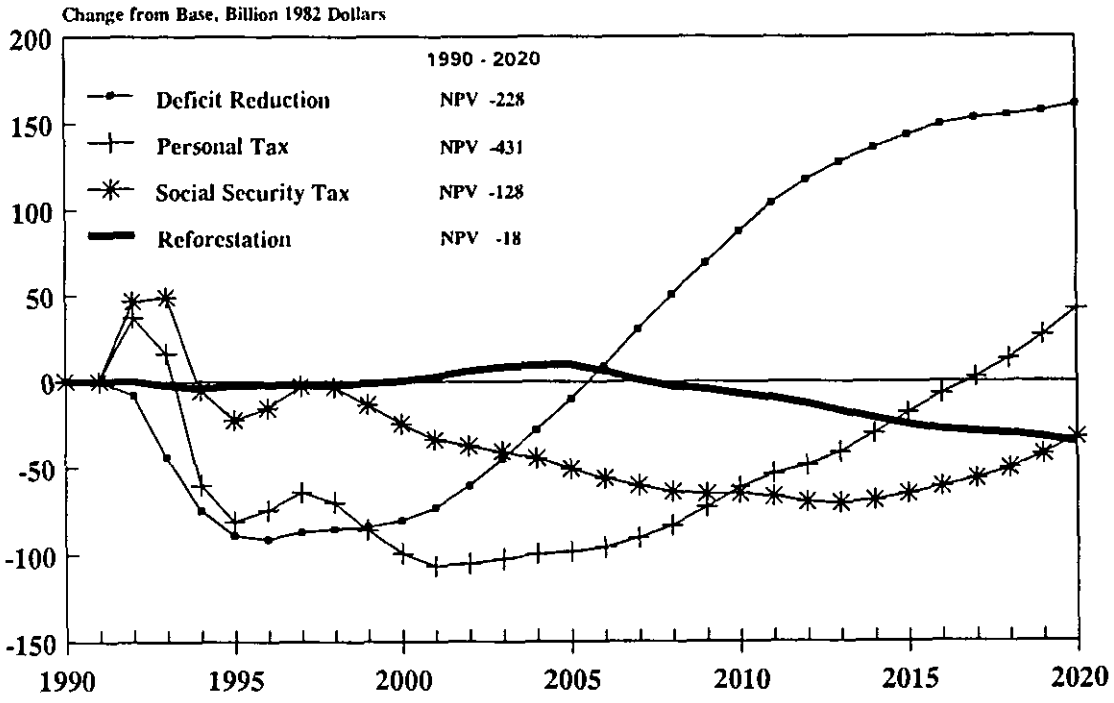
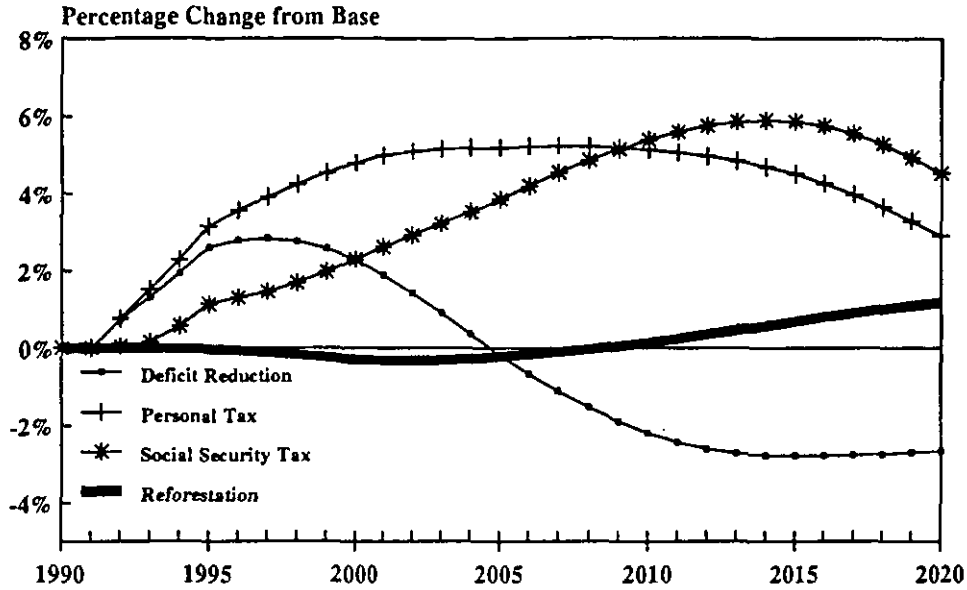
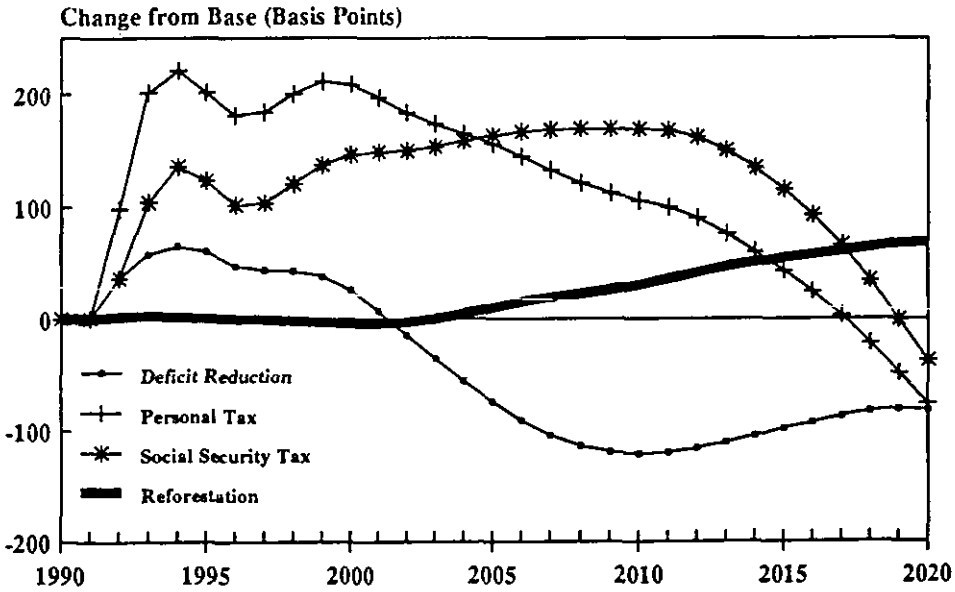


Figure 9.3. Efficiency Gain Case: Carbon Tax and Reforestation Cases--Real GNP



Consumer Prices



3 Month Treasury Bill

Figure 9.4. Efficiency Gain Case: Carbon Tax and Reforestation Cases

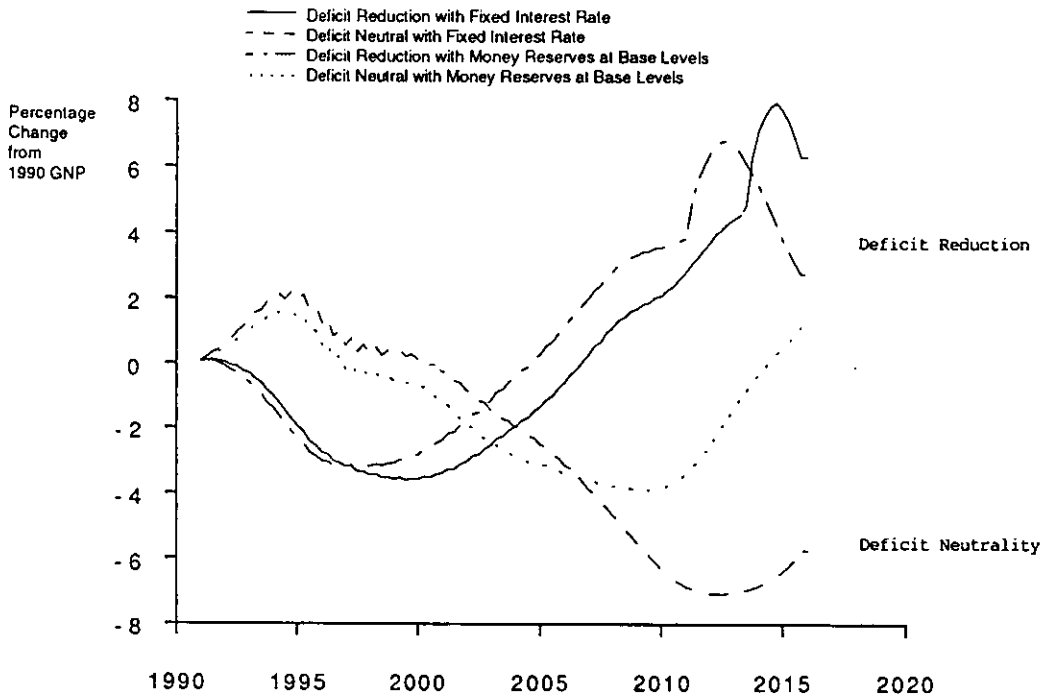


Figure 9.5. Impacts of GNP in Argonne Simulations: Constant Money Supply or Fixed Short-Term Interest Rates for Deficit Neutrality and Deficit Reduction

10.0 CARBON TAXATION AND INTERNATIONAL TRADE

10.1 INTRODUCTION

Previous sections have focused principally on U.S. energy policy options for reduction of greenhouse gas emissions in microcosm. The purpose of this chapter is to highlight some of the possible international ramifications of the previously discussed policies in terms of the effects of these policies on other nations, as well as the implications for the U.S. energy economic system of a global energy-economic system. The analysis in the following section, although based on standard economic principles, is highly speculative in nature. The possible outcomes are by no means certain, but they are the sorts of considerations that must be addressed in policy formulation in order to avoid unintended consequences. In the final section, the results of selected model studies are reviewed in terms of the effects on international trade and global emissions shares resulting from various policy initiatives.

10.2 COMPETITIVENESS AND TRADE EFFECTS

American participation in a climate convention is likely to have a significant impact on the international competitiveness of the United States. Some industries may be disadvantaged by measures to reduce U.S. emissions; however, others may be provided with new opportunities. Such opportunities may be especially important in energy efficiency and other technologies for reducing greenhouse gases or adapting to changing climate regimes. Clear examples exist in the areas of substitutes for CFCs and the potential of genetic engineering technology for fast-growing biomass or reducing methane emissions from wet-rice agriculture. American participation in stimulating the development of such technologies could result in U.S. manufacturers being major world suppliers of new technology when it is required by other nations. In some cases, especially small renewable electricity supply and storage systems, products could find immediate markets in developing countries independent of any commitment by such countries to reducing greenhouse gas emissions.

The effects of U.S. action will also be felt by foreign manufacturers producing for the large U.S. market. When technological innovations are required for goods to be admitted to American markets, foreign manufacturers tend to add them to models produced for other markets. In this way, American requirements influence foreign manufactured goods consumed far from U.S. markets.

In the international arena, it is likely that the United States will influence the shape of major multilateral development programs such as those of the World Bank that will alter the current balance of global emissions, as well as adjust America's own international development activities.

An international treaty is not necessarily a *sine qua non* for reductions in current global emissions. The Netherlands has already committed itself to reducing its national emissions. Unilateral actions by several nations could cumulatively take a bite out of global emissions, especially if those nations include the top five producers of carbon emissions from fossil fuels: the United States, the U.S.S.R., China, Japan, and the Federal Republic of Germany. The countries need not even adopt the same reduction targets. In addition, it is important to recall that a handful of nations have 95% of the world's coal-carbon resource base, and that policies in these countries, including the United States, the U.S.S.R., and China, can have a major effect on global carbon emissions. Nevertheless, reductions in future emissions will depend heavily on the developing countries. In that event, countries that undertook emissions reduction policies outside of a convention are likely to want credits for their prior achievements. Each country need not adopt the same reduction targets in order to achieve significant overall reductions.

If greenhouse gas-emitting activities are regulated or taxed in the United States, but not elsewhere, American goods will be more expensive than competitors' goods, and production may be moved offshore to countries with lower environmental standards. Even within the context of a framework convention and international protocols setting reduction targets, national implementation policies need to be analyzed for their potential impacts on the U.S. trading position.

The effectiveness of a country's economic policies hinges on the extent to which foreign suppliers, not directly subject to those policies, compete with domestic suppliers (Dixit 1985). Consider, for example, an American firm that emits greenhouse gases in the course of making cement. The government might tax the firm according to its output to reduce greenhouse gas emissions by cutting back production. Such taxation would tend to raise the price of that firm's product and reduce the quantity of it demanded by consumers; if a foreign supplier were not subject to the same tax, domestic consumption might continue unabated to the disadvantage of the local producer.

However, where there is international trade in the product, taxation of outputs can lead to an unintended and undesirable outcome. If the United States is a relatively small supplier (so that its production has little or no influence on the world price of the product), the price that American consumers face for the product will be unaffected by the tax on the American producer. If American producers were able and willing to accept a lower rate of return on the capital invested in their production facilities, they could keep their post-tax sale prices unchanged and retain their market share, but if they must raise their prices, they will lose sales. If the product were an undifferentiated commodity, such that name brand commanded little or no particular value, U.S. firms could lose all their sales, leaving the American market to be served by foreign suppliers.

Under circumstances in which U.S. producers supply a large enough share of the world output of a product to affect the world price, the scenario would unfold in the same manner, although a tendency for the world price to rise somewhat could dampen the loss in American market share. It is even possible that, if foreign demands are sufficiently insensitive to price, U.S. foreign exchange earnings could rise with the use of cleaner, but more expensive production technology (Baumol and Oates 1989).

Regulatory policies may have similar international consequences (McGuire 1982). Regulations restricting production methods will have, by and large, the same effects as taxes, as they move producers away from least-private-cost production methods. Regulations restricting product composition, construction, operating characteristics, etc., would have some of the same effects as consumption taxes: initially leaving U.S. producers unaffected relative to foreign suppliers, but finally leaving them facing higher labor costs. On the other hand, to the extent that the United States comprises a relatively large share of the world market for a particular product, foreign producers may choose to make all their production conform to U.S. product regulations, forcing consumers in other countries to upgrade their consumption.

Whereas negative incentives for U.S. industry to deal with global climate policy needs may damage American competitiveness, positive incentives may also lead to difficulties, with trading partners objecting to subsidies that they perceive as unfair. Other import/export conditions also need to be evaluated, including the effects of the balance of trade on agricultural or land use conversion practices. If the United States were to limit domestic agricultural production severely (for example, of wet rice that produces methane) or remove existing barriers that restrict foreign competition, then domestic reductions of that land use may be more than offset by increases in foreign land use to

produce the same commodity. This would be true especially if foreign producers used inferior land-conserving methods (because of differing relative input prices) or if they expanded their activities at the expense of existing forests.

10.2.1 The Impact of Tariffs

One recourse for domestic producers faced with production taxes or production regulations designed to reduce greenhouse gas emissions is to lobby the government to impose tariffs on imports. It would be straightforward to find the tariff that would maintain U.S. suppliers' post-tax domestic market share, and it might even be possible to lobby successfully to secure that tariff. However, this ignores the very real possibility of foreign retaliation through either tariffs or administrative trade restrictions (Johnson 1954; Corden 1974).

Tariffs may be considered as a means to restrict the entry of products such as tropical hardwoods that cannot be produced in the United States, but whose production nonetheless increases net global carbon emissions. Again, the practical consideration of foreign interests complicates the simple application of tariff policy to such a problem.

Reducing greenhouse gas emissions in any given country may be made more difficult by extensive international trade and high capital mobility. Coordination among countries in taxing or regulating externalities could increase the effectiveness of each nation's environmental policies, although such coordination might well have to encompass a large share of world markets for such improvement to be realized. For instance, coordination between, say, the United States and Canada to tax a product might, as its principal effect, reduce those two countries' aggregate competitiveness relative to Western Europe, South America, and East Asia.

More flexibility to affect production decisions in other countries may actually exist if it is determined that those decisions confer unacceptable externalities upon the United States. For instance, expansion of coal-fired electricity generation capacity in China and India could raise temperatures for the United States as well as for those two countries, but the climate change could be more acceptable to the developing countries in their efforts to raise their incomes, at least in the short term, even though long-term effects such as sea level rise might be devastating. Cleaner coal technology could be available, but be more expensive than less environmentally benign technologies and hence might not be chosen for Chinese and Indian expansion. The value of the damages to the United States from climatic changes could make it worthwhile for the United States to subsidize Chinese and Indian investment in clean-coal technologies. The same could hold true for consumer goods such as non-CFC-using domestic refrigeration equipment. Subsidies to foreign consumers could, in some cases, have real effects similar to taxes on U.S. consumers.

The difficulty in implementing such subsidy policies lies in the absence of domestic lobbies in the United States that would stand to benefit directly and visibly from such expenditures. Tariffs certainly have such domestic interests, and lobbies exist whose interests are impinged by taxes. Foreigners, however, are not directly represented in the government and are, at any rate, nonvoting. Nonetheless, the concept of the foreign subsidy as an alternative or possibly a supplement to domestic taxation is worth exploration. As an alternative to increasing the total level of foreign assistance, it might be useful to ensure that current funds are directed towards efforts that reduce emissions or at least those activities that cause no additional damage.

10.2.2 Implications of U.S. Policies for International Development

In considering the benefits and costs of domestic greenhouse gas reduction policy, it is prudent to consider the additional burdens and opportunities presented by the international development and foreign assistance policy that would be essential to the long-term effectiveness of domestic measures.

Given the global emissions trends, the United States and other industrial countries attempting to reduce their emissions are likely to adjust their development assistance to reduce growth of greenhouse gas emissions in developing countries. In so doing, the industrialized countries must anticipate that many developing countries are likely to approach the climate change issue with perspectives that differ sharply from those in developed countries. Developing countries can make the point that they have not contributed much to the present accumulation of atmospheric CO_2, that emissions are continuing to increase in the developed countries, and that their own limited economic development constrains their ability to do anything about the problem, relative to the capacity of the industrial world. Comments made by decisionmakers from developing countries at international meetings suggest that they will expect developed countries to take the lead in reducing emissions. In addition, if development alternatives that reduce emission rates prove to be more expensive or less effective, decisionmakers from developing countries are likely to expect developed countries to bear the added cost of using these alternatives.

Increased assistance may be required if low-emission technologies for application in developing countries cost more than existing high-emission alternatives. Increased support for research and development may be needed to develop less costly low-emission alternatives for both domestic and developing country use, with impacts on both markets. Increased assistance may also be needed to encourage development practices that do not require deforestation. Relative to industrial countries, developing countries tend to have less capacity for long-term planning, fewer available financial resources, and less information about likely changes. Indeed, much development assistance has been given either to train people, build institutions, and improve the flow of information into developing countries to help them deal more effectively with their development problems or to make more financial resources available. Finally, if present or anticipated concentrations of greenhouse gases have already committed the global climate system to change, then developing countries will require additional resources to adapt to change. Unless increased development assistance is made available for developing countries to grapple with climate change, the opportunity costs to their trade and economic development likely will prove unacceptable.

The United States provides development assistance in the form of direct funding for training, for institution building, and for constructing or operating facilities; loan guarantees; food and emergency assistance; and research, development, transfer, and adaptation of technology to meet the needs of developing countries. The United States is also a major contributor to multilateral assistance agencies such as the United Nations Development Programme and the World Bank, which offer loans and technical assistance to developing countries.

Most development assistance has been undertaken to promote economic growth or improve the provision of basic services, rather than to deal with global climate change. However, much assistance for economic development supports activities that affect greenhouse gas emissions either directly (rice agriculture, energy resource development and use) or indirectly (through industrialization, urbanization, or higher incomes). Some of the indirect interdependencies between development and environment may be inescapable except by reducing the rate at which population increases. In addition, much assistance supports activities that would be affected by global climate change (forestry, agriculture, coastal cities). Some development assistance can be refocused to reduce future emission rates or to assist in adapting to change. In other cases, effective assistance may require major changes in strategies by the United States and multilateral agencies.

Energy and manufacturing R&D in industrialized countries tends to match technologies with conditions in these countries, but not in developing nations, where technological, social, organizational, and economic conditions may be substantially different. Thus, if the United States undertakes

additional R&D to reduce its own emissions, many results of this effort may be inapplicable to conditions in many developing countries. Additional development assistance may be needed to support R&D oriented specifically toward problems and conditions in developing countries, either to adapt technology from industrial countries or to develop new technology for local circumstances.

10.3 QUANTITATIVE EFFECTS OF ENERGY POLICIES IN THE INTERNATIONAL CONTEXT

To illustrate some potential trade effects of the emissions reductions policies previously discussed, results of two different modelling studies are included, which highlight the impact on U.S. net energy imports.

10.3.1 Fossil2 Model Results from Previous Chapters

Previous modeling studies in this report have been run using the Fossil2 Model, which makes only limited reference to international market forces. Specifically, coal exports are essentially exogenous in the model. Oil imports are calculated as the difference between U.S. demand and indigenous supply and assume that the difference will be available at the price specified. Natural gas imports are in two fractions: pipeline imports, which are limited by exogenously specified pipeline capacities, and LNG imports, which must compete with local prices. Nonetheless, since these effects work equally on the model for the various cases, it is illuminating to extract for comparison the trade data from the cases described in previous chapters.

The **fossil fuel taxes based on carbon content** (see Chapter 6) had small effects on energy imports by the year 2030. The $25/mtC fossil fuel tax changed net imports less than 1% compared to the NES Actions Case. With a $250/mtC tax, net imports increased 22% in 2005 and 11% by the year 2030. When a $750/mtC fossil fuel tax is added to the NES, however, net imports are reduced by 28% in 2030, relative to the NES. The same tax generated a 45% decrease in net imports in the year 2005.

The effect of a **GWP** tax on energy imports (see Chapter 6) was negligible in the smaller tax ranges such as $25/mtC, $50/mtC, and $100/mtC. With a $50/mtC GWP tax, net imports were reduced by 4% relative to the NES Actions Case in the year 2010. As the tax increased to $750/mtC, so did the import reductions. Imports were reduced 50% in 2005, with a slightly less dramatic reduction of 31% by the year 2030. Net imports increased more slowly with the higher GWP tax, from 15.4 quads to 16.8 quads in 2030.

The **NES Actions Case with Building Standards** (see Chapter 7) at $250/mtC and $500/mtC levels had virtually no effect on oil imports. Net imports in the $250/mtC Building Standards Case decreased by 0.3 quad by the year 2030.

The **NES Actions with Reforestation Case** (see Chapter 8) had an impact on gas imports, which increased 16% in the year 2030 from 2.6 quads to 3.0 quads. Net imports are raised only slightly from the NES, from 23.7 quads to 24.8 quads.

A combination of Reforestation and $250/mtC Building Standards Case (see Chapter 8) had a smaller effect on net imports, which increased 4%, from 23.7 quads to 24.6 quads by 2030. Oil imports increased slightly, from 24.8 to 25.4 quads.

The **Powerplant Efficiency Standards ($300/mtC) with NES Actions Case** (see Chapter 7) increased gas imports 45%, from 2.6 quads to 3.7 quads. Net imports increased 11% from the NES by the year 2030.

The **NES Actions with Bryan Transportation Energy Efficiency Standards Case** (see Chapter 7) reduced oil imports 5%, due to transportation restrictions. **Bryan-Plus Transportation Energy Efficiency Standards Case** reduced oil imports by 9% by 2030. Gas imports in both cases were reduced less than 1%. Net imports in both cases were reduced 6% and 9%, respectively.

The fiscal instruments are not the most powerful instrument for reducing net imports, but do have some impact in the higher tax cases. The regulatory cases did not produce much of a reduction in net imports by 2030. Reforestation and Reforestation plus Building Standards actually raised net imports by 2030. One reason for this is that reforestation decreases the reliance on coal and thus increases oil and natural gas dependence. Coal changes do not emerge in the overall net imports figure because coal is mainly supplied domestically.

Powerplant Efficiency Standards also increase imports of oil and gas because they reduce coal use. Powerplants are penalized for non-efficient energy output, and coal technologies are fined more heavily than is natural gas or oil.

Tabular results of the above cases are given in Tables 10.1 to 10.4.

10.3.2 Edmonds-Reilly Model Results

Because it is a partial equilibrium world model, the Edmonds-Reilly Long-Term, Global, Energy-Economic Model (Edmonds and Reilly 1985) is more suited to demonstrating the policy measures affecting U.S. energy demand as they affect the world trade balance. For this study, the Edmonds-Reilly Model was used with recalibration of parameters so that, with no tax imposed, the U.S. results closely paralleled the Fossil2 NES Actions Case. Then carbon taxes in the amount of $100/mtC were imposed, first on U.S. energy consumption and then on energy production. Finally, the model was used to explore a variety of schemes to reduce global carbon emissions.

Reference Case Fossil Fuel Carbon Emissions

A reference case consistent with NES Actions was developed and introduced into a global economy driven by non-U.S. population growth assumptions consistent with those of the Intergovernmental Panel on Climate Change (IPCC 1989). Global fossil fuel carbon emissions increase in the reference case from approximately 5.8 PgC/yr to 9.3 PgC/yr in the year 2035. One of the clear implications of the reference case is that the United States acting alone cannot possibly hold global fossil fuel emissions constant. By the year 2010, emissions by the rest of the world increase by more than the 1300 TgC/yr emissions associated with the United States in the year 1990. Thus, even if the United States were somehow to reduce its emissions to zero, and even if this could be accomplished in a way that did not result in an increased availability of fossil fuel energy for the rest of the world, increases in fossil fuel carbon emissions by the rest of the world would have more than made up the reduction by the year

Table 10.1. Net Energy Imports--Fiscal Instruments (quads)

Year	NES Only	$25/mtC Fuel Tax	$250/mtC Fuel Tax	$1000/mtC Fuel Tax	$25/mtC$_e$ GWP Tax	$50/mtC$_e$ GWP Tax	$1000/mtC$_e$ GWP Tax
1990	15.4	15.4	15.4	15.4	15.4	15.4	15.4
1995	19.1	18.6	15.3	11.4	18.6	18.1	11.4
2000	17.8	17.2	14.1	10.3	17.2	16.8	10.3
2005	16.0	15.5	12.5	8.9	15.6	15.2	8.8
2010	17.0	16.6	13.4	10.5	16.6	16.2	10.4
2015	20.4	19.9	17.1	13.3	19.9	19.5	13.2
2020	21.9	21.6	19.1	15.1	21.7	21.4	14.9
2025	22.8	22.6	20.1	16.2	22.6	22.4	16.0
2030	23.7	23.6	21.1	17.0	23.6	23.6	16.8

Table 10.2. Net Energy Imports--Regulatory Instruments (quads)

NES Year	Building Only	$250/mtC Utility Standard	$250/mtC Bldg Std Reforest	Bryan ANL Trans. Eff. Reforest	Bryan-Plus Trans. Eff. Standards	Powerplant Efficiency Standards	Standards
1990	15.4	15.4	15.4	15.4	15.4	15.4	15.4
1995	19.1	18.9	19.1	18.9	18.9	18.9	19.1
2000	17.8	17.6	17.7	17.6	17.2	17.2	18.9
2005	16.0	16.0	15.9	15.9	15.0	14.9	15.4
2010	17.0	16.7	17.0	16.8	15.6	15.2	17.9
2015	20.4	20.1	20.7	20.3	19.1	18.4	21.9
2020	21.9	21.5	22.5	22.1	20.7	19.8	23.4
2025	22.8	22.6	23.6	23.3	21.5	20.6	24.7
2030	23.7	23.4	24.8	24.6	22.4	21.4	26.2

Table 10.3. Percent Increase in Net Imports vs. NES Actions Case--Fiscal Instruments

Year	$25/mtC Fuel Tax	$250/mtC Fuel Tax	$750/mtC Fuel Tax	$25/mtC$_e$ GWP Tax	$50/mtC$_e$ GWP Tax	$750/mtC$_e$ GWP Tax
1990	0%	0%	0%	0%	0%	0%
1995	-2%	-20%	-40%	-2%	-5%	-40%
2000	-3%	-21%	-42%	-3%	-5%	-42%
2005	-3%	-22%	-45%	-3%	-5%	-45%
2010	-2%	-21%	-38%	-2%	-4%	-39%
2015	-2%	-16%	-35%	-2%	-4%	-36%
2020	-1%	-12%	-29%	-1%	-2%	-30%
2025	-1%	-12%	-29%	-1%	-2%	-30%
2030	0%	-11%	-28%	0%	0%	-29%

2010. By the same logic, even the entire OECD acting alone cannot hold emissions constant beyond the year 2025.

The implication of this observation is extremely powerful: without mechanisms for involving a substantial portion of the world community, including especially the presently developing nations of the world, it will be impossible to hold global fossil fuel carbon emissions constant.

Example of a Carbon Tax on U.S. Consumption

Figure 10.1 shows the model forecast that, in the absence of any emissions reduction policies, U.S. primary energy consumption will grow to over 120 quads by the year 2030. Application of the moderate consumption tax (roughly equivalent to $1.50 per thousand cu ft of natural gas or $45 per ton of coal) serves to reduce U.S. primary energy demand by 15% by 2030, as shown in Figure 10.2. It also

Table 10.4. Percent Increase in Net Imports vs. NES Actions Case--Regulatory Instruments

Year	$250/mtC Building Standard	Utility Reforest	$250/mtC Bldg Stnd Reforest	Bryan ANL Trans. Eff. Standards	Bryan-Plus Trans. Eff. Standards	Powerplant Efficiency Standards
1990	0%	0%	0%	0%	0%	0%
1995	-1%	0%	-1%	-1%	-1%	0%
2000	-1%	0%	-1%	-3%	-3%	6%
2005	0%	-1%	-1%	-6%	-7%	-4%
2010	-2%	0%	-1%	-8%	-11%	6%
2015	-2%	1%	0%	-6%	-10%	6%
2020	-2%	3%	-1%	-6%	-9%	7%
2025	-1%	3%	-2%	-6%	-10%	8%
2030	-1%	5%	-4%	-6%	-9%	11%

forces a major shift away from coal and natural gas to nuclear and renewable energy. Because the transportation sector is essentially totally dependent on oil, demand response to price is much lower, and oil consumption is reduced by only about 9%. As a result of this reduction in demand, coupled with the shift away from fossil fuels (especially coal, with the highest carbon content), U.S. carbon emissions show an 18% reduction in the year 2030. This is significantly greater than was the case with the Fossil2 Model. The different assumptions regarding demand responsiveness are the primary reason for the differences between the two models' results.

In the international context, several things are likely to happen. First, the reduction in demand for fossil fuels can improve the U.S. energy trade situation. Figure 10.3 shows the energy trade forecast without a carbon tax; oil and gas imports are partially offset by coal exports. Figure 10.4 indicates that a carbon tax might reduce oil imports by about 12.5%. Moreover, the model indicates that reduction in demand for gas and coal would make up to 4 quads and 28 quads, respectively, of indigenous production available for export at competitive prices, although the advisability of exporting fossil fuels while imposing carbon taxes locally is dubious. Omitting the exports in both cases, the net effect of the consumption tax on energy imports would then be an overall reduction of about one-quarter by the year 2035.

Second, the reduced U.S. demand for oil and gas in the international market would tend to drive prices down slightly. As a result, consumption of these fuels in the rest of the world would tend to rise slightly. On balance, the rest of the world's demand for fossil fuel actually increases by about 1% while the United States is cutting back. Finally, changes in world energy prices may have effects on gross national products. In most cases, higher prices tend to reduce GNP. A notable exception might be the Middle East, which might profit from higher oil prices unless demand were substantially reduced.

Example of a Carbon Tax on U.S. Production

As an alternative approach, the model was modified to impose the same set of carbon tax rates used in the last analysis on U.S. producers of fossil fuels. The result was that, absent import restrictions, U.S. energy demand continues unabated, but local suppliers are unable to compete with cheaper imports, and indigenous production of oil and gas is virtually extinguished, while coal production is reduced to about one-third of total demand. This, in turn,

causes nearly all U.S. fossil energy to be imported, as reflected in Figure 10.5. This increased demand in the world market tends to drive oil and gas prices up. Consequently, fossil energy consumption in the rest of the world diminishes slightly, with a small shift in the direction of coal. The net effect on global carbon emissions is a barely perceptible reduction. Presumably, this major shift from local to offshore sources could be eliminated by the imposition of import trade barriers equivalent to the tax on producers, so that the overall effect would be the equivalent of a tax on consumption.

In summary, for the United States acting alone, a consumption tax is much more effective. Carbon emissions are reduced substantially, as shown in Figure 10.6, whereas the severance tax has little effect. Moreover, the consumption tax significantly reduces imports, while the severance tax has exactly the opposite effect. For a severance tax to be effective, it must be accompanied by an equal tariff on fossil fuel imports.

Approaches to Global Carbon Emissions Reduction

Finally, the Edmonds-Reilly Model was used to explore the effects of applying a carbon tax on consumption in various combinations, especially in regard to the U.S. role in global carbon emissions. As a point of reference, Figure 10.7 shows U.S. carbon emissions in the NES Actions Case (same as the left-hand columns in Figure 10.6) along with emissions from other regions of the world. In this case, global emissions increase from about 5500 million mtC in 1990 to about 9400 million mtC by 2035. The U.S. share declines slightly from 24% to 19%. The OECD countries, as well as the U.S.S.R and Eastern Europe, show a similar relative decline, while the developing countries show a threefold growth in emissions. At the same time, coal's importance as an energy source grows in virtually all regions, increasing from about one-fourth of total primary energy to about one-third.

In the first variation, the model was run iteratively to determine what tax level would reduce U.S. emissions by 20% relative to 1990. Figure 10.8 portrays this unilateral action in the global context. The U.S. share of the total now declines from 24% to 12% by 2035, while global total emissions are reduced by 9% from what they would have been in 2035, had no action been taken. The carbon taxes required to accomplish this would be $107, $142, and $103 (per mtC) in the years 2005, 2020, and 2035 respectively. Note that this level of taxation is similar to that of the example in Section 10.3.2, so that the resulting U.S. energy trade is much like that shown in Figure 10.4; that is, slightly reduced oil imports and greatly expanded coal exports. The increased coal exports, brought about by lower domestic demand and resulting lower coal prices, are balanced by increased imports in the developing countries, as well as reduced exports from European coal exporters.

Next, the model was used to determine the set of carbon taxes that would yield a 20% reduction from 1990 emissions levels in each of the three OECD regions, i.e., a common target achieved with likely different tax rates. The resulting rates were (in $/mtC):

	Year		
	2005	2020	2035
USA	$107	$142	$103
OECD Europe	165	260	280
OECD Pacific	290	420	415

The rates for the United States are essentially unchanged from the previous case, as expected. For the Pacific Region, the rates are much higher because the potential growth in energy demand is substantially greater; that is, the taxes imposed on consumption in the United States suppress demand by about 15%, whereas in the Pacific Region, the higher growth rate must be suppressed by about 23%. Figure 10.9 shows this action, wherein global emissions in 2035 are now reduced by about 18%

from the unconstrained case in the same year (compared with 9% with the United States acting alone). In terms of international trade, the results are similar to the last case. The carbon tax virtually eliminates domestic consumption of coal, and the excess supply is exported, while oil imports in all three regions are down slightly.

As a variant to the previous case, the model was used to impose a uniform level of taxes on all OECD countries in order to attain an overall reduction of 20% from 1990 OECD levels, i.e., a common set of taxes to achieve likely different reductions in support of a single result. The required taxes were $157/mtC, $250/mtC, and $230/mtC for the three periods in question. These rates were higher for the United States than in the previous case, but lower for the other OECD countries. As a result, the United States incurred a greater share of the burden as shown in Figure 10.10, but since the overall OECD result was essentially the same, the effect on the rest of the world was the same as above.

Finally, as an outgrowth of the last case, a single set of taxes was found which, applied worldwide, would result in a global 20% reduction in carbon emissions. Here, the world carbon tax rates were $119/mtC, $236/mtC, and $304/mtC, the sharply increasing rates reflecting the force needed to control dramatic increases in Third World energy demand. Figure 10.11 shows that there is still some growth in emissions in the developing countries, which must be offset by reductions in the developed nations. For the United States, this results in a 43% reduction from 1990 levels, or a nearly 60% reduction from the level that would have obtained in 2035 had no action been taken. Coal consumption outside of China is virtually eliminated, along with international trade in coal.

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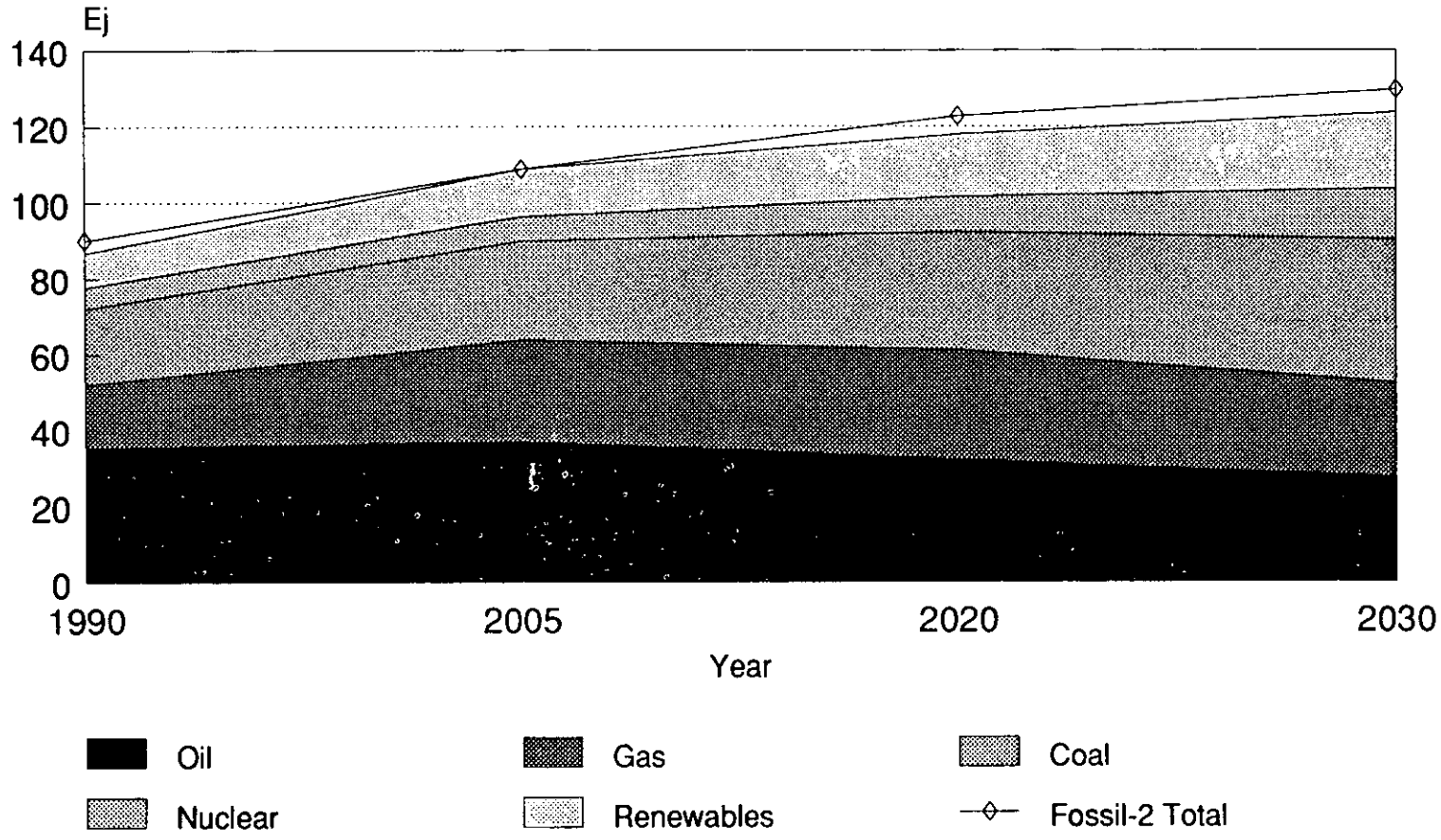

Figure 10.1. NES Actions Case: International Considerations--U.S. Primary Energy Consumption

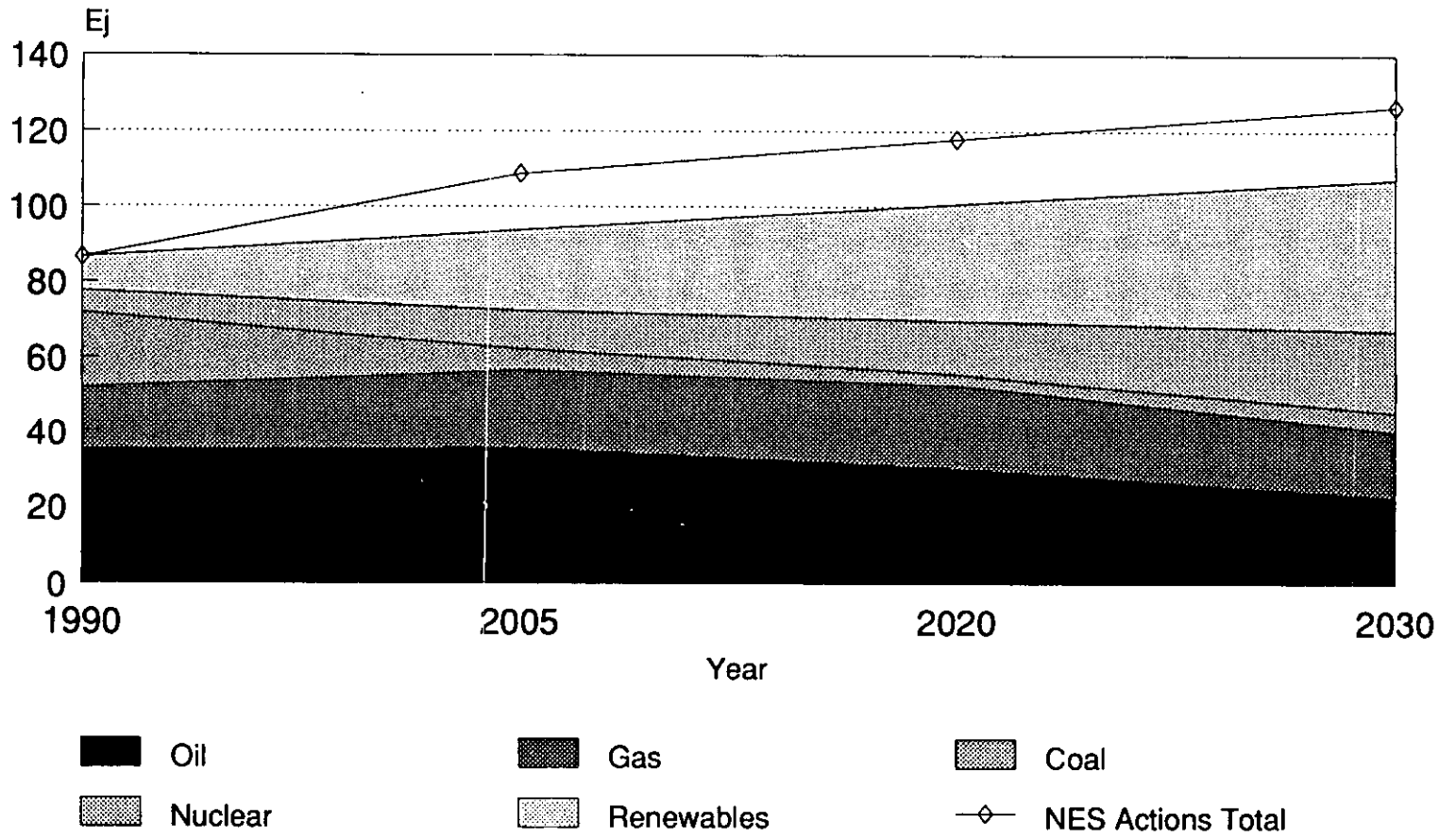

Figure 10.2. Consumption Tax of $100/mtC: International Considerations--U.S. Primary Energy Consumption

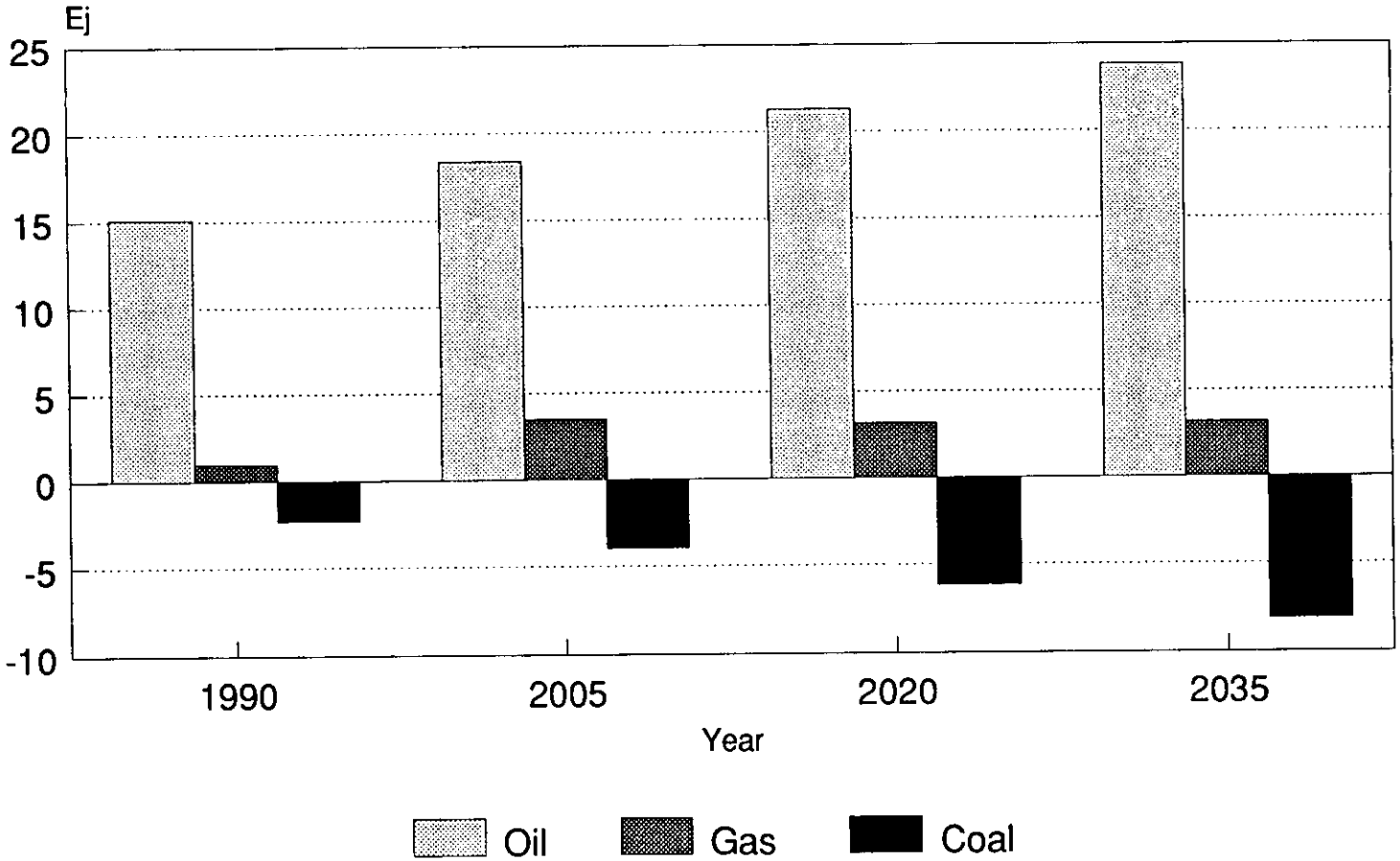

Figure 10.3. NES Actions Case: International Considerations--U.S. Net Imports of Energy

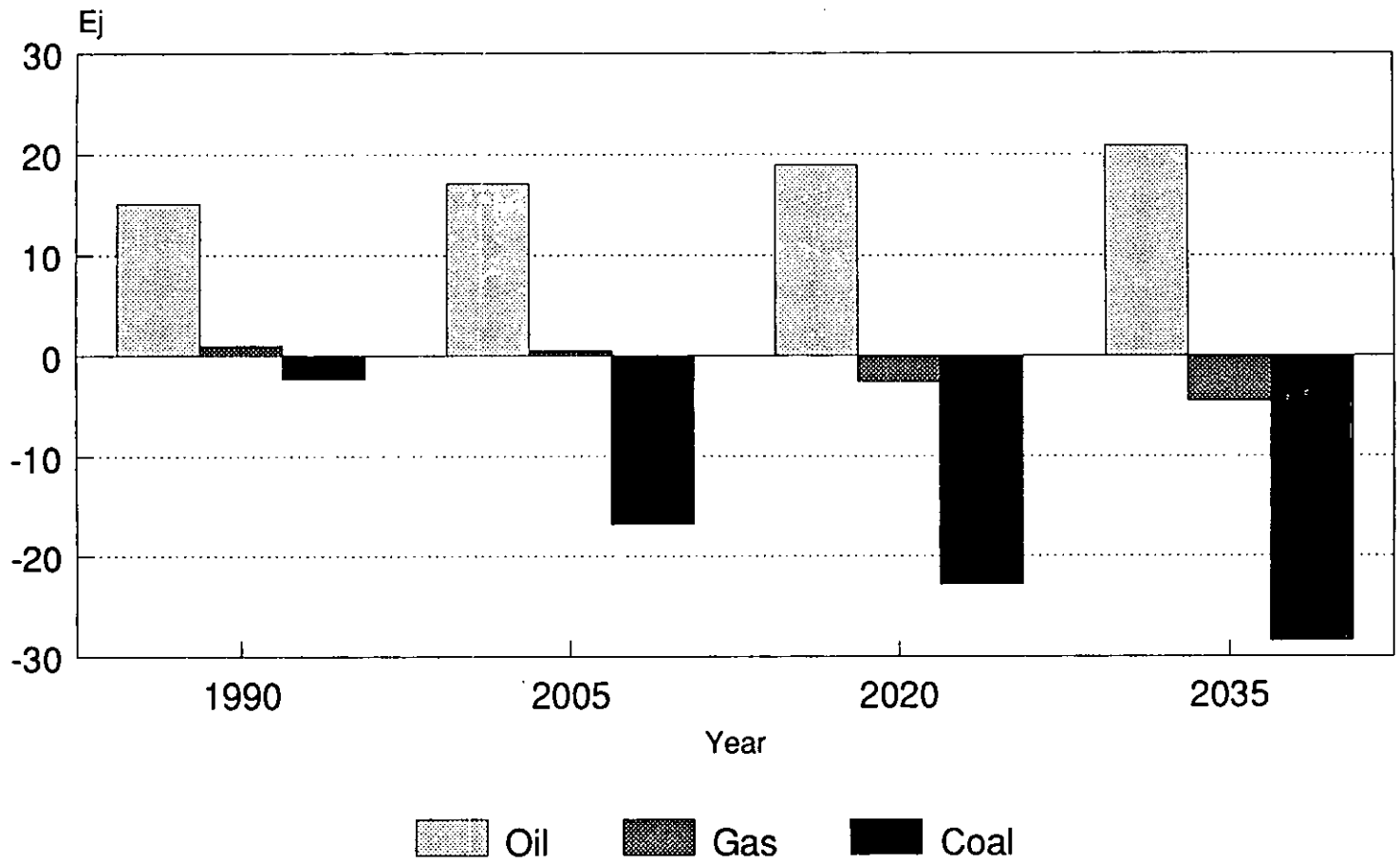

Figure 10.4. Consumption Tax of $100/mtC: International Considerations--U.S. Net Imports of Energy

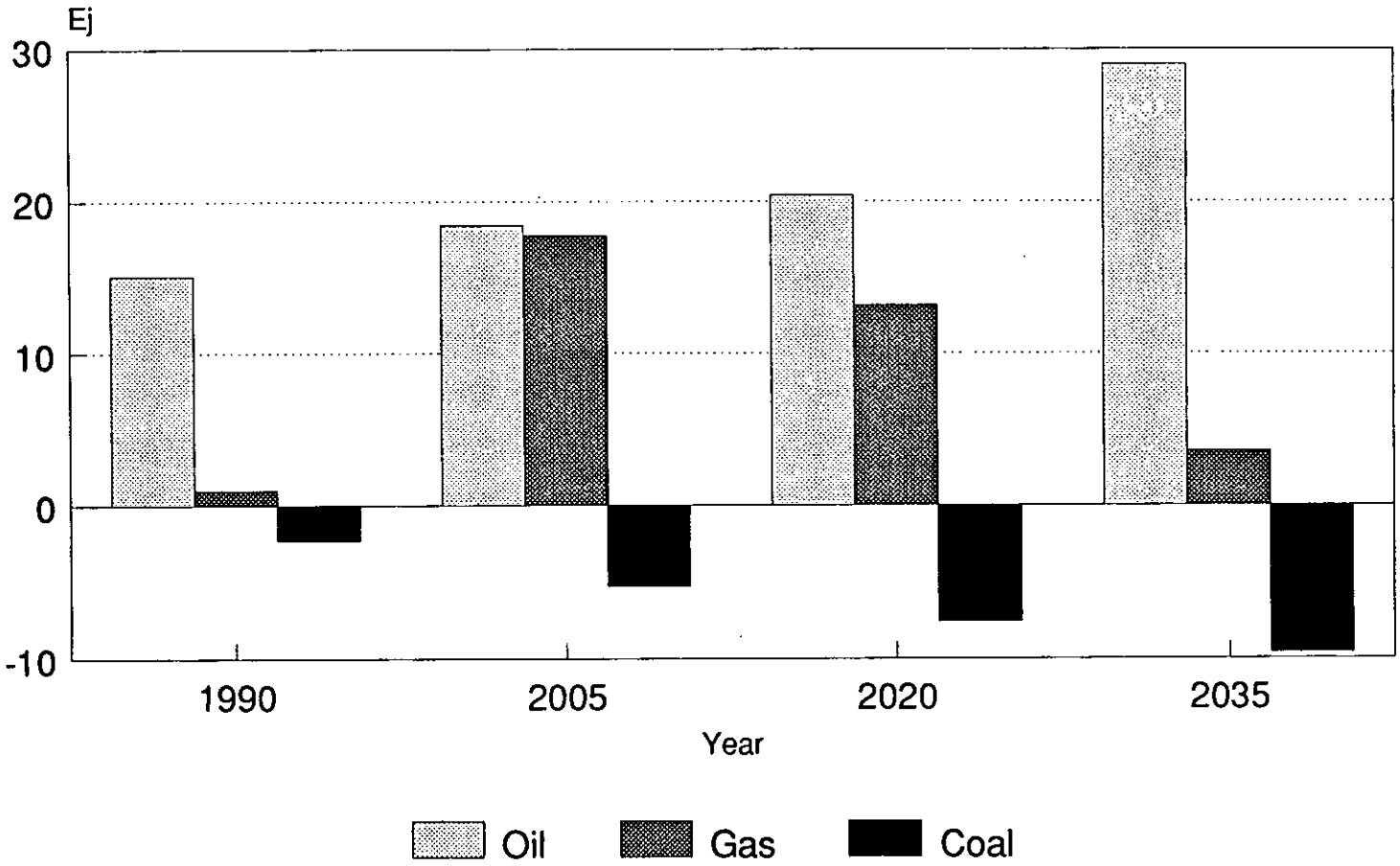

Figure 10.5. Severance Tax of $100/mtC: International Considerations--U.S. Net Imports of Energy

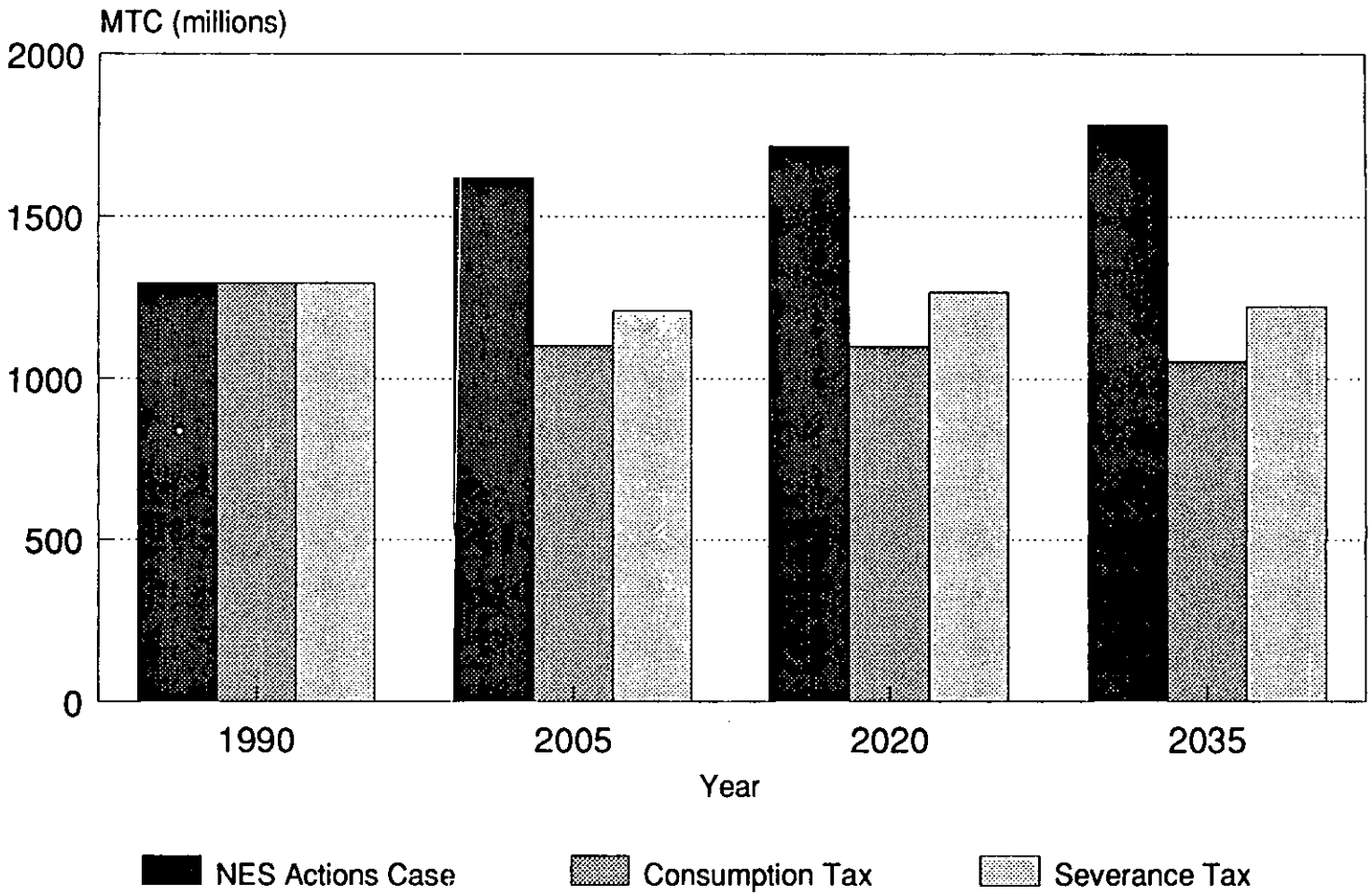

Figure 10.6. International Considerations--U.S. Carbon Emissions

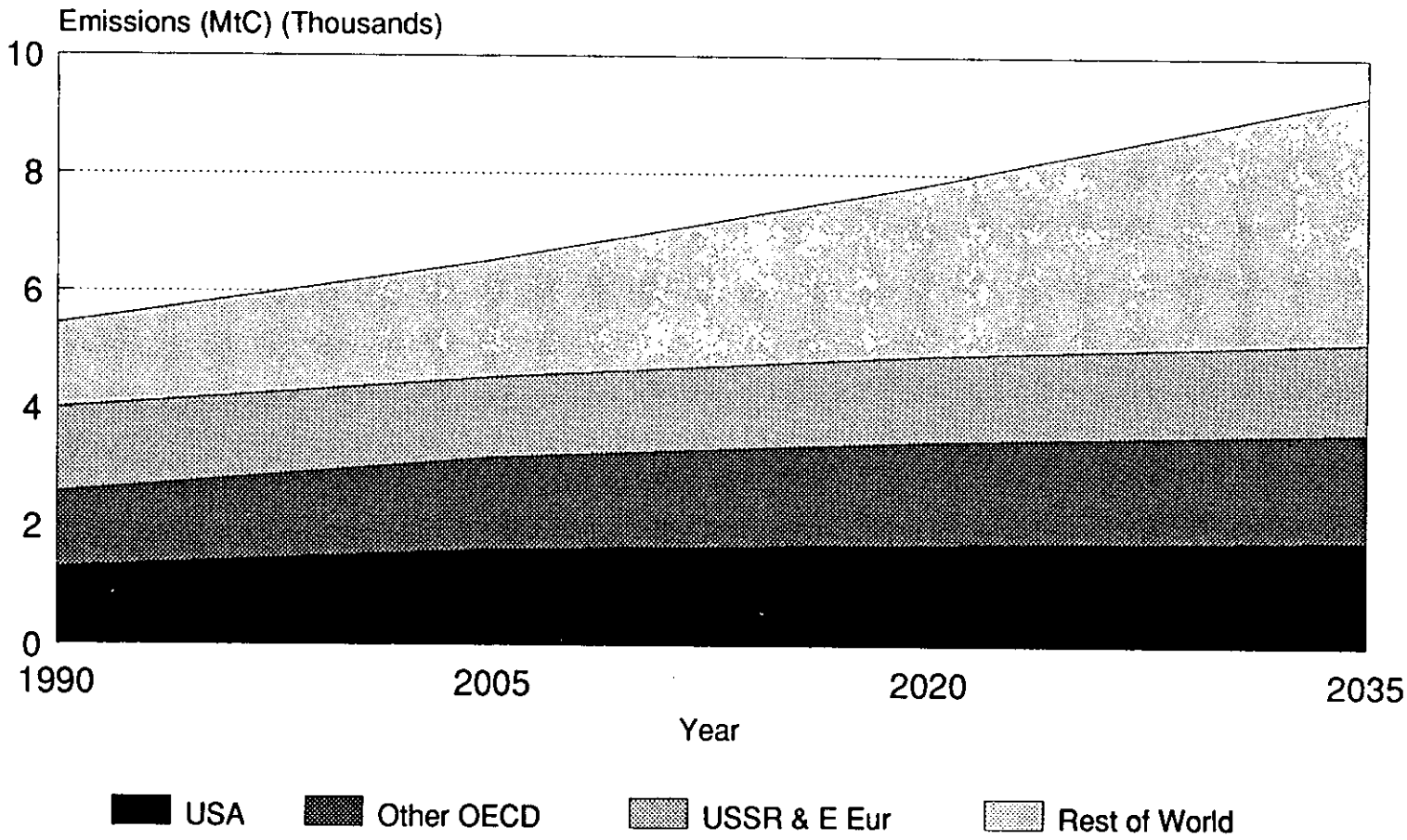

Figure 10.7. NES Actions Case, No Tax: International Considerations--Regional Carbon Emissions

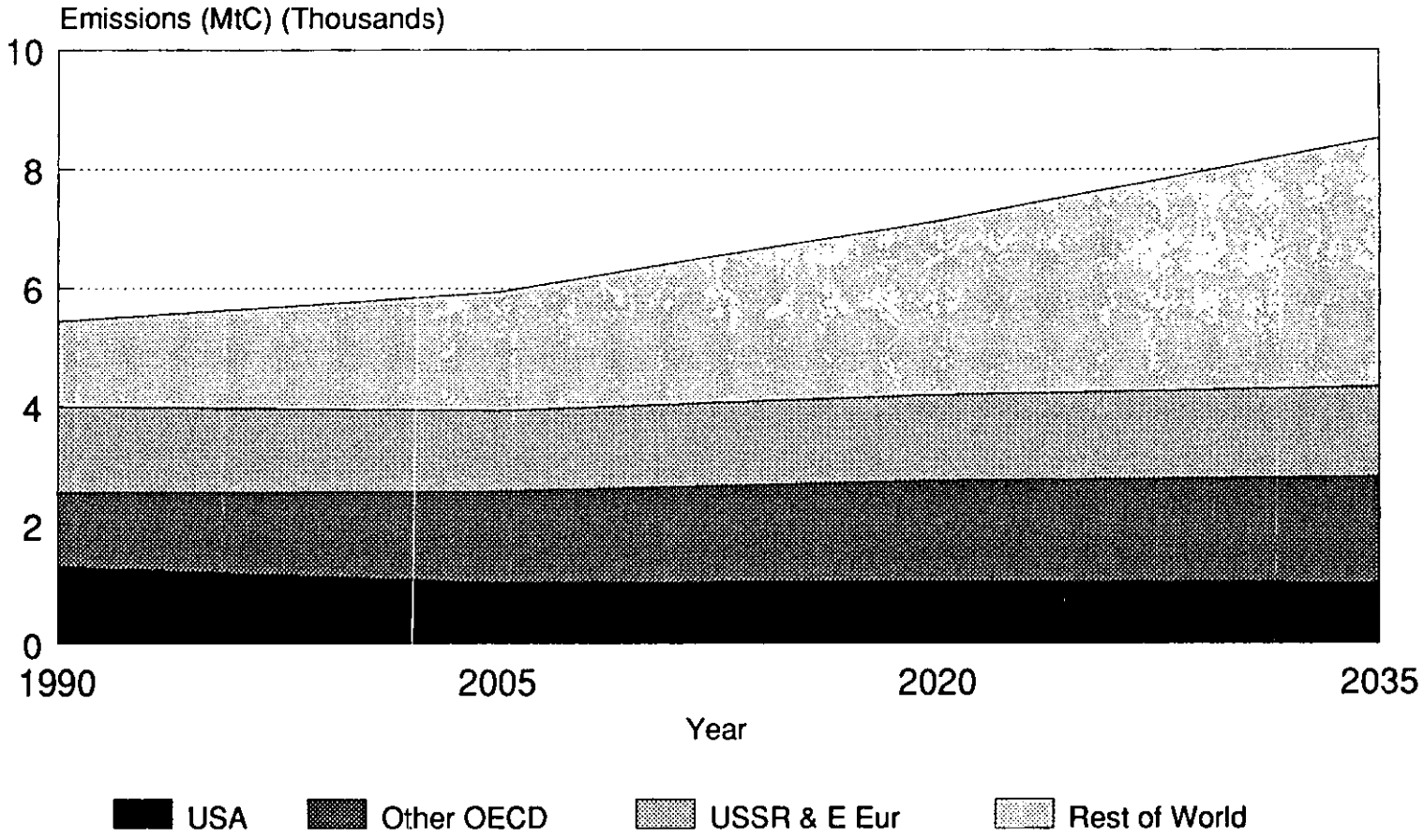

Figure 10.8. Tax to Reduce U.S. Emissions by 20%: International Considerations--Regional Carbon Emissions

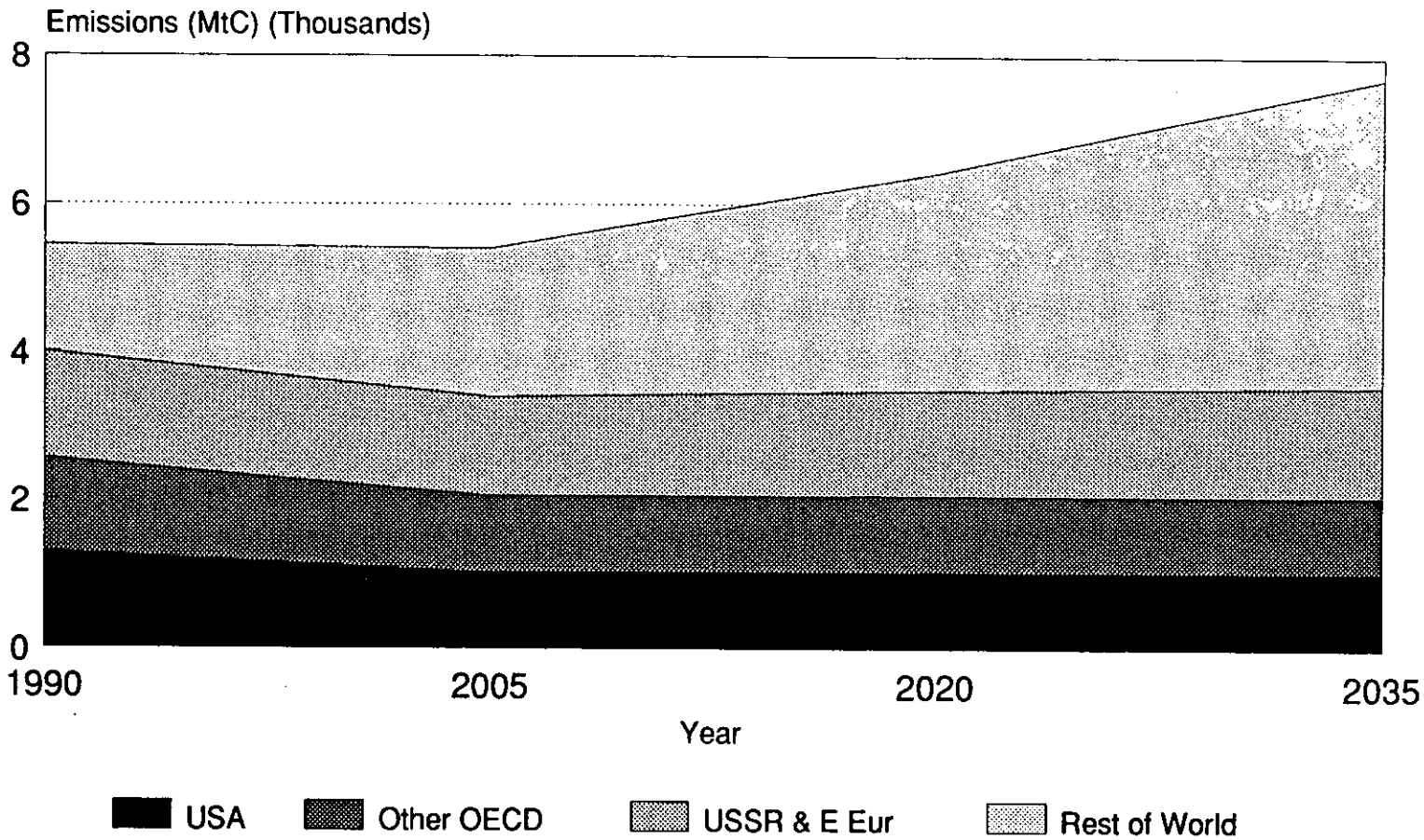

Figure 10.9. OECD Regional Emissions Reduced by 20%: International Considerations--Regional Carbon Emissions

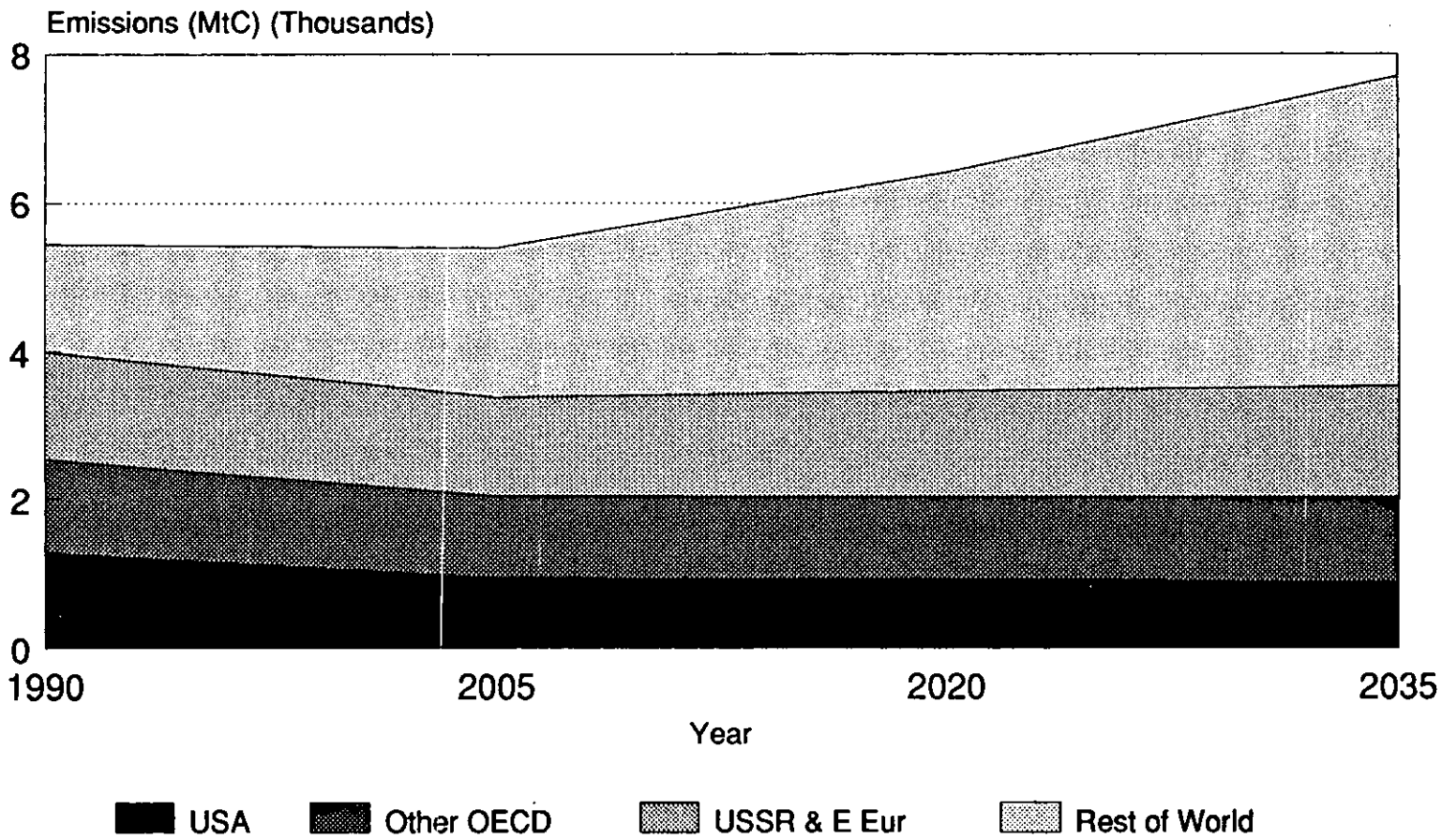

Figure 10.10. OECD Total Emissions Reduced by 20%: International Considerations--Regional Carbon Emissions

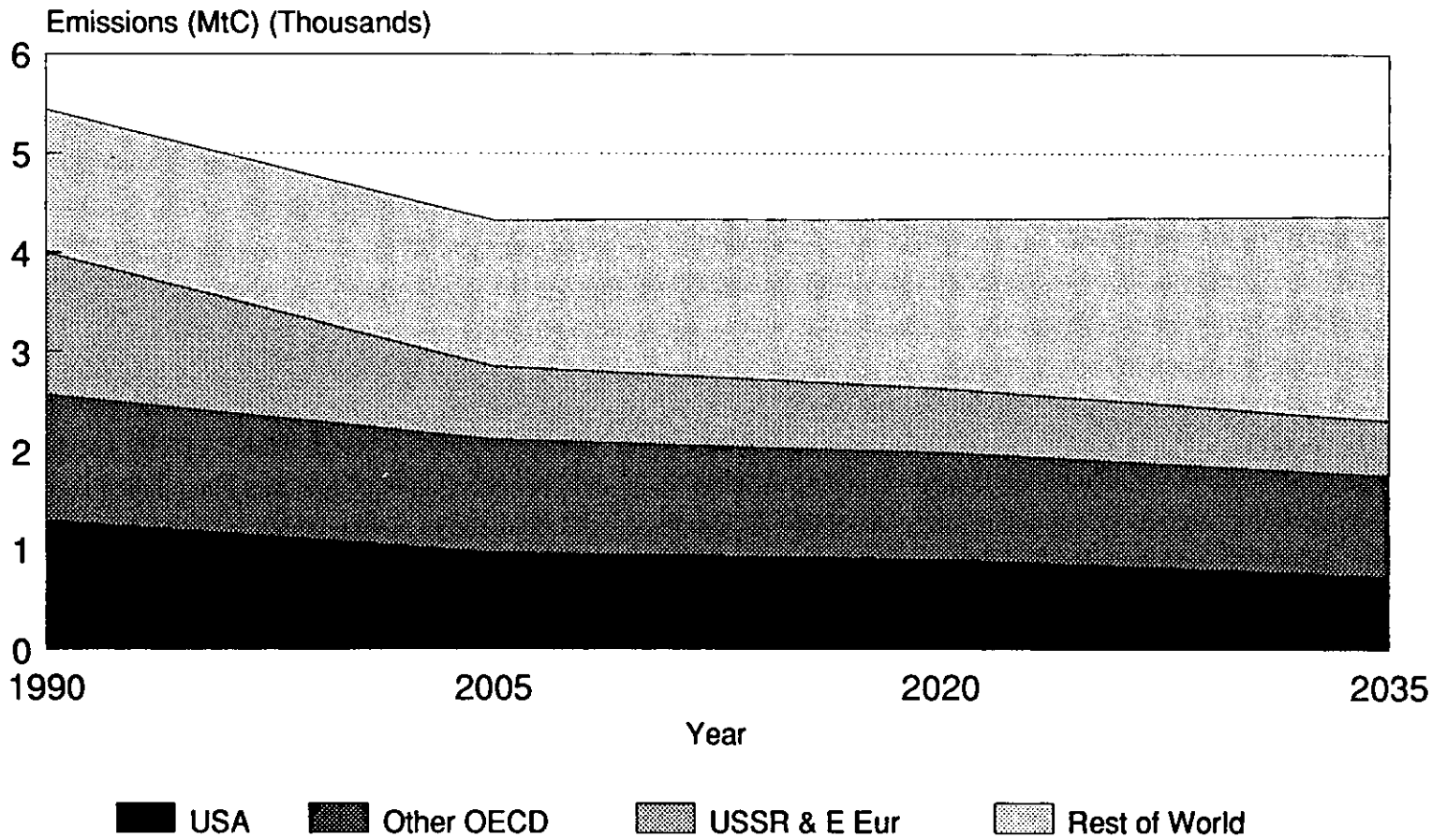

Figure 10.11. World Total Emissions Reduced by 20%: International Considerations--Regional Carbon Emissions

11.0 A COMPARISON TO OTHER STUDIES

11.1 INTRODUCTION

Limiting Net Greenhouse Gas Emissions in the United States is not the first study to look at the feasibility and cost of reducing potential future U.S. greenhouse gas emissions; other studies have also been conducted. These studies include Cheng et al. (1985), Goldemberg et al. (1987), Edmonds et al. (1989), Lashof and Tirpak (1989), IPCC (1990), Manne and Richels (1990a, b, c), Carlsmith et al. (1990), Chandler and Nicholls (1990), Jorgenson and Wilcoxen (1990), Morris et al.,[a] CBO (1990), CRS (1990), OECD (1991), CSIS et al. (1991), Scheraga et al. (1991), Ogawa (1991), OTA (1991), NAS (1991a, b), and DRI (1991). Earlier papers, for example, Cheng et al. (1985), Goldemberg et al. (1987), and Edmonds et al. (1989), examined only the feasibility of reducing potential future greenhouse gas emissions. More recent papers address both the feasibility and cost issues. The purpose of this chapter is to review the results of other studies so as to provide a broader context in which to view the results of this effort. Other reviews of the literature on the cost of emissions reductions include Nordhaus (1990), Hoeller et al. (1990), Rothman and Chapman,[b] and Darmstadter (1991).

In general, we will restrict our attention to studies of reducing potential future greenhouse gas emissions of the United States, although references will be made to studies of other regions of the world. This chapter will be divided into four parts: reference case emissions, emissions reductions and costs, a note on the recent National Academy of Sciences report, and discussion of results.

(a) S. C. Morris, B. D. Solomon, D. Hill, J. Lee, and G. Goldstein. Forthcoming. "A Least Cost Energy Analysis of U.S. CO_2 Reduction Options." *Energy and the Environment in the Twenty-First Century*. MIT Press, Cambridge, Massachusetts.

(b) D. S. Rothman and D. Chapman. 1991. *A Critical Analysis of Climate Change Policy Research*. Draft paper, Department of Agricultural Economics, Cornell University, Ithaca, New York.

11.2 A COMPARISON OF REFERENCE CASE EMISSIONS RESULTS

Reference case emissions are of particular interest to a study examining the reduction of potential future greenhouse gas emissions, as they determine the scale and scope of the problem. Much effort has been exerted in the analysis of fossil fuel carbon emissions reduction strategies for the United States. While the examination of potential future fossil fuel carbon emissions is an important part of the overall climate change issue, it is only one part. As discussed in Chapters 1 and 3, the determination of climate change depends on the entire emissions profile. A comprehensive approach is therefore needed to assess the impact of a nation's emissions on climate change. Studies have begun to go beyond the narrow examination of fossil fuel carbon emissions to take a more comprehensive approach to the study of greenhouse gas emissions. These studies include Cristofaro (1990), DOE (1991), OTA (1991), and CSIS et al. (1991). Most studies adopt global warming potential (GWP) weights with 100-year integration periods as computed by IPCC (1990) to compare alternative greenhouse gas emissions. Nevertheless, there is much less consensus regarding precisely which gases are to be included and the extent of human activities over which to accumulate emissions.[c] It is therefore difficult to compare GWP-weighted emissions across studies at this time.

From an analytical perspective, the comprehensive approach is preferable to an analysis of carbon emissions alone. From the perspective of comparing studies, it is very difficult to use GWP-weighted emissions, where they have been constructed. For most studies, only information regarding carbon

(c) We note that, for example, CSIS et al. (1991) includes only CO_2 and CFC emissions, while OTA (1991) includes CO_2, CFCs, CH_4, and N_2O. Cristofaro (1990), on the other hand, includes CO_2, CO, CH_4, CFCs, N_2O, NO_x, and volatile organic compounds (VOCs).

emissions is available. We will therefore compare reference case fossil fuel carbon emissions scenarios. Figure 11.1 displays reference case carbon emissions for various studies along with the NES Current Policies and NES Actions Cases (DOE 1991).

The NES has a longer timeframe, extending to the year 2030, than do most of the other studies that examine the issue of greenhouse gas emissions.[a] Only three other U.S.-focused studies, Scheraga et al. (1991) and Manne and Richels (1990a, c), consider energy issues over as long a time scale as the NES (DOE 1991). DRI (1991), CSIS et al. (1990), CBO (1990), Edmonds et al. (1989), and Cristofaro (1990) consider the period to 2010. Variation in time horizons among studies increased beyond the year 2010. The analysis contained in CBO (1990) extends to the year 2000, while OTA (1991) proceeds to the year 2015. Several of the global studies, which include the United States as one of many regions, have a long-term timeframe, extending to the year 2100. These include Lashof and Tirpak (1991), IPCC (1990), and Ogawa (1991). The National Academy of Sciences report (NAS 1991a, b) considered the potential for reducing 1988 emissions if contemporary technologies and infrastructure could be replaced by "best practice" applications.

Several interesting observations can be made regarding reference case carbon emissions trajectories shown in Figure 11.1. For the year 1990, there is approximately 10% difference between maximum and minimum values. For the year 2000, there is approximately 20% difference between maximum and minimum values, relative to the Current Policies Case (DOE 1991). This is about the same relative difference as is observed in the year 2010. There are reference cases that are both higher than the Current Policies Case and lower than the NES Actions Case. The Manne and Richels trajectory exceeds the Current Policies Case substantially by the year 2030, although the case is very similar to the Current Policies Case between 1990 and 2010. The Ogawa (1991) reference case has higher fossil fuel carbon emissions in the year 2000 than does the Current Policies Case, but looks very similar in the year 2025. The reference cases of Scheraga et al. (1991) and OTA (1991) look very similar to the Current Policies Case. Several studies produce reference cases that lie between the Current Policies and NES Actions Cases. These include Lashof and Tirpak (1989), both the Rapidly Changing World (RCW) and Slowly Changing World (SCW) Cases; Edmonds et al. (1989); IPCC (1989) High Case; CRS (1990); and DRI (1991). The IPCC (1990) Low Case looks very similar to the NES Actions trajectory, while the Cristofaro (1990)/ Jorgenson and Wilcoxen (1990) reference case has emissions 8% lower than those of the NES Actions Case.

11.3 EMISSIONS REDUCTIONS AND COSTS

As noted earlier, several studies have already addressed the issue of cost. Initial studies of options to control fossil fuel carbon emissions--for example, Edmonds and Reilly (1983), Nordhaus and Yohe (1983), and Nordhaus (1979)--were pessimistic regarding the cost of emissions reductions. Edmonds and Reilly (1983), for example, concluded that taxes on fossil fuels as high as 100% of the price of coal were ineffective in controlling emissions.[b]

While early studies of emissions reduction frequently focused on technological feasibility, more recent analysis has recognized that the issues of feasibility and cost of greenhouse gas emissions reductions were virtually inseparable. There is a general recognition that the greenhouse issue is a

(a) This is due, at least in part, to the Toronto Climate Conference Statement (1988), which called upon governments to "*Reduce CO_2 emissions by approximately 20 percent of 1988 levels by the year 2005 as an initial global goal.*" Frequent reference is made to this document in motivating analysis, which then focuses on the general timeframe surrounding the year 2005.

(b) It is interesting to note that, while the studies expressed pessimism about the ability of even "high" taxes on fossil fuels to stabilize or reduce fossil fuel carbon emissions, the notion of a "high" tax was very different when these studies were conducted.

multi-gas emissions issue, although the analysis of the potential for emissions reductions has focused primarily on fossil fuel carbon emissions. The costs of reducing fossil fuel carbon emissions vary greatly among studies. Table 11.1 attempts to summarize the findings of several studies regarding the marginal and average cost of reducing fossil fuel carbon emissions. As our previous discussions indicate, this is only one dimension of the cost issue. Marginal and average costs of emissions reductions of varying degrees are a frequently cited reference point.

A cursory examination of Table 11.1 reveals that the terms of reference of studies differ greatly. The time horizon, for example, varies from a decade to more than a century into the future. The geographical boundaries of the studies vary from the Netherlands to the Earth. The degree of severity of reductions from a future reference case that are considered vary from a few percent with total emissions continuing to grow, to 70% absolute reductions from current emission.

We note that differences between marginal and average cost can be the source of some considerable confusion, as the latter is always lower, and frequently substantially lower[(a)] than the former for any given study.[(b)]

(a) We note that the DRI (1991) study shows a higher average cost than marginal cost, though marginal cost is computed as the implied carbon value of a tradable permit and the average cost is computed as the GNP/GDP loss per unit emissions reduction relative to the reference case.

(b) The way in which costs are reported can lead to confusion. There are three related concepts that are important: total, marginal, and average cost. Total cost is the entire cost calculated at some period in time associated with an emissions reduction policy. Average cost is the total cost of the policy per unit emission reduction; that is, total cost divided by the total reduction. The marginal cost is the cost of the last unit of emission reduction. If total cost is to be minimized, each unit of emission reduction should be accomplished at minimum cost; that is, the least expensive options should always be executed before more expensive options. If this approach is taken, then the last unit of emission reduction is always the most expensive, for the simple reason that all of the less costly alternatives have already been undertaken. It is therefore also true that marginal costs must always exceed average costs.

In Chapter 6 of this volume, we examined the effects of carbon taxes without an option to sequester carbon in forests. We have plotted the results of that analysis in Figure 11.2 in two ways. We have also plotted the effect of the carbon tax, relative to the Current Policies case to show the combined effect of NES Actions and the tax case. We also plot emissions reductions from a carbon tax relative to the NES Actions Case alone. NES Actions substantially reduce carbon emissions, relative to the Current Policies case. Penetration of new energy-conserving and low-carbon energy supply technologies in response to a carbon tax is limited by the fact that NES Actions have already induced the introduction of many attractive options. We note that, while the absolute cost of stabilizing fossil fuel carbon emissions at 1990 levels rises between 1995 and 2015, the relative cost of an additional percent of fossil fuel carbon emissions reduction falls throughout the period of analysis. This is indicative of the benefits of additional time to respond to a carbon tax.

Several factors influence the cost of emissions reductions. These include the reference level of future emissions, the cost of energy conservation and non-fossil fuel energy supply technologies, the time to adjust to any set of changes, and the assumed energy system environment. In general, the greater the reference emissions trajectory for any forecast date, the greater will be the cost of achieving an emissions reduction relative to a prior date. (It is also true that the greater the reference emissions trajectory for any forecast date, the lower the cost of the first tonne of carbon emissions reduction.) The importance of the reference emissions scenario has been highlighted by Hogan and Jorgenson (1990), who argue that "simple calculations with the best available estimation results suggest that common assumptions in existing models may be missing as much as half of the total cost of controlling greenhouse gases."

As noted earlier, it is important to pay close attention to whether emissions reductions costs are reported as marginal or average, and whether total

Table 11.1. The Cost of Fossil Fuel Carbon Emissions Reductions: Summary of Studies Findings

Study	Region	Case	Forecast Year	Percent Emissions Reduction[a]	Ref. Year	Avg Cost (US1989$/ mtC)	Mar Cost (US1989$/ mtC)
Boonekamp	Neth.	2nd Stage					
et al.		Gas	2010	(10%)	1990	$100[b]	n.a.
(1989)		Nuc	2010	0%	1990	$0[b]	n.a.
		Gas	2030	(13%)	1990	$120[b]	n.a.
		Nuc	2030	6%	1990	$0[b]	n.a.
		3rd Stage					
		Gas	2030	27%	1990	$80[b]	n.a.
		Nuc	2030	46%	1990	$100[b]	n.a.
Gerbers	Neth.	Trend Case	2020	0%	1990	$31[b]	$31[b]
et al.			2020	20%	1990	$31[b]	$31[b]
(1990)			2020	30%	1990	$33[b]	$41[b]
			2020	40%	1990	$58[b]	$150[b]
			2020	50%	1990	$73[b]	$221[b]
			2020	60%	1990	$94[b]	$277[b]
			2020	70%	1990	$174[b]	$889[b]
Yamaji	Japan		2005	0%	1988	n.a.	$281[c]
et al.							
(1990)							
Manne and	U.S.A.		2030+	20%	1990	$210	$250
Richels							
(1990a)							
Manne and	U.S.A.	Optimistic	2050	0%	1990	n.a.	$110
Richels		Case	2100	0%	1990	n.a.	$250
(1990c)		Pessimistic	2050	0%	1990	n.a.	$250
		Case	2100	0%	1990	n.a.	$250
Jorgenson	U.S.A.		2100	0%	1990	n.a.	$17[d]
and Wilcoxen			2100	20%	1990	n.a.	$46[d]
(1990)			2100	0%	2000	n.a.	$7[d]
CBO	U.S.A.		2000	6%-(5%)[e]	1988	n.a.	$110[d]
(1990)			2100	20%	1988	n.a.	$110-$440[d]
Morris et	U.S.A.		2010	0%	1990	$ 4	n.a.
al. (1990)			2010	10%	1990	$15	n.a.
			2010	20%	1990	$28	$39
Chandler	U.S.A.		2000	0%	1989	n.a.	$82
and Nicholls							
(1990)							
DRI	U.S.A.		1995	1%[f]	n.a.[f]	($412)[f]	$ 26[f]
(1991)			2000	4%[f]	n.a.[f]	$1015[f]	$116[f]
			2010	8%[f]	n.a.[f]	$ 930[f]	$151[f]
Chandler	U.S.A.		2005	0%	1989	$0	n.a.
(1990)	U.S.A.		2005	20%	1989	$92	n.a.

Table 11.1. (contd)

Study	Region	Case	Forecast Year	Percent Emissions Reduction[a]	Ref. Year	Avg Cost (US1989$/ mtC)	Mar Cost (US1989$/ mtC)
OECD (1991)	N.Amer	1% Growth Reduc. Case	1995	5%	n.a.	n.a.	$7
			2000	30%	n.a.	n.a.	$15
			2005	58%	n.a.	n.a.	$24
			2010	72%	n.a.	n.a.	$36
			2020	72%	n.a.	n.a.	$67
Chandler (1990)	Canada		2005	20%	1988	($525)[g]	$410[g]
	France		2005	0%	1989	$0	n.a.
	Hungary		2005	0%	1989	$0	n.a.
	Poland		2005	0%	1989	$0	n.a.
	United Kingdom		2005	0%	1989	$0	n.a.
Nordhaus (1979)	World		2000	(56%)[d,h]	1988[b]	n.a.	$25[d]
			2020	(30%)[d,h]	1988[b]	n.a.	$232[d]
			2040	(58%)[d,h]	1988[h]	n.a.	$263[d]
			2100	(72%)[d,h]	1988[h]	n.a.	$422[d]
Nordhaus and Yohe (1983)	World		2025	(52%)	2000[i]	n.a.	$77[j]
			2050	(43%)	2000[i]	n.a.	$266[j]
			2075	(93%)	2000[i]	n.a.	$303[j]
			2100	(151%)	2000[i]	n.a.	$303[j]
Edmonds and Barns (1990)	World		2025	0%	2000	$55	$95
			2025	20%	2000	$65	$155
			2025	50%	2000	$128	$405
			2050	0%	2000	$83	$250
			2050	20%	2000	$120	$450
			2050	50%	2000	n.a.	n.a.
Manne and Richels (1990b)	World		2030+	20%	1990	$210	$250

NOTES: mtC=metric tonne of carbon. (a) Percentage emission reduction is measured relative to a reference year's emission and not the reference case emission for the designated forecast year. Negative values in (). (b) Values supplied via personal communication with Dr. P. Okken. Converted to 1990 constant U.S. dollars from 1990 Dutch Guilders at the rate of 1.80:1. (c) Tax rate begins at 4,000¥/mtC and rises at the rate of 4,000¥/mtC/yr until the year 2005 when it reaches the rate of 64,000¥/mtC. Tax rate reported is 64,000¥/mtC. Yen converted to U.S. 1990 $ at the rate of 227.68 ¥:$, the Tokyo exchange rate 22 November 1990. Assumptions incorporated in the trade component of the models differ and are 238.5¥/$, 1985; 127.3¥/$, 1990; 100.0¥/$, 2000; and 90.0¥/$, 2005. (d) Results reported in short tons of carbon converted to metric tonnes at the rate of 1.102. (e) Results ranged from 5% above 1988 levels to 6% below 1988 levels. (f) U.S. case only. This study does not apply a carbon tax, but rather assumes a cap on carbon emissions from oil- and coal-fired stationary emissions sources. It creates a tradable permit to distribute emissions rights, and the carbon value of the coal permit at 25.43 TgC/PBtu is reported as the marginal cost. Average cost is derived as the ratio of GNP/GDP loss to emissions reduction. (g) Value obtained via personal communication from Erik Haites, December 13, 1990. (h) Nordhaus does not attempt to achieve a carbon emission target. Rather he examines the larger carbon cycle system. The experiment he runs is to constrain cumulative carbon accumulation in the atmosphere. The 1988 reference year is arbitrary and supplied by the authors. The authors use 5.7 PgC/yr 1988 emissions. (i) As with Nordhaus (1979), Nordhaus and Yohe (1983) do not attempt to stabilize emissions at any particular level. We report the most stringent of the tax cases examined. This tax scenario is initiated in the year 2000. We therefore take the forecast year 2000 emissions rate of 5.54 PgC/yr as a reference emissions rate. (j) Carbon taxes reported in 1975 constant U.S. dollars per ton of coal equivalent were converted using $0.7682*10^6$gC/(short ton coal equivalent) and 1 1975$=2.1298482 1989$.

costs are reported in the year in which they occur or treated as a discounted stream of costs over some future period of time.

The studies reported here employ one of two generic approaches to the problem of computing costs. Some studies work from cost calculations based on individual technologies that might be available to replace present energy production, transformation, transport and consumption technologies, then aggregate up to a total cost for any reduction in emissions sought. These studies, for example NAS (1991a, b), OTA (1991), Chandler (1990), and Goldemberg et al. (1987), are referred to as "bottom-up" studies. Other studies begin with the macro energy-economic system and apply disaggregation strategies to estimate the cost of emissions reductions. These studies, for example, Edmonds and Barns (1990) and Manne and Richels (1990a, b, c), are referred to as "top-down" studies. Top-down studies generally begin with the presumption that the reference case economic system is in an equilibrium that minimizes all relevant costs given an unchanging set of institutional conditions; therefore, any departure from that equilibrium incurs costs.

Bottom-up studies frequently find that the cost of emissions reductions is not just low, but negative for the first emissions reductions, then eventually rises. Haites (1990), included in Table 11.1 under Chandler (1990): Canada, displays a negative average cost, but a very high, positive, marginal cost to reduce Canadian fossil fuel carbon emissions by 20% in the year 2005, relative to 1988 levels. This seemingly inconsistent result is possible because energy-efficient technologies are initially available that supply the same level of energy service at lower cost than at present. These emissions reduction opportunities are eventually exhausted, and marginal technologies for emissions reductions are available only at a substantial premium.

There are several differences between bottom-up and top-down studies that lead to different conclusions regarding the nature of cost and the rate at which costs rise. In general, the bottom-up studies do not allow for changes in the cost of energy or non-energy factors of production as the scale of activity of a technology grows from marginal to market-dominating. Similarly, the bottom-up studies frequently do not allow for the heterogeneity of end-use energy services that must be accommodated, and they frequently apply one generic technology to provide the entire spectrum of energy services within a category (for example, one kind of light bulb or one kind of automobile). These simplifications can lead to an underestimation of total costs by bottom-up studies.

But such differences are likely less important than the fundamental difference in presumption regarding the suite of available policy options: bottom-up studies estimate the levelized cost of technologies at market interest rates or social discount rates rather than implied internal rates of return. Because the consumer discount rate on energy investments is much higher than the market rate of interest, technologies penetrate more rapidly in bottom-up studies than they do in top-down studies. Implicitly, the bottom-up studies are assuming that a policy can be found and implemented that removes investment market frictions and imperfections. By adding this option, the "rules of the game" for market economies are changed. If market frictions and imperfections can be removed, of course, a new set of rules would be established, the market would be presumed to minimize total costs, and further emissions reductions could be obtained only at cost. The extent to which policy options that can improve market performance exist is a matter of some debate. Similarly, there is no reason to believe that the potential for improvements in market performance are limited to the energy sector. If the economy became generally more efficient and apparent discount rates for all activities fell, capital markets would be required to ration savings by raising the real interest rate and thereby the social discount rate. In the real world, apparently available gains may be reduced or even eliminated if markets take more time for cost-effective technologies to penetrate than bottom-up

analysis indicates, feedback and takeback effects erode apparently available gains, and the heterogeneity of energy-using activities restricts the generality of the paradigm technology specification.

It is also important to note that bottom-up studies are generally short-term in their temporal reference, while top-down studies span a greater time scale, though this generalization has notable exceptions. Cheng et al. (1985), for example, couple a bottom-up approach with a top-down model to examine the potential for new technology to reduce future fossil fuel carbon emissions.

Edmonds and Barns[(a)] have explored the sensitivity of the cost of reducing potential future global fossil fuel carbon emissions to variation in assumptions, including the rate of labor productivity growth, the rate of end-use energy intensity improvement, the cost of non-fossil energy supply options, the size of the fossil fuel resource base, population, and price and income effects. They conclude that the minimum cost of global fossil fuel carbon emissions reductions depends on a large number of factors. Two factors, the rate of labor productivity growth and the rate of exogenous end-use energy intensity improvement, created the greatest divergence in the observed tax rate necessary to achieve a given emission level in either 2025 or 2050.

Edmonds and Barns ran two additional productivity cases, "Closing Down the Patent Office" and "Technological Nirvana." Both cases tied the assumed rates of exogenous labor and energy productivity together so that when one was high, so was the other, and when one was low, so was the other. Curiously, both of these cases had relatively low costs of emissions reductions, with "Closing Down the Patent Office" leading to trivial emissions reduction costs. "Technological Nirvana" exhibited only slightly higher cost characteristics. The implication of the analysis of exogenous productivity assumptions leads to some important implications for further research into the issue of whether these parameters can be linked or independent.

The Edmonds and Barns study also found that the extent to which other, non-greenhouse, environmental, health, and safety concerns add to energy production costs has a major impact on the cost of emissions reductions. Simply put, the broader the "No Regrets"[(b)] umbrella, the lower the costs associated directly with greenhouse gas emissions reductions. This raises the issue of the interconnections among a wide variety of environmental, health, and safety issues. The efficient formulation of policy requires that interconnections be taken explicitly into account. For example, an efficient set of energy-environmental charges developed jointly in light of both acid deposition and the greenhouse might look somewhat different than either a set of charges developed independently for each issue or the sum of the charges developed for each issue.

The fourth parameter, generally associated with wide cost variations in the Edmonds and Barns study, was the income elasticity of demand for energy. This parameter is particularly important for developing nations. It reflects the changing economic composition in developing economies. As Goldemberg et al. (1987) suggest, low income elasticity development paths as well as high ones are available. The cost of emissions stabilization depends heavily on which parameter value represents the actual development process.

The cost of stabilizing emissions in the Edmonds and Barns analysis was relatively sensitive to two variables, the resource base of conventional fossil fuels and the price elasticity of demand for energy. The appearance of the resource base of fossil fuels as an important determinant of cost was something of a surprise to the researchers. This is particularly

(a) J. Edmonds and D. W. Barns. 1991. *Factors Affecting the Long-Term Cost of Global Fossil Fuel CO2 Emissions Reductions.* PNL Global Studies Program Draft Working Paper.

(b) "No Regrets" is a term used to refer policy actions that are prudent to take for reasons unrelated to the atmosphere/climate change issue, but which reduce the emissions of radiatively important (greenhouse) gases.

true in light of the fact that the abundance of coal resources, in terms of the time frame of the analysis, means that fossil fuels provide no meaningful constraint on the ability of human energy activities to emit carbon into the atmosphere over the course of the next century. But the presence of abundant conventional fossil fuel resources, in particular conventional oil and gas resources, leads to higher costs of emissions stabilization because it retards energy price escalations in the Untaxed Case, and greater carbon tax rates are therefore required to stabilize emissions.

The price elasticity of demand for energy was somewhat less surprising as an important determinant of future costs of emissions stabilization in the Edmonds-Barns research. The greater the ability of society to substitute energy conservation and restructure end-use demand in response to higher energy prices, the smaller any carbon tax needed to achieve a reduction in carbon emissions.

Surprisingly absent from the list of important factors influencing the sensitivity of the costs of stabilizing future global carbon emissions in the Edmonds and Barns study was population growth. This absence can be explained by the fact that the major effect of population growth on carbon emissions is through its effect on the size of the labor force and thereby on GNP. Thus, the time required for those changes in population to affect the labor force lags behind the effect of changes in population growth rates. In addition, variation in the population growth parameter was relatively small when compared to factors such as labor productivity growth and exogenous end-use energy productivity growth.

While variations in the resource base of biomass energy supply were not associated with wide variation in the tax rate needed to stabilize global fossil fuel carbon emissions, increased use of biomass energy was a major response mode in all but the very low biomass supply sensitivity, accounting for up to half of the marginal rate of emissions reductions in the Edmonds-Barns analysis.

The array of costs shown in Table 11.1 is generally consistent with that found in the Edmonds and Barns study. The range of tax rates that stabilize emissions more than spans the values obtained by the studies cited in Table 11.1. Edmonds and Barns plot the change in fossil fuel carbon emissions in the Untaxed Reference Case for various studies as a percentage increase over the stabilization target emission against the tax rate that stabilizes emissions at the target level in that forecast year for their various sensitivity cases. There was a very strong correlation between the percentage increase in the untaxed reference emissions rate and the tax rate that stabilizes emissions (Figure 11.2). It is hard to escape the general conclusion that the greater the untaxed reference emissions trajectory diverges from the target emissions stabilization rate, the higher the required tax. Even more interesting is the fact that the relationship mapped out by this sensitivity is strongly linear and independent of whether the forecast year is 2025 or 2050. For the Edmonds-Barns sensitivity, the rule of thumb was that for every percent the untaxed trajectory exceeds the stabilization target, a increase in the tax rate of $2.00/mtC was needed to stabilize emissions. There were, of course, exceptions to this generalization. Some sensitivity cases deviate substantially from this rule. For example, the high fossil fuel resource base sensitivity generated a stabilization tax rate of more than $500/mtC, while untaxed emissions grew by less than 150% by the year 2050. Similarly, the high non-greenhouse environmental cost sensitivity led to a relatively modest increase in untaxed emissions, but required a tax rate of almost $200/mtC to stabilize emissions. A range of between $1.00/mtC and $4.00/mtC of additional tax rate for each percentage point by which the untaxed trajectory exceeds the stabilization trajectory spans all but one of the sensitivity observations. It is not at all clear why the array of sensitivity points in Figure 11.2 mapped out an essentially straight line, while the marginal cost schedule for any given sensitivity clearly showed increasing marginal costs.

It is possible to compute the relationship between the tax rate needed to stabilize emissions and

the percentage difference between the Untaxed Reference Case and the emissions stabilization target for some other studies. These results are plotted in Figure 11.3. The rays showing tax rate increasing at $1.00/mtC, $2.00/mtC and $4.00/mtC for each percentage point increase in the difference between the Untaxed Reference Case and the emissions stabilization target. Observations that lie below the $1.00/mtC/% line display more price sensitivity than the Edmonds-Reilly long-term, global energy and greenhouse gas emissions model (ERM); they are more "cost" optimistic. Observations which lie above the $4.00/mtC/% line display less price sensitivity than the ERM; they are "cost" pessimistic. Studies that were more "cost" pessimistic than the ERM include Yamaji et al. (1990), DRI (1991), and this study in the period between 1990 and 2015 and when only policies beyond NES Actions were considered. The translation of results from yen to dollars is sensitive to the specific exchange rate employed. Interestingly, of the various exchange rates suggested by Yamaji et al. (1990), the one employed here yields the lowest tax rate. This is consistent with the relatively high GNP loss (6%) associated with the tax stabilization scenario. DRI (1991) is the most pessimistic, in terms of the marginal cost of emissions reductions, of any of the scenarios examined. The present study differs significantly in that it stabilizes emissions from stationary sources of combustion of oil and coal only and uses a tradable permit to auction emissions rights. It is also worth noting that, in contrast to most other studies, the average cost of a fossil fuel carbon emission reduction in terms of GNP loss is almost an order of magnitude greater than the carbon value of the U.S. tradable permits in the years 2000 and 2010, while the GNP actually increases in the year 1995 in response to the oil and coal stationary source emissions cap. Interestingly, the OECD (1991) study lies close to the $2.00/mtC/% line.

In contrast, several studies fell below the $1.00/mtC/% line. The Manne and Richels (1990c) Pessimistic Case extends beyond the line because it contains a "backstop" technology that is available in infinite supply at constant prices. In this sense, the Manne and Richels model might be viewed as a cost "optimistic" model. This is interesting because the marginal cost of stabilization of $250/mtC appears high relative to other studies. Figure 11.3 shows that these costs are similar to those found in the Edmonds-Barns ERM sensitivity analysis. The range of cost estimates associated with Manne and Richels (1990a, b, c) are obtained by computing the relationship between the Untaxed Reference Case and the emissions stabilization target over the period 2050 through 2100. The Jorgenson and Wilcoxen (1990) study, which lies completely below the $1.00/mtC/% line, is associated with low emissions relative to the stabilization target.

11.4 A NOTE ON THE NATIONAL ACADEMY OF SCIENCES REPORT

The National Academy of Sciences (NAS) recently released a report which concluded that,

> ...the United States could reduce its greenhouse gas emissions by between 10 and 40 percent of the 1990 level at very low cost. Some reductions may even be at a net savings if the proper policies are implemented. (NAS 1991a, p.63)

While this conclusion may seem substantially different from the results of other studies discussed here, it appears more consistent when set in proper context. The most important point to observe about the NAS study is that the emissions reduction is to be accomplished in the year 1990. The hypothetical scenario is that the U.S. demands for energy services can be met at some future date using present "best available" technologies. The U.S. economy is treated as if the scale of economic activities were frozen at steady-state levels observed in the year 1990.

The analysis of an economy in steady-state can be helpful in defining the ultimate shape of an economic system. But such analysis is limited in that it

completely neglects the problems of transitions from the present economy to the idealized steady-state economy and is relevant to an economy characterized by a different scale only to the extent that the options analyzed also scale with the level of economic activity.

Some of the emissions reductions potential clearly will not scale with the overall level of economic activity. The phaseout of chlorofluorocarbons (CFCs), for example, represents a reduction in emissions which is fixed in magnitude. In fact, it is possible that these gains could be eroded with time, depending on the character of replacement compounds.

There is a similar problem with the treatment of trees as a carbon sink. This sink has a limited capacity and lifetime that will not necessarily scale with the overall level of economic activity, although the report reduces the sequestration potential estimates of Moulton and Richards (1990) by approximately two-thirds.

Another problem encountered with a growing economy is that even if emissions reduction options scale with the overall level of economic activity, they do not scale relative to an absolute target. Take for example an economy that grows by 50% and for which a 50% emissions reduction is potentially available. A 50% emission reduction in the future is only a 25% emission reduction relative to the reference year. Most proposed emissions reduction targets are couched in terms of a reduction relative to an absolute base. For example the Toronto Climate Conference Statement (1988) urged nations to cut carbon emissions by 20% relative to 1988.

A comparison between the National Energy Strategy analysis and the Mitigation Panel report is instructive. The two reports, NAS (1991b) and DOE (1991), are referenced to 1988 and 1990 respectively. Reference year GWP-weighted emissions are given in Table 11.2.

Table 11.2. Comparison Between Base Year GWP-Weighted Emissions in the NAS and NES Cases ($PgCO_2e/yr$)

	NAS (1991b)		DOE (1991)	
Year	1988	Steady-State	1990	2030
CFCs	1.64[a]	0.24[a]	1.83[b]	0.20[b]
Energy	6.26[c]	3.76[c]	5.63[d]	10.35[d]
Total	7.90	4.00	7.46	10.52

(a) Includes CFCs: $CFCl_4$ (CFC-11), CF_2Cl_2 (CFC-12), and $CFCl_2CF_2Cl$ (CFC-113).
(b) Includes CFCs, HCFCs, and HFCs.
(c) Includes both energy-related emissions and emissions from other activities including landfills, rice cultivation, cattle raising, and land-use change.
(d) Includes energy-related emissions and emissions from landfills, but not emissions from rice cultivation, cattle raising, or land-use change.

The steady-state 1988 emissions scenario indicates that, given a sufficient amount of time to implement the transition, net emissions can be cut from 7.9 $PgCO_2e/yr$ to 4.1 $PgCO_2e/yr$ at an approximate net marginal cost of $5/mtCO_2e$ to society and at a total benefit to society. Steady-state CFC emissions are assumed to be reduced by 85% relative to 1988 levels, while energy-related emissions are reduced by 38%. This yields an overall decrease in GWP-weighted emissions of 48% for the steady-state 1988 economy, as reported by NAS (1991b).

Now let us assume that the NAS steady-state energy-economic system is as large as the NES Current Policies Case in the year 2030. The NAS "energy" sector grows by approximately 80%. Assuming that the CFC component of the system remains fixed, the overall scale of the system would increase as indicated in Table 11.3, to 13.2 $PgCO_2e/yr$.

Applying the same rates of emissions reductions to the CFC and energy sectors, respectively, yields the same 48% emissions reduction for the 1988

Table 11.3. Comparison Between NAS Steady-State with and Without All Zero and Negative Marginal Cost Options Implemented Base Year 1988 and Scaled to Year 2030 Rates ($PgCO_2e/yr$)

	Steady-State No Reductions		Steady-State With Reductions	
Year	1988	2030	1988	2030
CFCs[a]	1.64	1.64	0.24	0.24
Energy[b]	6.26	13.52	3.86	7.10
Total	7.90	13.16	.10	7.34

(a) Includes CFCs, HCFCs, and HFCs.

(b) Includes both energy-related emissions and emissions from other activities including landfills, rice cultivation, cattle raising, and land-use change.

steady-state, but only a 7% emissions reduction relative to historical 1988 when the steady-state is scaled to NES year-2030 levels. In fact, energy-related emissions are greater in the year 2030 in the "NES scale" case than in 1988, despite the application of cost-effective technologies.

The point of this exercise is not to argue that the numbers constructed here are correct, but rather that the results of a current year steady-state analysis do not translate directly to future years.

11.5 DISCUSSION

There is a wide variation in the reference case potential future fossil fuel carbon emissions developed for various studies. These cases span the range defined by the Current Policies and NES Actions Cases (DOE 1991); that is, some reference cases show potential future U.S. fossil fuel carbon emissions higher than in the Current Policies Case (for example, Manne and Richels (1990a) Pessimistic Case), while other reference cases project lower potential future fossil fuel carbon emissions than does the NES Actions Case (Jorgenson and Wilcoxen 1990). As might be expected, the range of reference case forecasts of potential future fossil fuel carbon emissions expands with time. Even for the year 1990, there is a 10% difference between high and low estimates of carbon emissions.

The tax rate needed to hold emissions constant also varies greatly among studies. A variety of specific factors contribute to variation in tax rates obtained in studies. The rate of labor productivity growth (which strongly affects GNP) and the rate of exogenous end-use energy intensity improvement appear to be of particular importance. The reference case plays an important role here in affecting the tax rate observed to be required to hold emissions constant. The average carbon tax rate required to hold emissions constant for each percentage point the reference case lies above the target emission rate varies greatly among studies. For *Limiting Net Greenhouse Gas Emissions in the United States*, the average carbon tax rate percentage reduction from the Current Policies Case falls from \$10/mtC/% in 1995 to approximately \$1/mtC/% in the year 2030 when the carbon tax is combined with the NES Actions. It falls from \$10/mtC/% in 1995 to approximately \$3/mtC/% when taxes are considered separately. Other studies can be found that appear to be either more optimistic or more pessimistic about the effectiveness of an additional dollar in tax rate.

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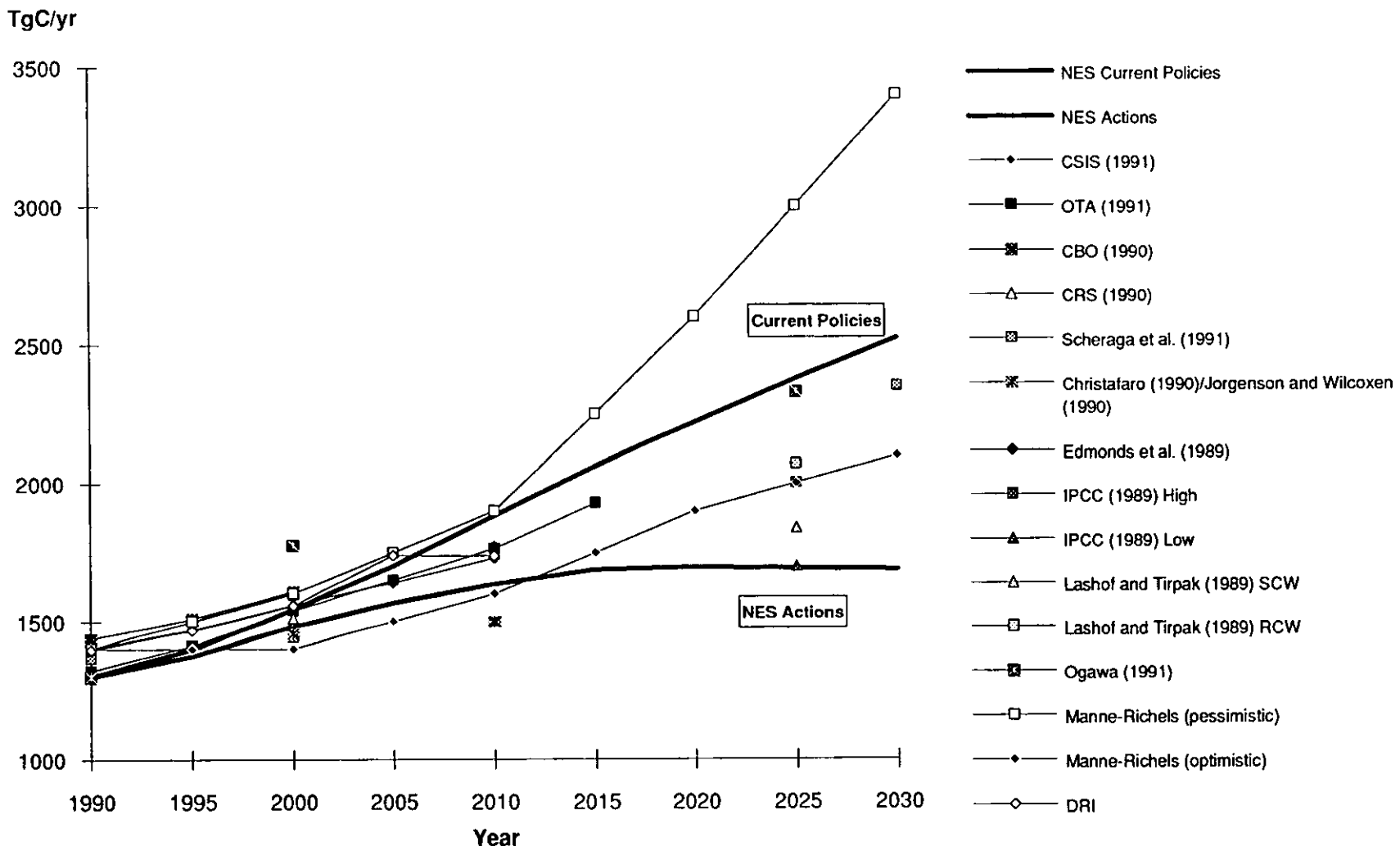
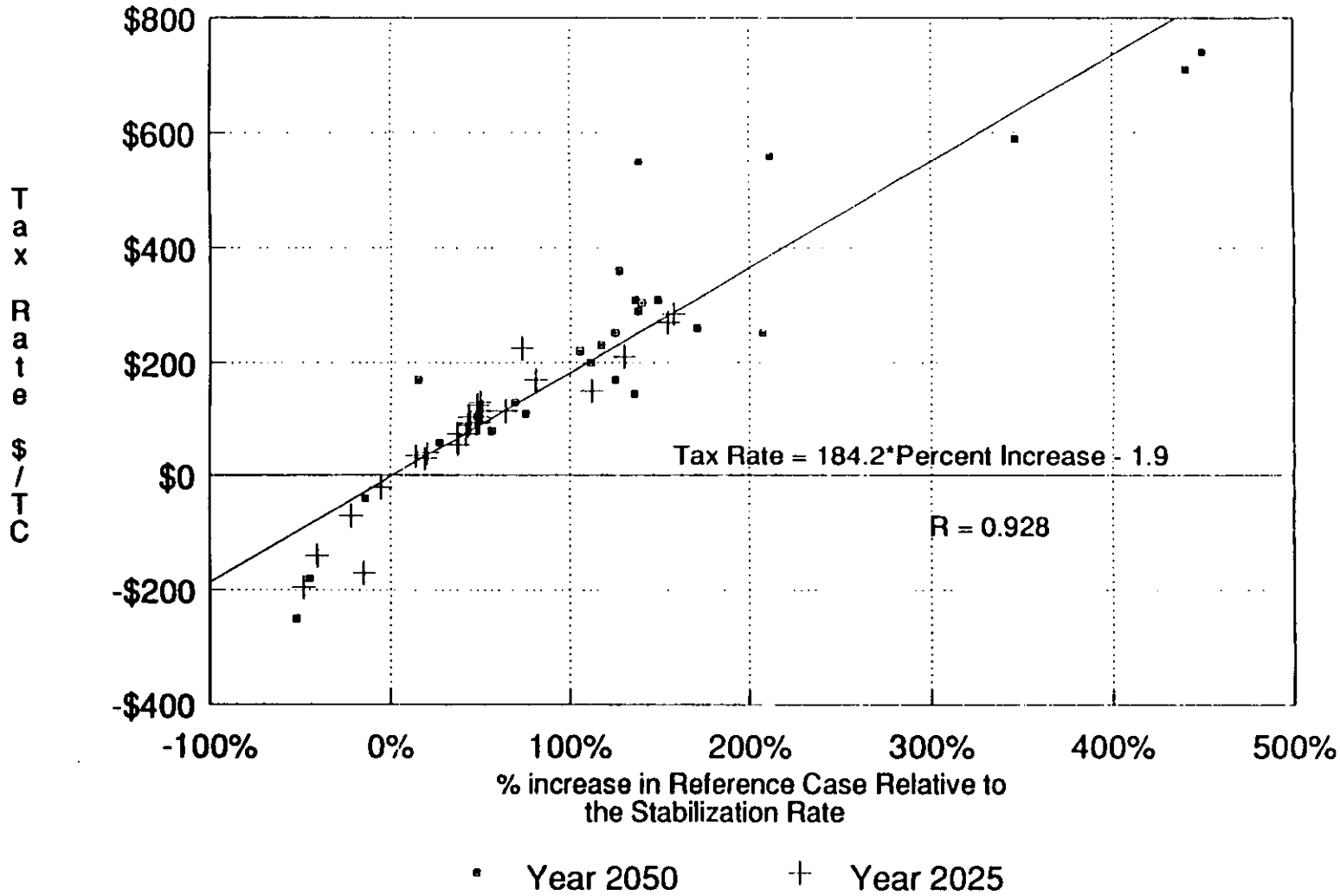


Figure 11.1. A Comparison of Reference Case Carbon Emissions Trajectories from Various Studies



Note: Tax Rates less than zero or greater than $500/TC are extapolations.

Figure 11.2. Percentage Increase in the Reference Untaxed Case Fossil Fuel CO_2 Emissions Relative to Stabilization Target vs. Stabilization Tax Rate for Years 2025 and 2050.

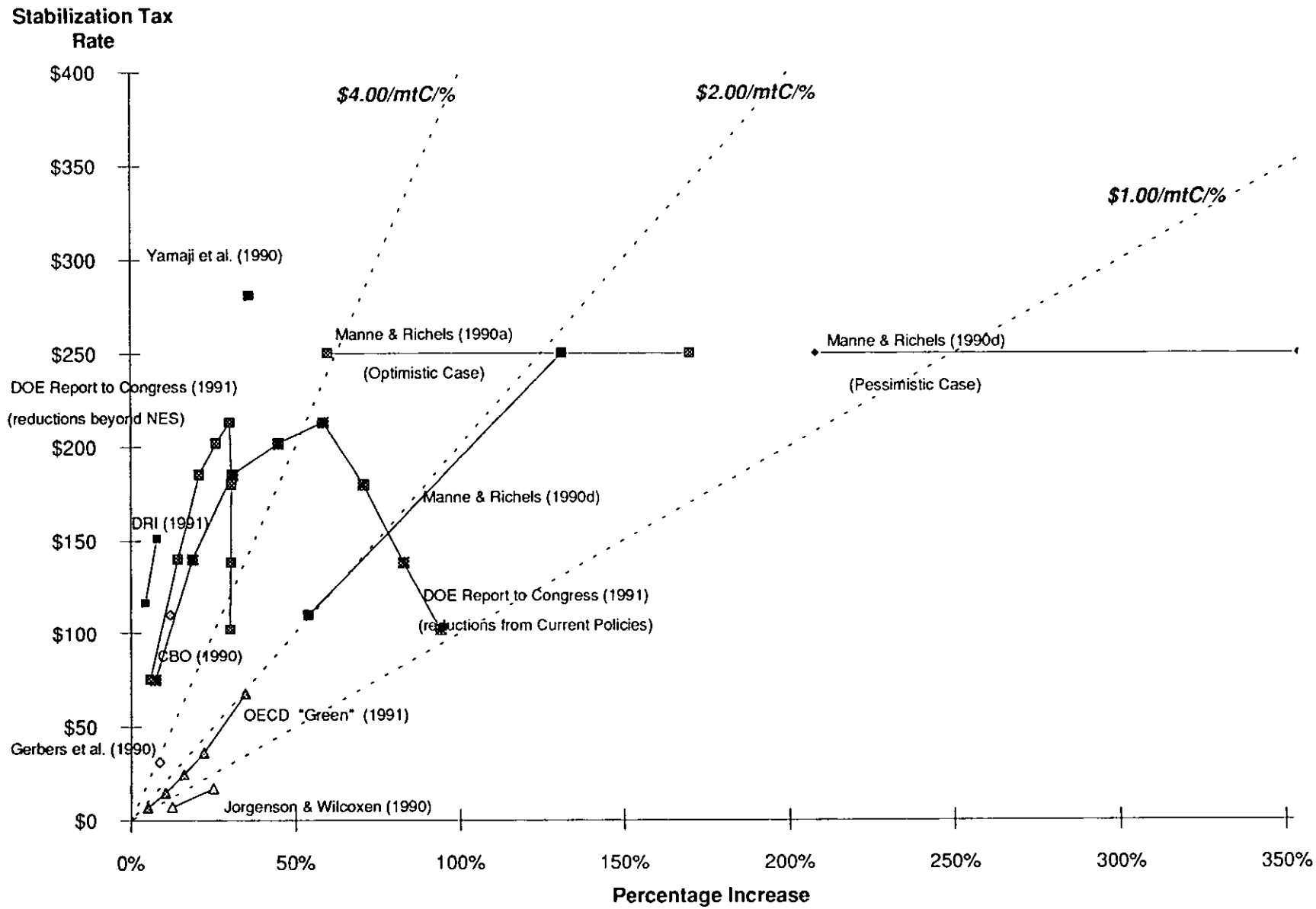


Figure 11.3. Stabilization Tax Rate vs. % Increase in Reference Case Carbon Emissions Relative to Target

APPENDIXES A-I

APPENDIXES A-I

Due to their size, these appendixes are not included in this document. They are available from the U.S. Department of Energy, Washington, D.C.

APPENDIX J

COMPUTATION OF COSTS AS LOSS IN GNP

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To demonstrate the computation of GNP loss, we construct the following simple representation of an energy-economy interaction. Assume that GNP is the only output of the economy and is produced using energy and labor. There are two kinds of interchangeable energy, renewable and fossil fuels. Each of these is produced using only labor. Labor is always fully employed and CO_2 emissions are a linear function of fossil fuel production.

The model, depicted in Figure J.1, is the essential "two-sector" model. Its equations are:

$$Y = F(Ly,E) \qquad \text{The GNP Equation} \qquad (1)$$

where Y = GNP, F is a production function satisfying the usual neoclassical regularity conditions, Ly is the amount of labor employed in the direct production of GNP, and E is total energy usage;

$$E = R + FF \qquad \text{Energy Equations} \qquad (2)$$

where R is renewable energy production, and FF is fossil fuel energy production;

$$R = R(Lr) \qquad (3)$$
$$FF = FF(Lf) \qquad (4)$$

where Lr is the amount of labor employed in the production of renewable energy and Lf is the amount of labor employed in the production of fossil fuel energy;

$$L^* = Ly + Lr + Lf \qquad (5)$$

where L^* is the fully employed labor force; and

$$CO2 = \alpha FF, \qquad (6)$$

where α is the fossil fuel CO_2 emission coefficient.

In a competitive equilibrium, the cost of producing energy must be identical for fossil fuels and renewable energy sources, as they are assumed to be perfect substitutes for each other. That is,

$$Pe = MPEy = Pr = Pff + \alpha \cdot tax, \qquad (7)$$

where MPEy is the marginal product of energy in the production of energy, $\partial F(Ly,E)/\partial E$, Pr is the supply price of renewable energy, and Pff is the supply price of fossil fuel energy.

Furthermore, labor is paid the value of its marginal product. The wage rate, in terms of GNP, then is equal to w, and

$$w = MPLy = Pe \cdot MPLr = (Pe - \alpha \cdot tax) \cdot MPLf, \tag{8}$$

where MPL is the marginal product of labor in the production of GNP, renewable energy (r), and fossil energy (f), that is $MPLy = \partial F(Ly,E)/\partial Ly$; tax is the carbon tax rate, and Pe is the price of energy.

By rearranging Equation (8), we can see that the carbon tax rate must be

$$tax = (MPEy - MPLy/MPLf)/\alpha. \tag{9}$$

The schedule mapped out by $MPEy/\alpha$ is the marginal product of CO_2; that is, it is the increase in GNP that would be obtained if fossil fuels equivalent to one additional tonne of carbon were available to produce GNP. It is the "demand schedule" for carbon. The schedule mapped out by $MPLy/(MPLf \cdot \alpha)$ can be interpreted as the marginal cost of CO_2. It is the amount of GNP that would have to be given up to obtain the additional resources, in this case labor, to produce additional fossil fuel energy sufficient to generate one additional tonne of carbon. In the absence of a tax, the economy produces GNP at the point where the marginal product of carbon, $MPEy/\alpha$, just equals the marginal cost of a tonne of carbon, $MPLy/(MPLf \cdot \alpha)$. This rate of emission maximizes GNP. Increasing carbon emissions further reduces GNP because the increase in GNP from the presence of the additional fossil fuel is less than the GNP loss when labor is shifted from the direct production of GNP to produce the additional fossil fuels.

In addition, it is worth noting that the tax rate is equal to the rate of change in GNP per additional tonne of carbon used; that is, it is the net value marginal product of carbon to the economy. If we define CO_2^* as the tax free rate of carbon emission and CO_2^t as the rate of emission under a tax case, then the total decline in GNP can be calculated as,

$$\text{GNP loss} = \int_{CO_2^t}^{CO_2^*} (MPEy - MPLy/MPLf)/\alpha \, dCO_2. \tag{10}$$

Note that the assumption of competitive equilibrium implies that GNP loss evaluated at $CO_2^* = 0$. This is an important condition because it implies that the initial, non-taxed condition of the economy is, from the perspective of GNP, a maximum, given the resources available to the economy. If the institutional setting remains in effect, this is in fact the case; that is, despite the fact that there may be individual technologies that could be introduced at lower cost than those actually adopted in the reference scenario, the failure to adopt these technologies represents either the existence of some adjustment costs, localized deviation from average conditions, or an artifact of the preceding history of energy prices, policies and expectations.

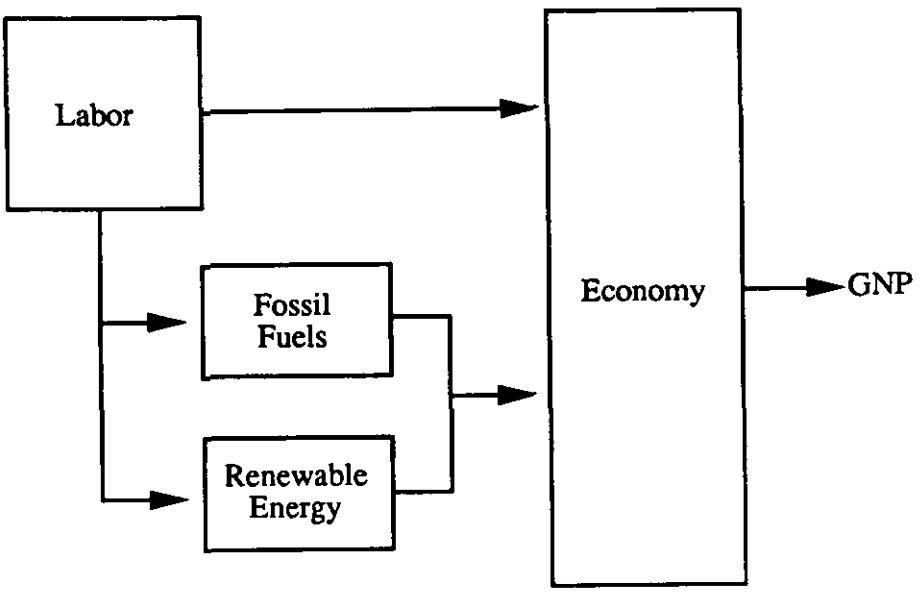

Figure J.1. A Reduced Form Energy-Economy Model

APPENDIX K

COMPUTATION OF COSTS OF REFORESTATION

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COMPUTATION OF COSTS OF REFORESTATION

The marginal cost schedule for carbon emissions reduction is a set of combinations of marginal cost (tax rate) and emissions reductions. Whereas in the analysis of the carbon tax case, the marginal cost schedule was constructed by setting a carbon tax and holding it constant throughout the course of the analysis, the marginal cost schedule for carbon emissions reductions can be computed as the set of points

$$C(T_i,t), \quad T_i, i=1,...t.$$

where C is the carbon emission reduction from the price effect for marginal cost T_i in period t. It is critical to also specify the carbon emissions fees charged in periods prior to period t.

Consider a Reforestation Case that exhibits the following marginal cost of carbon emissions reduction, expressed in terms of dollars per metric tonne of carbon, in each of the eight forecast periods as follows:

Forecast Year	Marginal Cost
1995	T1
2000	T2
2005	T3
2010	T4
2015	T5
2020	T6
2025	T7
2030	T8

In the first period, the marginal cost of carbon emissions was T1, and since no taxes were imposed in the previous period, 1990, that prior history can be taken as given for all cases.

In the second period, 2000, the existence of a specific tax rate having been applied in that year makes a difference. If the tax rate in period 2 were also T1, then this would be a point on the conventional marginal cost schedule constructed by putting in place a fixed tax rate and maintaining it constant throughout the analysis. But if the tax rate is higher, then the fact that the prior period tax rate was lower results in less carbon emissions reduction than would have been the case had the tax rate T2 been imposed in the prior period.

The reason that emissions reductions are less is that Fossil2 has a memory. It made investment decisions in the year 1995 on the basis of a set of tax rates T1. The capital stocks in existence at the beginning of period 2 are therefore more carbon intensive than they would have been had a higher tax rate been in effect in period 1. This is shown graphically in Figure K.1.

In Figure K.1 a long-run and short-run marginal cost schedule are depicted. The long-run marginal cost schedule for period 2, LRMC(2,C), is constructed by examining carbon emissions reductions associated with a tax rate that goes into effect in the first period and remains in effect throughout the course of the analysis. The short-run marginal cost schedule for period 2, SRMC(2,T1,C), is derived by relating carbon emissions reductions in period 2, with different tax rates in period 2, on the condition that tax rate T1 was in effect in period 1. The short-run marginal cost schedule is less elastic than the long-run marginal cost schedule for the reasons given above, that capital investments made in period 1 were undertaken with a lower carbon cost than in the second period, and therefore the existing capital stock at the beginning of period 2 is more carbon intensive than it would have been had a higher tax rate been in effect in period 1.

As discussed in Chapter 6, the long-run total cost schedule is derived by integrating over carbon emissions reductions under the condition that LRTC(t,C) is zero if carbon emissions reductions, C, are zero, i.e.

$$LRTC(t,C) = \int_0^C LRMC(t,C)\, dC, \text{ and}$$

$$LRTC(t,0) = 0.$$

Total cost for emissions reductions given that a tax rate of T1 was imposed in period 1 is computed similarly, except that SRTC(t,T1,C) is equal to the LRTC(t,C) when the carbon emission reduction, C, is that obtained for a tax of T1 in both periods one and two, that is

$$SRTC(t,C) = \int_0^C SRMC(t,C)\, dC, \text{ and}$$

$$SRTC(t,T1,C(T1)) = LRTC(t,C(T1)).$$

In Figure K.1, the total cost of an emission reduction obtained from the sequence of taxes, T1 in period one and T2 in period 2, can be obtained by computing the area under the LRMC(2,C) between 0 and C_A, together with the area under SRMC(2,T1,C) between C_A and C_B. This approach can be generalized for multiple periods and multiple taxes.

We can construct a set of marginal cost schedules as follows. Begin with the relationship between a carbon tax, T, and carbon emissions reductions, C, in the period t, given a history of prior period tax rates which are associated with the parameter r such that,

$$T = T_i \text{ in period } i,\ i<r,\ r\leq t,$$
$$T = T_r \text{ in period } i,\ i\geq r,\ r\leq t,$$
$$T = 0 \text{ in period } 0.$$

Carbon emissions reductions relative to a reference case may thus be expressed as,

$$C = C(t,r,T).$$

when $r=1$, the carbon emissions reductions are those obtained from the long-run marginal cost schedule.

We will assume that for r and t fixed, the relationship between T and C is one-to-one, so that we may compute

$$MC(t,r,C) = C^{-1}(t,r,T).$$

The total cost of carbon emissions reductions of $C(t,t,T_t)$ is given by

$$TC(t,C(t,t,T_t)) = \sum_{r=1}^{t} TC(t,r,C(t,r,T_r))$$

where

$$TC(t,r,C(t,r,T_r)) = \int_{C(t,r-1,T_{r-1})}^{C(t,r,T_r)} MC(t,r,C)\, dC$$

with

$$TC(t,C(t,r-1,T_{r-1})) = 0.$$

This analysis also suggests that an approximation to the total cost of the price component of the Reforestation Case can be obtained by constructing the following set of runs and assuming that the marginal cost schedules are linear between points. A carbon tax equivalent rate of levelized capital cost can be calculated for each of the fossil fuel-powered utility electricity-generating technologies corresponding to tax rates T1 through T8. Eight cases can then be run with this levelized charge rate varying by period. The levelized charge rates for each period are given for the eight cases in the table below:

Case	1995	2000	2005	2010	2015	2020	2025	2030
1	T1	T1	T1	T1	T1	T1	T1	T1
2	T1	T2	T2	T2	T2	T2	T2	T2
3	T1	T2	T3	T3	T3	T3	T3	T3
4	T1	T2	T3	T4	T4	T4	T4	T4
5	T1	T2	T3	T4	T5	T5	T5	T5
6	T1	T2	T3	T4	T5	T6	T6	T6
7	T1	T2	T3	T4	T5	T6	T7	T7
8	T1	T2	T3	T4	T5	T6	T7	T8

Define C(z,t) as the carbon emission reductions reduction for case z in period t. An approximation of total cost of fiscally induced emissions reductions in period t, TC(t), can be obtained by computing the following sums:

$$TC(t) = \begin{cases} 0.5 \cdot C(t,t) \cdot T_t & t=1; \\ 0.5 \cdot C(t,t) \cdot T_t + \sum_{z=1}^{t-1} C(z,t) \cdot T_{z+1} + T_z \cdot C(z+1,t), & t>1. \end{cases}$$

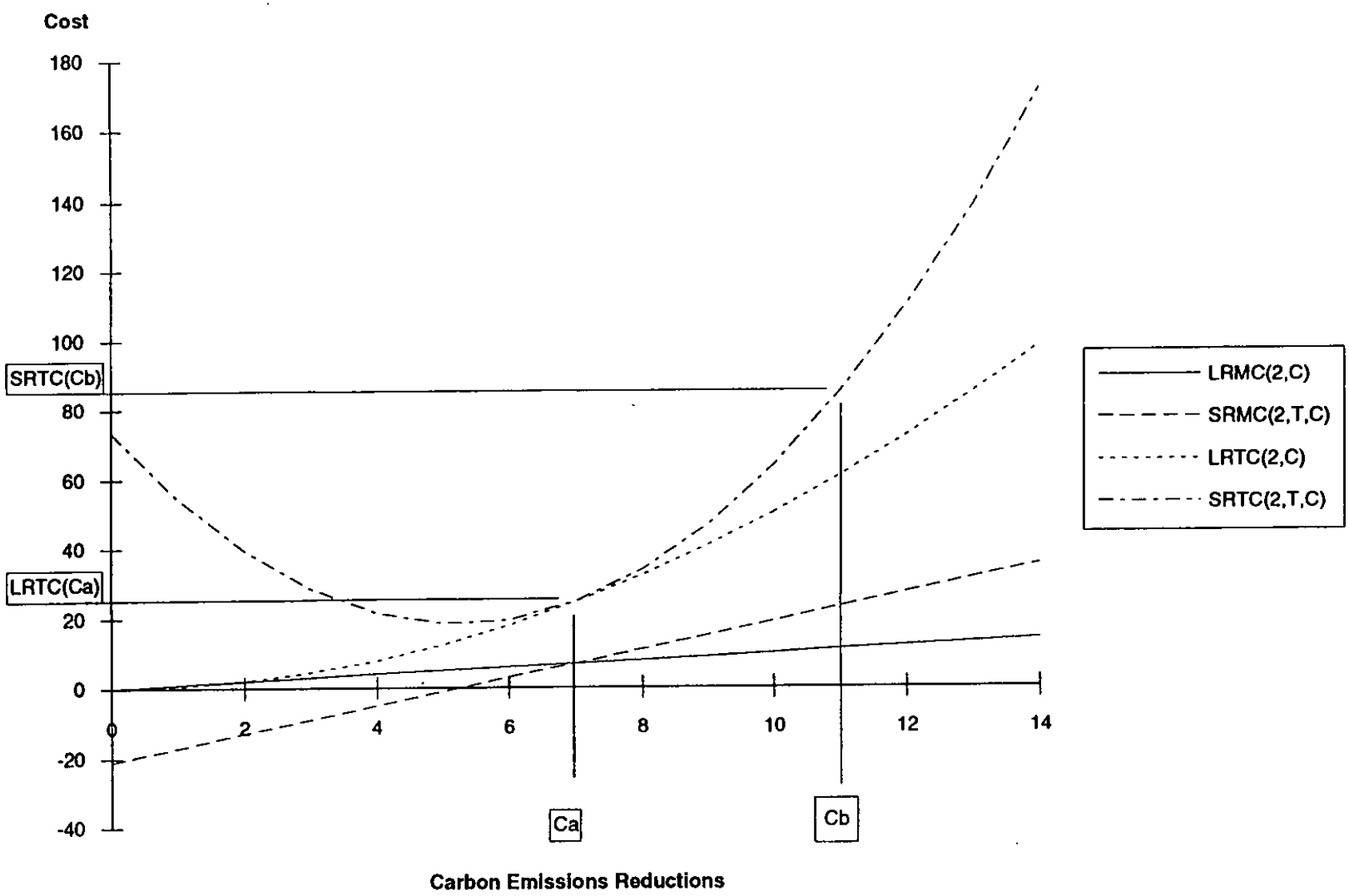

Figure K.1. The Relationship Between Short-Run and Long-Run Costs of Carbon Emissions Reduction

APPENDIX L

CONSTRUCTION OF THE BUILDINGS STANDARDS CASE

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CONSTRUCTION OF BUILDINGS STANDARDS CASE

The Buildings Standards Case for this study was constructed in two separate steps. First, Carbon Tax Cases of $250/mtC, $500/mtC, and $1000/mtC were constructed and run in conjunction with the NES Actions Case without imposing any buildings standards beyond the NES. For each of the end uses and fuel types, the resulting levels of investment in conservation were then recorded from these tax cases. These values are the marginal costs shown in the table below, which correspond to points on the NES conservation supply curves (DOE, 1991). In the second step, the marginal costs of investment in buildings conservation equipment that result from the carbon taxes become the standards. These buildings standards are modeled in Fossil2 by establishing them as floors or minimum levels in the conservation supply curves that consumers of energy-consuming equipment in buildings must meet. This investment is done at the costs taken directly from the conservation supply curves in the model. Note that in some instances, the standard for a particular end use does not increase with an increase in the tax rate. This implies that the level of investment inherent in the NES assumptions exceeds the level associated purely in economic terms with a carbon tax for reducing carbon emissions.

Table L.1. Buildings Standards: Values on the NES Conservation Supply Curves ($1989/mmBtu)

	Level 1 ($250/mtC)	Level 2 ($500/mtC)	Level 3 ($1000/mtC)
Residential Space Heat			
Oil	$117	$124	$182
Gas	$117	$117	$147
Coal	$96	$115	$198
Electric	$131	$178	$272
Solar	$117	$117	$151
Residential Space Cool	$131	$178	$272
Residential Thermal			
Oil	$67	$88	$129
Gas	$65	$77	$104
Electric	$93	$131	$201
Solar	$24	$33	$50
Residential Appliances	$38	$52	$79
Commercial Space Heat			
Oil	$117	$117	$133
Gas	$117	$117	$117
Coal	$96	$96	$147
Electric	$117	$127	$193
Solar	$117	$117	$117
Commercial Space Cool	$117	$127	$193
Commercial Thermal			
Oil	$33	$45	$68
Gas	$34	$41	$56
Electric	$50	$68	$104
Solar	$13	$17	$26
Commercial Appliances	$47	$64	$98

APPENDIX M

AUTHORS

APPENDIX M

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CHAPTER 5: PRESENT POLICIES AND NES ACTIONS
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CHAPTER 6: FISCAL INSTRUMENTS
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CHAPTER 7: REGULATORY INSTRUMENTS
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CHAPTER 8: COMBINED STRATEGIES AND INSTRUMENTS
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CHAPTER 9: MACROECONOMIC IMPACTS
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CHAPTER 10: CARBON TAXATION AND INTERNATIONAL TRADE
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CHAPTER 11: A COMPARISON TO OTHER STUDIES
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