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Report to the Congress of the United States

Limiting Net Greenhouse Gas Emissions in the United States

Volume I

Energy Technologies

Editors:
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September 1991

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

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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 I.

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).

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

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

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 \$30/mtC_e and \$40/mtC_e and would cost between \$6 billion and \$13 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 \$150/mtC_e and \$500/mtC_e and would cost between \$55 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

$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 ($/mtCO_2e$) of reductions from all nine scenarios that go beyond the NES Actions. (Note the change in units of measure from mtC_e to $mtCO_2e$. 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 supply options on-line, particularly new renewable energy technologies and a second generation of nuclear facilities. The first new reactors, for example, will 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.

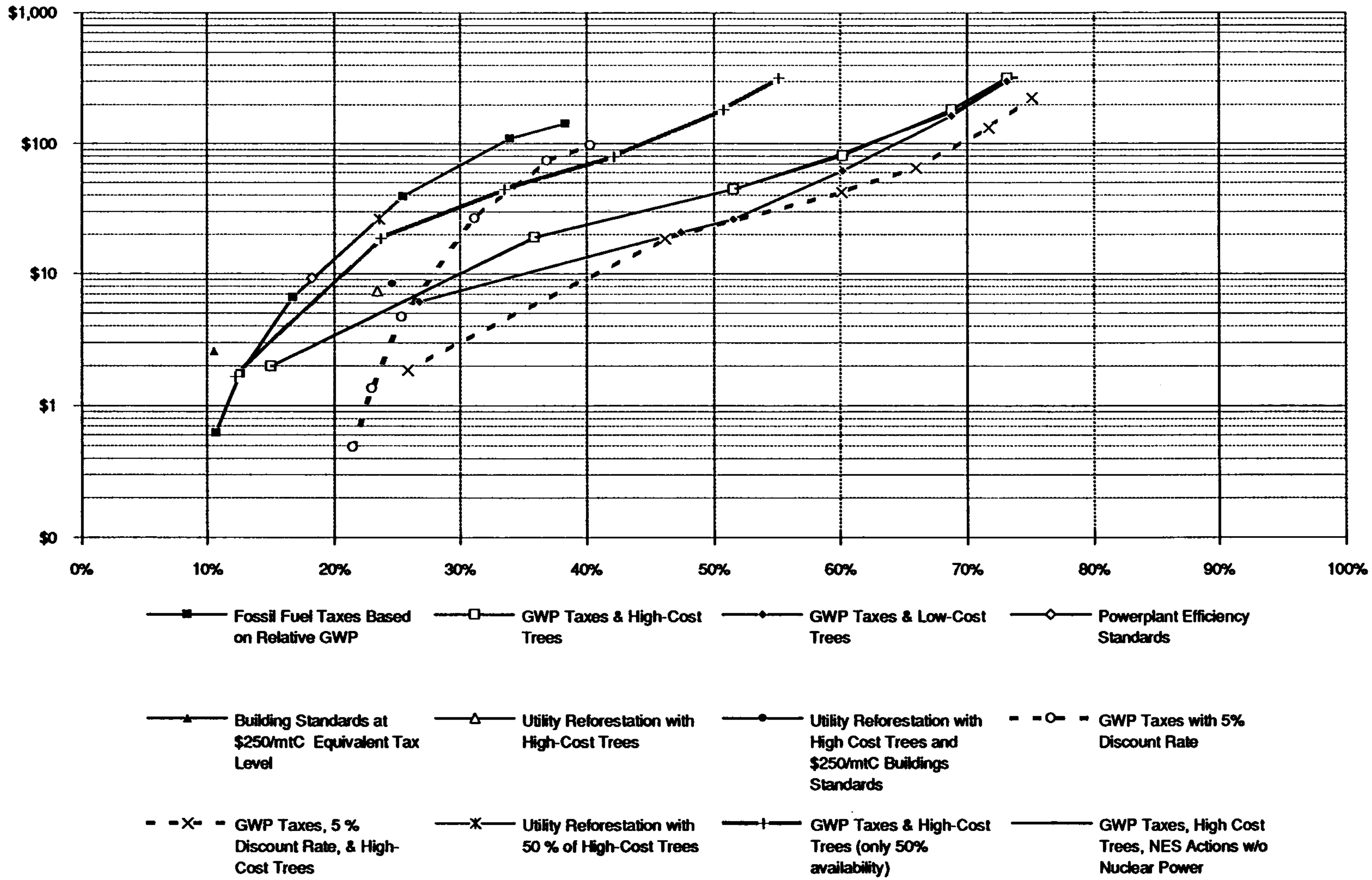

Figure ES.1. Total Cost (billions of 1989$) in the Year 2000 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

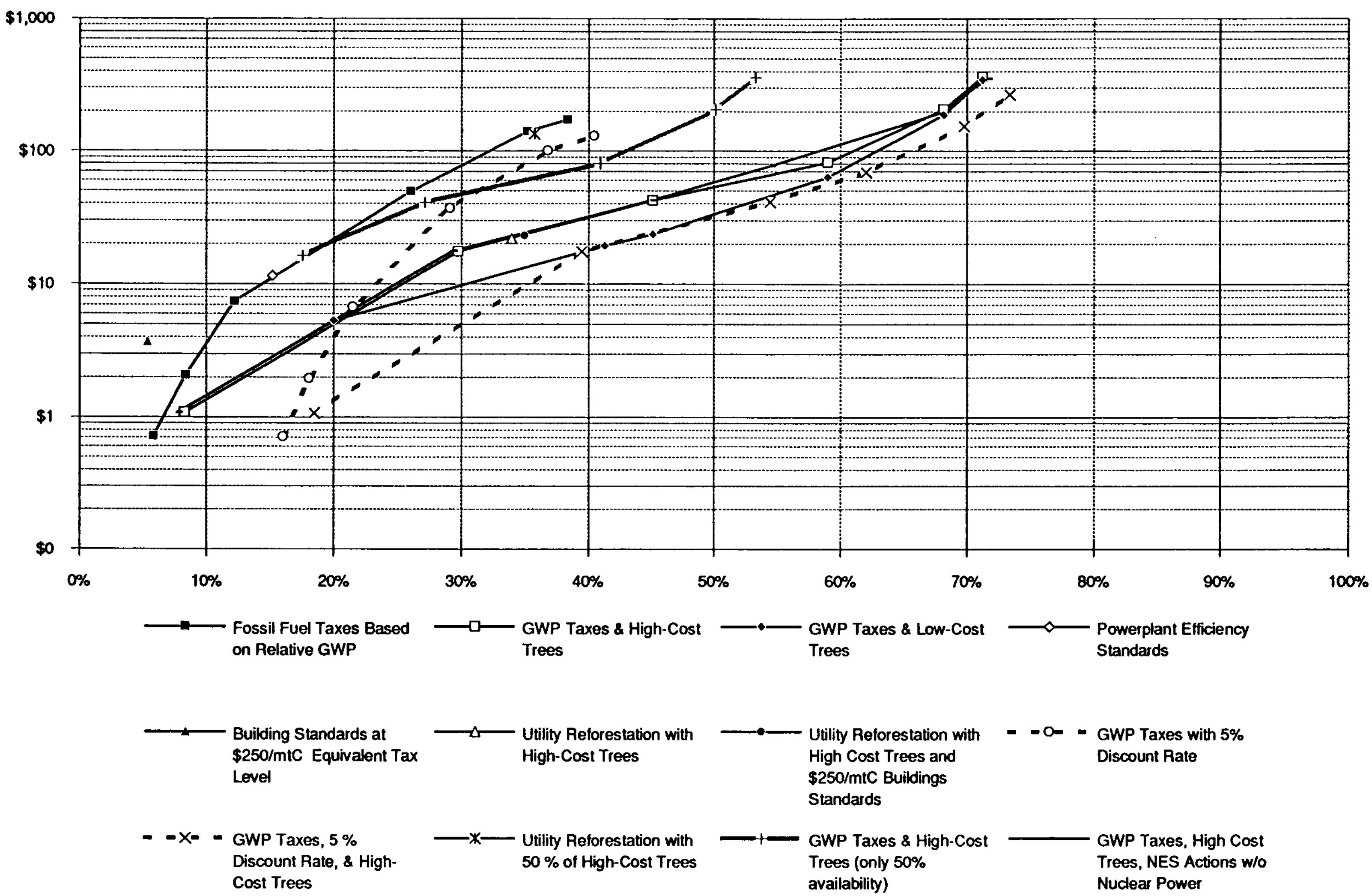

Figure ES.2. Total Cost (billions of 1989$) in the Year 2010 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

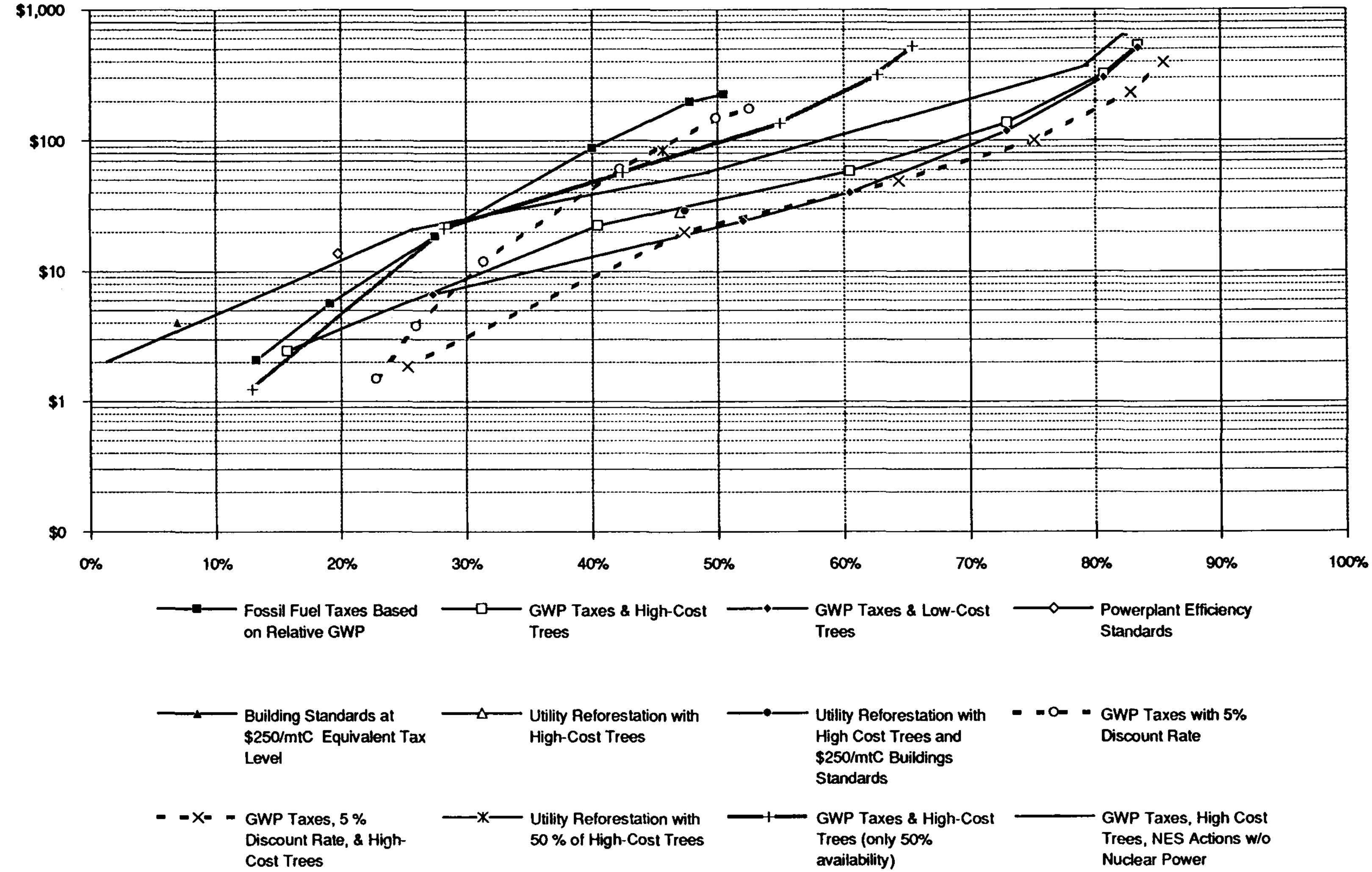

Figure ES.3. Total Cost (billions of 1989$) in the Year 2030 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

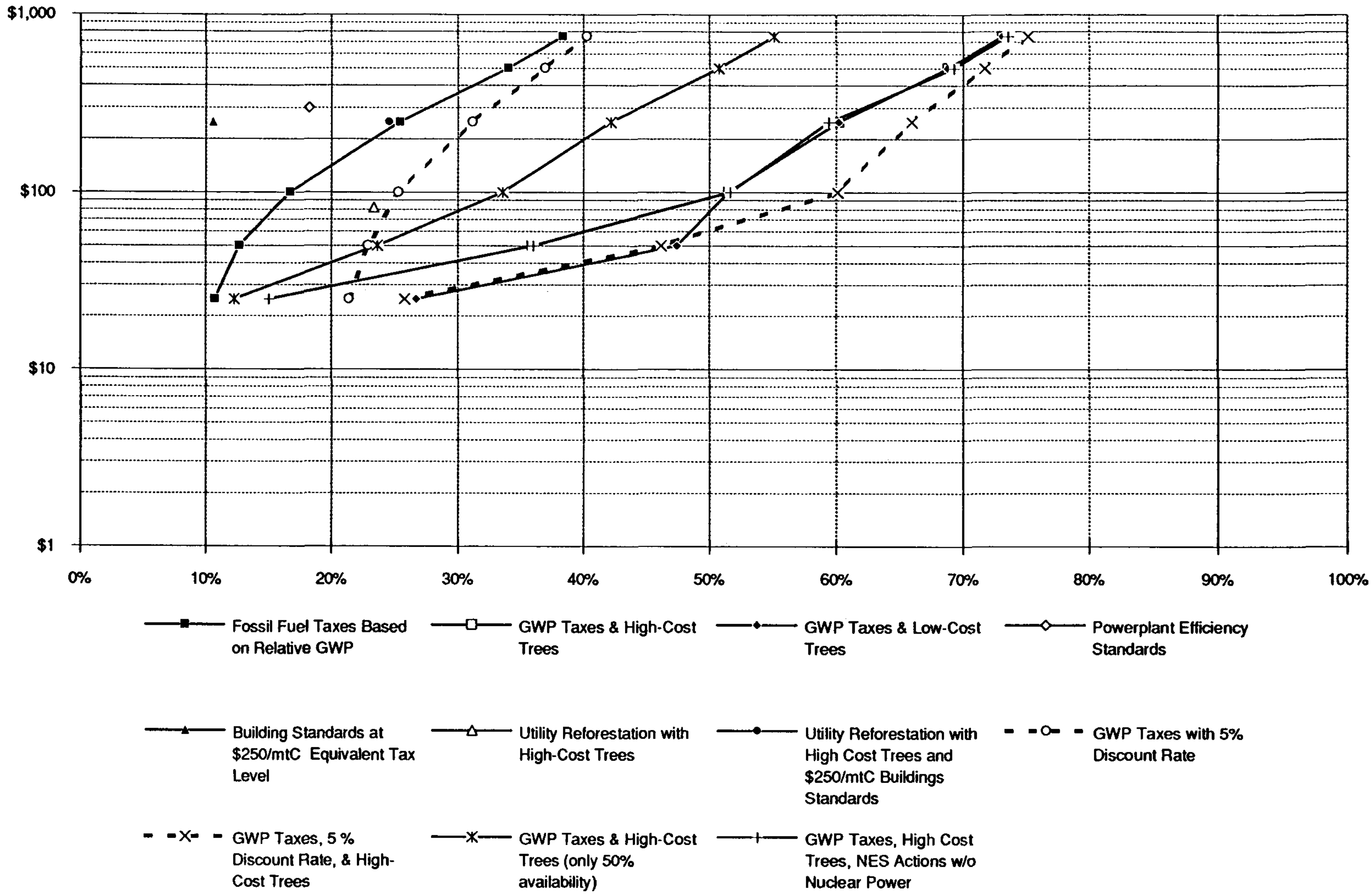

Figure ES.4. Marginal Cost ($\$/mtC_e$) in the Year 2000 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

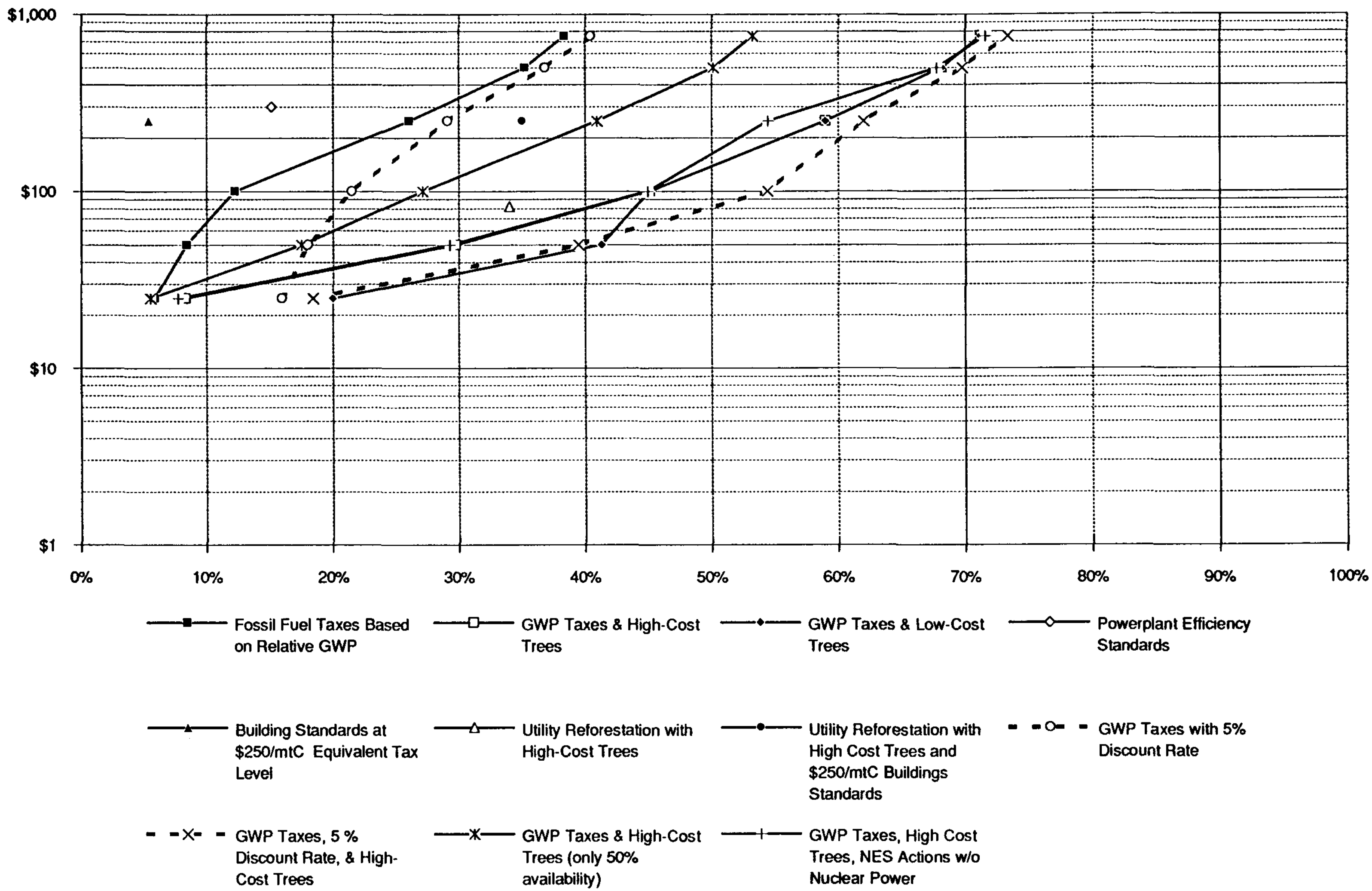

Figure ES.5. Marginal Cost ($\$/mtC_e$) in the Year 2010 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

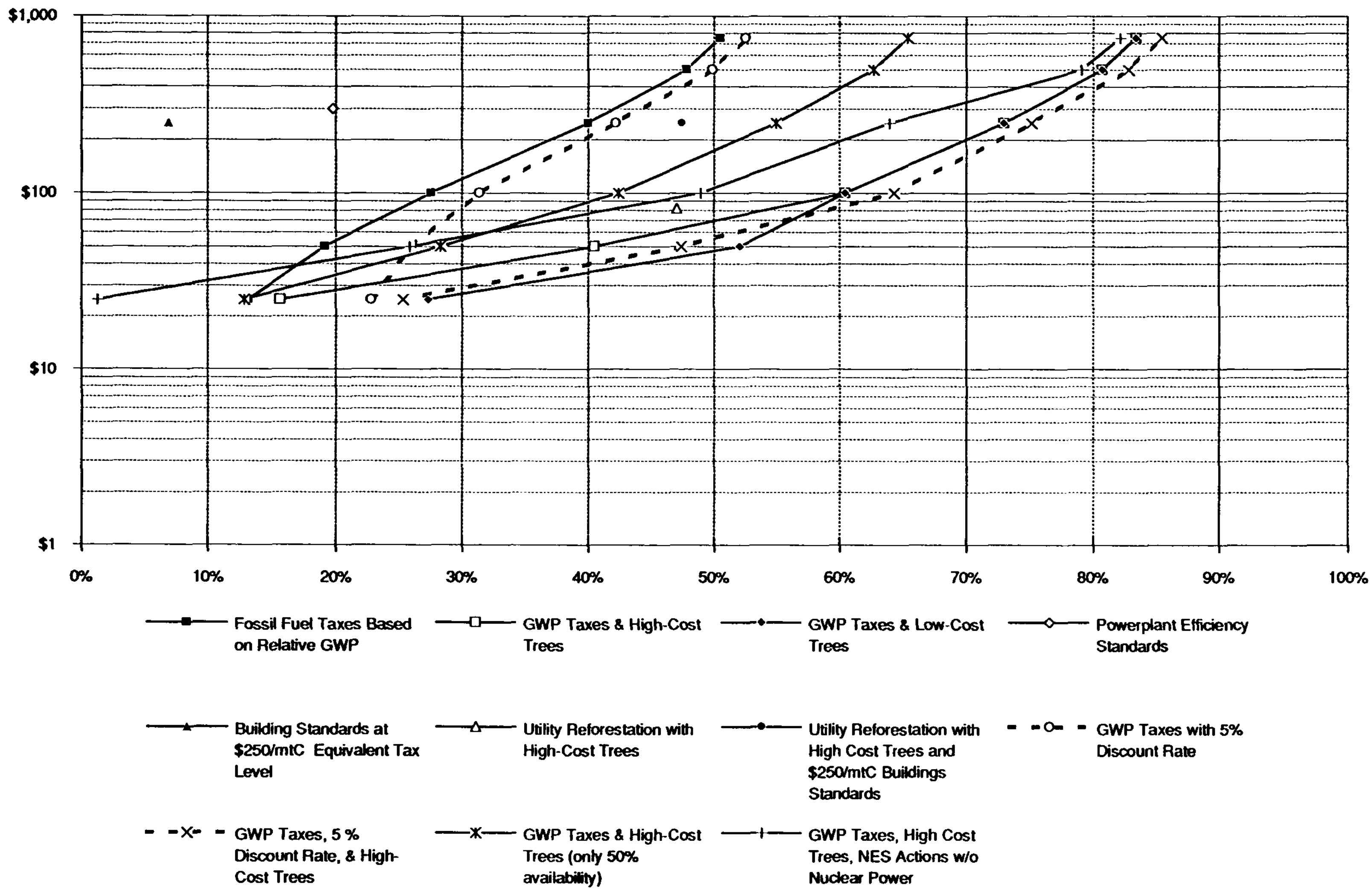

Figure ES.6. Marginal Cost ($/mtC$_e$) in the Year 2030 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

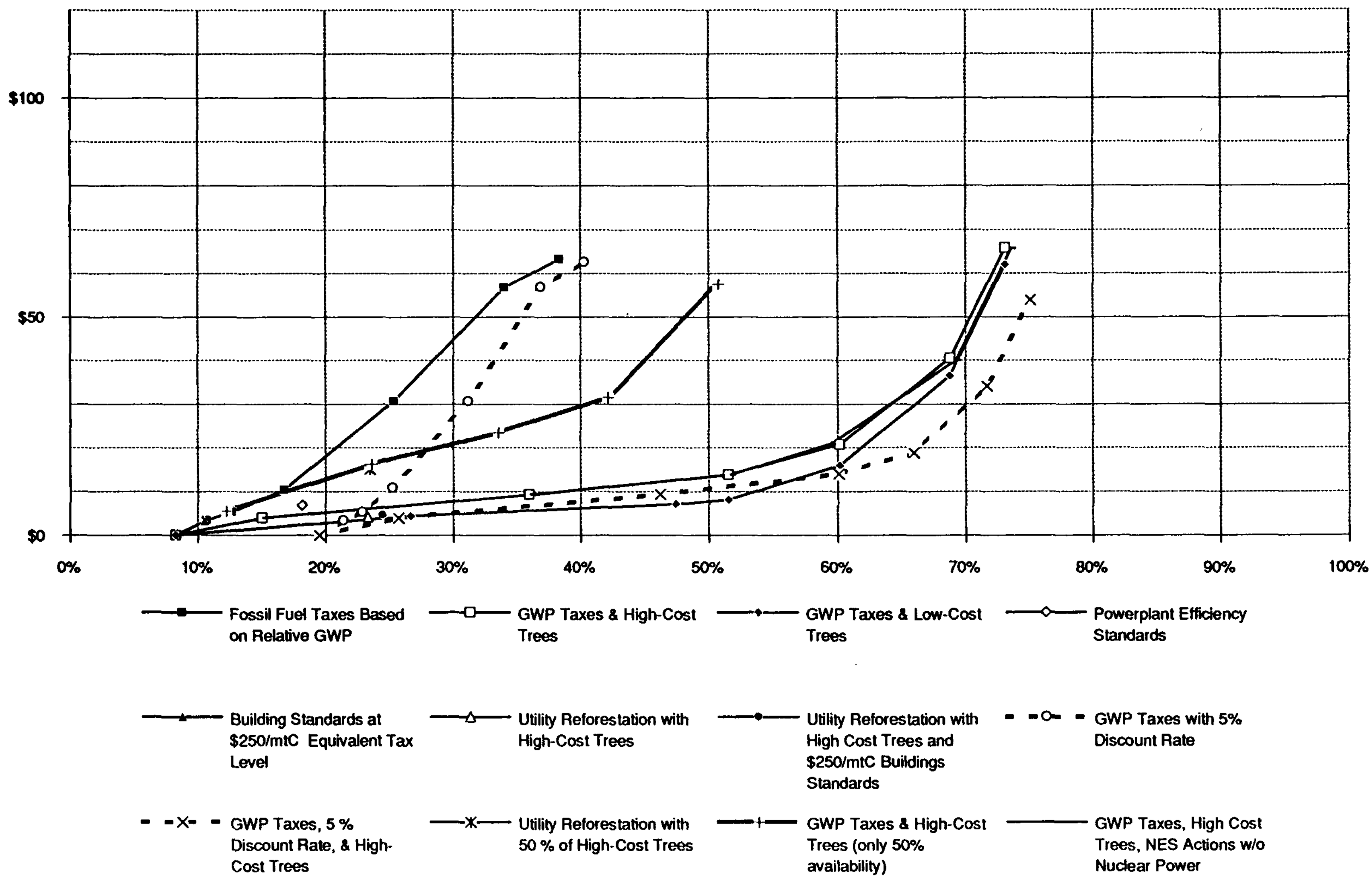

Figure ES.7. Average Cost ($\$/mtCO_2e$) in the Year 2000 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

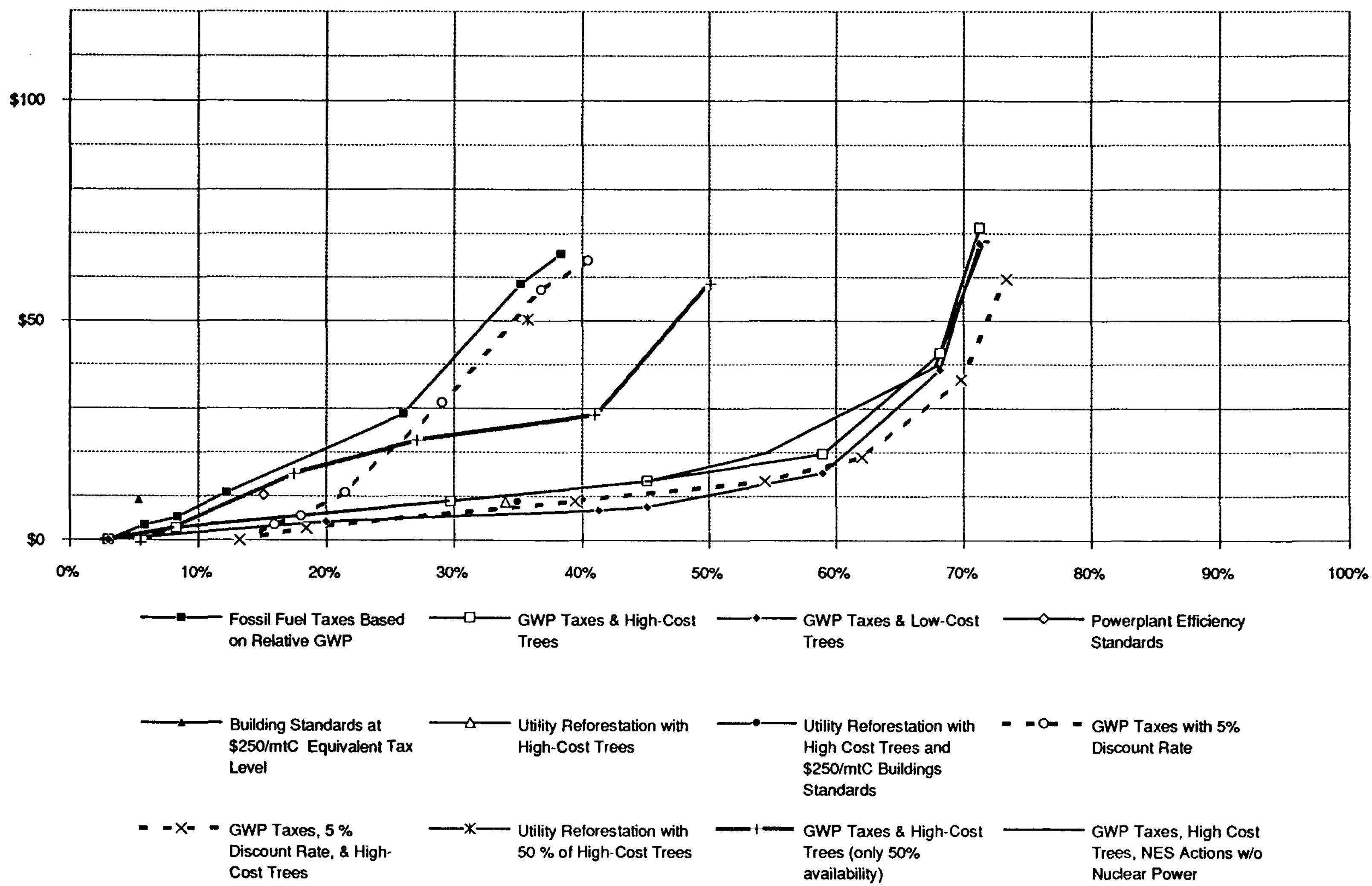

Figure ES.8. Average Cost ($/mtCO$_2$e) in the Year 2010 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

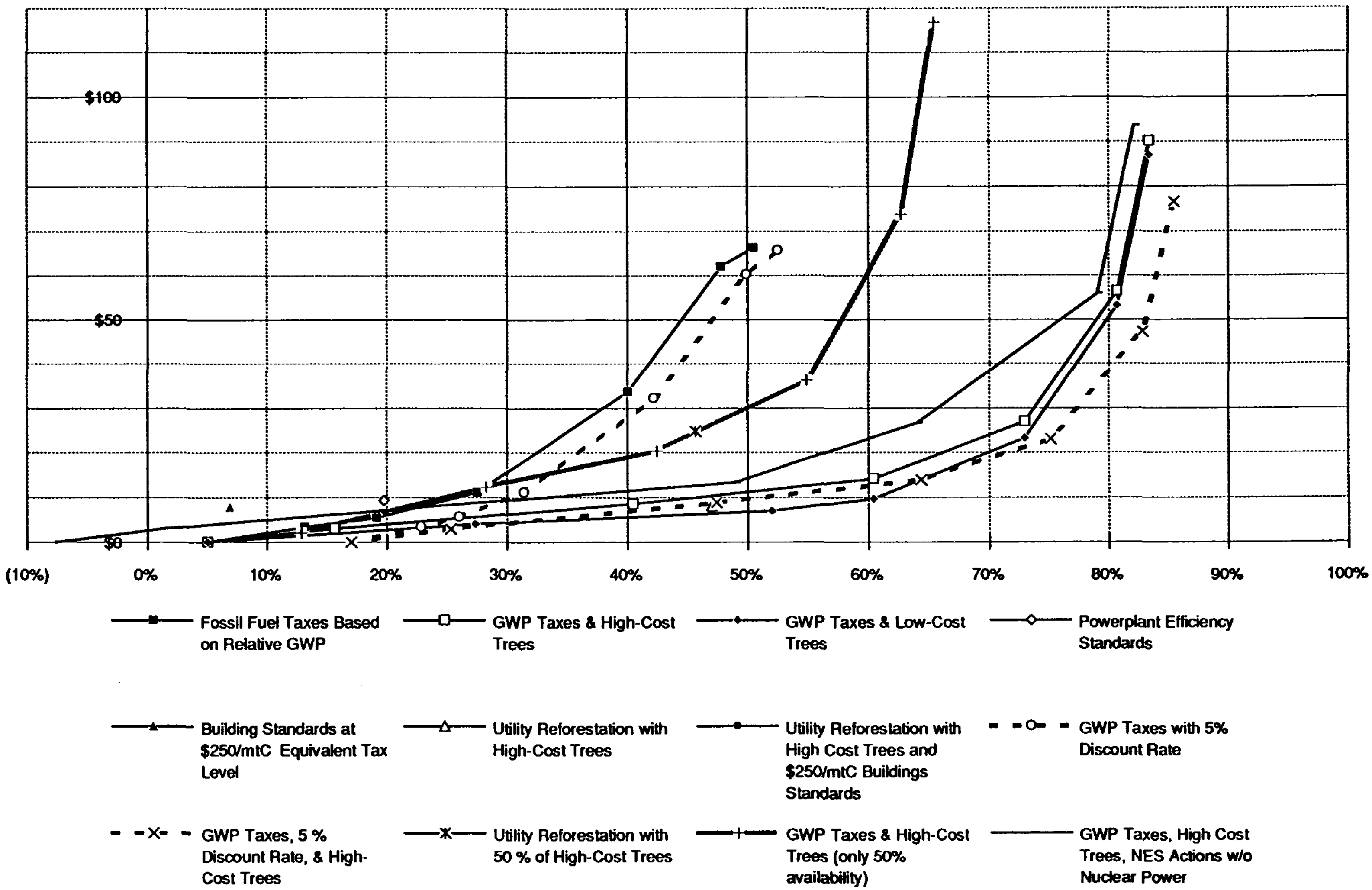

Figure ES.9. Average Cost ($/mt$CO_2$e) in the Year 2030 vs. % Carbon Equivalent Emissions Reductions Relative to 1990

LIST OF ACRONYMS

ABWR	advanced boiling water reactor
AC	alternating current
ACH	air changes per hour
AFBC	atmospheric fluidized-bed combustion
AFUE	annual fuel utilization efficiency
ALMR	advanced liquid metal reactor
ALWR	advanced light water reactor
APWR	advanced pressurized water reactor
ATES	aquifer thermal energy storage
atm	atmosphere
bbl	barrel
bsf	billion square feet
Btu	British thermal unit
BWR	boiling water reactor
°C	degrees Celsius
CAES	compressed air energy storage
CAFB	circulating atmospheric fluidized-bed
CAFE	corporate average fuel economy
CAPP	cost of avoided peak power
CCE	cost of conserved energy
CFCs	chlorofluorocarbons
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
CPH	conventional pumped hydroelectric
CRI	color rendering index
CSOM	customer side of the meter
CVT	continuously variable transmission
DC	direct current
DISC	direct-injection stratified-charge
DOE	U.S. Department of Energy
DOHC	double overhead camshaft
DOT	Department of Transportation
DRI	Data Resources, Inc.
EAF	electric arc furnace
E/GNP	total energy use divided by gross national product
ECPA	Electric Consumers Protection Act of 1986
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
GBR	gas-cooled breeder reactor
GJ	gigajoule
GNP	gross national product
GtC	gigatons of carbon
GW	gigawatt
GWe	gigawatt-electric
GWP	global warming potential
GWt	gigawatt-thermal
HFCs	hydrogenated fluorocarbons
HTGR	high-temperature gas reactors
HTS	high-temperature superconductor
HVAC	heating, ventilating, and air-conditioning
ICCT	Innovative Clean Coal Technology
IFR	Integral Fast Reactor
IGCC	integrated gasification combined cycle
IPCC	International Panel on Climate Change
ISTIG	intercooled steam-injected gas turbine
kBtu	thousand Btu
kWh	kilowatt-hour
LHR	low heat rejection
LMFBR	liquid metal fast breeder reactor
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LWR	light water reactor
Maglev	magnetically levitated
mbd	million barrels per day
MBOE	million barrels of oil equivalent
mcf	thousand cubic feet
MCFC	molten carbonated fuel cell
MHD	magnetohydrodynamic
MHTGR	modular high-temperature gas-cooled reactor
MMBtu	million Btu
mpg	miles per gallon
MRS	monitored retrievable storage
MTBE	methyl tertiary butyl ether
mtC	metric tonnes of carbon
MWe	megawatt-electric
MWh	megawatt hour
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 material
PEAR	Program for Energy Analysis of Residences
PEM	proton exchange membrane
PFBC	pressurized fluidized-bed combustion/combustor
PIUS	process-inherent ultimately-safe (reactor)
ppm	parts per million
PRISM	power reactor inherently safe module
psi	pounds per square inch
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
TES	thermal energy storage
TMP	thermomechanical pulping
TVA	Tennessee Valley Authority
UPH	underground pumped hydroelectric

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

CONTENTS

FIGURES

TABLES

1.0 ENERGY AND ENVIRONMENTAL TECHNOLOGY TO REDUCE GREENHOUSE GAS EMISSIONS

A wide range of human activities--including agriculture, land development, industrial materials production and energy use--is responsible for large quantities of greenhouse gas emissions to the atmosphere. Because of their high magnitude, energy-related emissions are the most significant anthropogenic source of these releases and are of fundamental importance in efforts to reduce total emission growth.

Volume I of *Limiting Net Greenhouse Gas Emissions in the United States* examines emissions from energy-related sources and the role of technology in both producing and mitigating the release of greenhouse gases. An essential component of actions to reduce these emissions is fundamental changes in the way energy is used in the U.S. economy and, therefore, introduction of new energy and environmental technologies into the marketplace. The purpose of the volume is to describe the main technological opportunities that hold the potential for cost-effective emissions reductions within the next 20 to 30 years.[a]

1.1 INTRODUCTION TO VOLUME I

The material presented in Volume I characterizes the current and projected state of the art for most energy technologies that can reduce greenhouse gas emissions and provides some quantitative estimates to supplement the policy analysis presented in Volume II. The technology characterizations in this volume emphasize technical performance, cost and development status; a separate analysis of the potential for selected technologies to penetrate energy markets and reduce emissions under various policy scenarios is contained in Volume II. In addition, Volume I discusses the important area of modifications to energy demand, which provides sizable potential to restructure energy use and cut emissions.

Chapter 1 provides an overview of the energy and environmental technologies addressed in the remainder of the volume. The key features of major technologies are summarized here. The material contained in the overview is discussed in greater detail in later chapters, as shown below:

Chapter 2	Fossil Energy Technology
Chapter 3	Nuclear Energy Technology
Chapter 4	Renewable Energy Technology
Chapter 5	Energy Storage, Transmission, and Distribution Technology
Chapter 6	Transportation Technology
Chapter 7	Industrial Technology
Chapter 8	Residential and Commercial Buildings Technology
Chapter 9	Greenhouse Gas Removal Technology
Chapter 10	Approaches to Restructuring the Demand for Energy.

Not all of the energy technologies relevant to greenhouse gas emissions reductions are included in this chapter or the volume; the principal technologies currently anticipated to have important emissions reduction potential in the study time frame are discussed. In addition, some advanced technologies now projected to be available beyond this study's horizon are mentioned because of their high potential importance to future emission reduction and their prominent role in current research and development programs.

1.2 ENERGY-RELATED SOURCES OF GREENHOUSE GAS EMISSIONS

Energy-related greenhouse gas emissions arise principally from use of fossil fuels throughout the

(a) For purposes of this discussion, "technology" is defined to include equipment, processes, design, information systems, and management and control systems.

full cycle from primary fuel production to end use. The levels of U.S. energy use and corresponding CO_2 emissions in 1990 are shown in Table 1.1 for the power generation and principal end-use sectors. About 86 quads of energy was consumed and 1299 TgC of carbon dioxide (in carbon weight) was

Table 1.1. U.S. Energy Use and Carbon Emissions, 1990[(a)]

Fuel Use (quadrillion Btu)

	Utilities	Transportation	Industry	Residential Buildings	Commercial Buildings	Total[(b)]
Oil	1.7	21.6	8.7	1.6	1.0	34.6
Coal	16.5[(c)]	--	2.8	0.1	0.1	19.5
Gas	2.7	0.7	8.2	4.9	2.8	19.3
Nuclear	5.9	--	--	--	--	5.9
Renewable[(d)]	3.9	0.1	1.8	0.9	0.1	6.8
Total	30.7	22.4	21.5	7.5	4.0	86.1

Carbon Emissions (Teragrams of Carbon)[(e,f,g)]

	Utilities	Transportation[(h)]	Industry[(i)]	Residential Buildings	Commercial Buildings	Total[(b)]
Oil	36	373	89	31	19	548
Coal	400[(c)]	--	72	2	2	477
Gas	61	10	100	65	37	274
Renewable[(i)]	2	--	--	--	--	2
Total	499	383	261	98	58	1299

(a) The values given are based on DOE estimates and are consistent with those used for both the National Energy Strategy analysis and the second volume of this study. For more recently updated 1990 values see, *National Energy Strategy: Technical Annex 2. Integrated Analysis Supporting the National Energy Strategy Methodology, Assumptions, and Results.*

(b) Totals may not sum due to independent rounding.

(c) Value includes about 0.1 quad of coal that was converted to synthetic gas, with corresponding emissions of about 4 TgC.

(d) Renewable energy includes hydroelectric power, biomass-derived fuels, solar energy, and geothermal energy.

(e) Carbon emissions have been computed with standard carbon-to-fuel ratios for each fossil fuel. Average coefficients are as follows: Coal - 25.42 TgC/quad; oil - 20.98 TgC/quad; gas - 14.55 TgC/quad. One teragram is equal to one million metric tonnes.

(f) No net carbon emissions are assumed for biomass fuels.

(g) Carbon emissions, as reported in this study, refer to carbon dioxide and carbon monoxide emissions stated by weight of carbon.

(h) A smaller carbon emissions coefficient of 14.7 TgC/quad is used for motor gasoline.

(i) Industrial fuel use totals include non-energy and feedstock consumption, for which no carbon emissions are generated.

(j) Renewable emissions are for geothermal electricity production.

produced. These data also indicate key differences among the sectors with regard to direct fuel emission sources. (Of course, if electricity emissions were allocated to end-use sectors, the fuel contributions for each sector in the table would change.) As shown, coal is responsible for most electric utilityCO_2 emissions (80%); oil is the primary source of transportation emissions (97%); and gas is the largest non-electricity source for industry (38%), residential buildings (66%), and commercial buildings (63%). A more detailed inventory of emission sources for all greenhouse gases appears in Volume II (Chapter 3) of this study.

To describe how new technologies can be used to alter current emission levels, this chapter uses a broad reference energy-cycle framework, both for identifying emission sources and describing the role of emissions-related technology. This perspective is adopted because the stages of the energy cycle are linked in important ways. When a significant action is taken to reduce emissions in one stage, impacts of that choice will frequently surface in other stages of the energy cycle as well.

The reference energy cycle is shown in Figure 1.1. The energy cycle represents the life history of energy as it is transformed from one form to another and ultimately used. The stages of the energy cycle include primary fuel extraction and preparation, conversion and processing to other forms, transmission and distribution, and final end-use. Several different pathways for energy flows among the four stages are illustrated to show that many sequences of intermediate steps between primary extraction and end use are possible considering the wide range of fuel/energy service combinations. This chapter uses this framework to summarize the technologies discussed in the remaining chapters.

As shown in Figure 1.1, fossil-fuel-related emissions can occur in all stages of the energy cycle. Changes in the use of a fuel can have repercussions throughout the cycle--for example, reducing coal use reduces greenhouse gas emissions that arise both from coal combustion and from coal mining. If another fuel is substituted for coal, the net emissions may increase or decrease depending on the characteristics of the substitute fuel. Table 1.2 indicates how emissions arise in each stage of the energy cycle. The stages and their associated emissions are described below.

1.2.1 Primary Fuel Extraction and Processing

Three types of naturally occurring fuels are available for energy applications: fossil fuels (coal, oil, natural gas), uranium, and renewable fuels. Renewable fuels include municipal wastes and

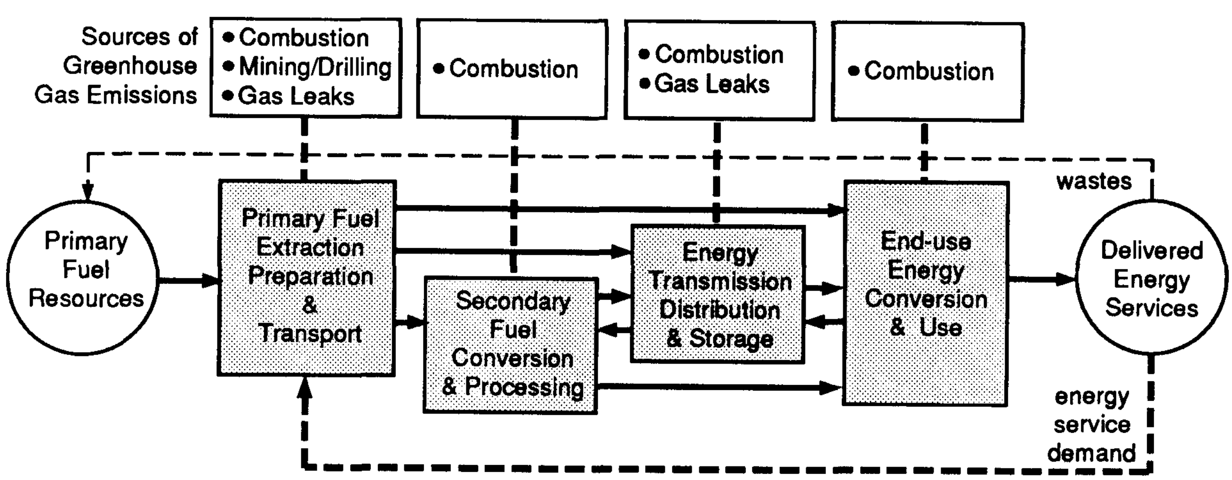

Figure 1.1. Reference Energy Cycle

Table 1.2. Direct Anthropogenic Sources of Greenhouse Gas Emissions[a]

	Energy (Fuel Cycle) Sources				Non-Energy Sources
Gas	Primary Production	Secondary Conversion	Energy Transfers	End-Use Consumption	Activity or Material
CO_2	combustion	boiler/engine combustion	combustion	boiler/engine/furnace combustion	deforestation, cement manufacturing
CH_4	coal mines gas wells	--	gas transfer	incomplete combustion (auto, wood)	landfills, animals, rice, slash & burn agriculture
CO	--	--	--	incomplete combustion (auto, wood)	deforestation, agriculture
N_2O	--	--	--	combustion[b]	soil cultivation, fertilizer production, slash & burn agriculture
CFCs	--	--	--	mobile refrigeration[c] A/C foams (insulation)	aerosols, foams, solvents

(a) Direct emissions sources are those that burn fuels or emit gases directly; indirect sources are those that affect loads on direct sources or otherwise cause them to emit (e.g., indirect source: electrical equipment; direct sources: fossil-fueled electricity generation plant).
(b) Because of the discovery that N_2O forms as an artifact of the measurement process, N_2O emissions from combustion are highly uncertain (Muzio and Kramlich 1987).
(c) While chlorofluorocarbons (CFCs) are emitted from the refrigeration working fluid itself, rather than as a result of using energy to circulate the fluid, refrigeration is often classified as an energy-related emission source. This convention is followed here.

biomass, as well as energy carriers such as sunlight and wind. Most primary fuels must be extracted from their original locations and processed for subsequent use. Activities in this stage of the energy cycle include all fuel preparation and processing operations that do not change the fuel form.

Some greenhouse gases are emitted during extraction operations. These emissions are primarily methane from coal mining and from oil and gas drilling. The level of fugitive methane emissions from a deep coal mine can be up to 1% of the coal weight, depending on factors such as coal volatility and mine depth and age; Fisher[a] estimates the emissions from coal mines to range from 0 to 0.82 million tonnes/quad of coal mined, with a mid-range estimate of 0.14 million tonnes/quad. Drilling emissions may result from well blowouts and from seal and valve leakage. Because natural gas is primarily methane, the most significant fugitive methane emissions are associated with gas drilling. Other sources of greenhouse gas emissions in

(a) Fisher, D. 1990. Draft report. Options for Reducing Greenhouse Gas Emissions. The Stockholm Environment Institute, Stockholm, Sweden.

the extraction process are small; they include combustion engines, compressors, and pumps.

Fuel processing operations also result in greenhouse gas emissions. Inventory data from the National Acid Precipitation Assessment Program (NAPAP) suggest that fugitive methane emissions from oil refining are greater than those from any other fuel production technology (see Chapter 2). These emissions result primarily from leaks in seals and valves. Fugitive methane emissions can also occur at gas processing plants, and carbon dioxide is released during production of shale oil from shale rock.

1.2.2 Secondary Fuel Conversion and Processing

In the end-use stage, primary fuels are converted into intermediate fuels and energy carriers (e.g., hydrogen, synfuels, and electricity). Some fuels, such as oil and natural gas, may be transferred directly from primary extraction and processing to end uses in applications, such as home furnaces and industrial boilers.

The secondary fuel conversion processes are some of the most significant sources of greenhouse gas emissions in the energy cycle, and fossil fuel combustion is the principal emission source. Fossil fuel combustion results in significant carbon dioxide emissions, as well as emissions of trace gases such as nitrous oxide. For the current U.S. fuel mix to generate electricity, approximately 2.2 pounds of carbon dioxide are released per net kWh of fossil electric generation, on average.

1.2.3 Energy Transmission, Distribution, and Storage

This stage includes all transmission, distribution, and storage activities necessary to transfer electricity or fuels from production to their points of end use and to store them at those locations. Emission sources at this stage include fugitive methane emissions from the transport and handling of petroleum products and from the large number of pipeline connections and valves used in transporting natural gas. One gas utility study estimated natural gas leakage from a new, well-maintained transmission and distribution system at 0.14% of throughput.[a] Losses from older systems could be much higher. The gas industry's current best estimate overall is that 1.2% of gas produced in the United States escapes from the gas transmission and distribution system (Burklin et al. 1991). Also, electricity transmission losses are an important indirect source of emissions in that they require that more energy be used to satisfy a given level of demand. Overall, emissions in this stage are generally low relative to those in other stages, but are not insignificant. Improvements in transfer efficiency can reduce energy use and energy-related emissions.

1.2.4 Energy End Use

Delivery of the services that energy carriers provide, such as heat for buildings and work from motors, occurs at an end-use point of application. End uses include combustion of gasoline to power automobiles, combustion of oil or gas to fuel building heating systems or industrial machinery, and use of electricity to run appliances or industrial processes. End users are generally divided into three sectors: buildings (residential, commercial, and industrial structures), industry, and transportation. These sectors provide a convenient way to organize and describe energy technologies, fuel use, and emissions.

In the end-use stage, most of the direct emissions are associated with the combustion of fossil fuels in engines, furnaces, and boilers. Some activities that are considered end uses are conducted in other stages of the energy cycle--for example, emissions from combustion to run mining equipment or pumped storage systems, or to power the trucks used to transport gasoline, would be considered end-use emissions. End uses also include indirect emission sources from consumption of secondary energy carriers such as electricity. These activities

(a) Fisher, D. 1990. Draft report. Options for Reducing Greenhouse Gas Emissions. The Stockholm Environment Institute, Stockholm, Sweden.

do not cause emissions directly, but are important as drivers of emissions from secondary conversion processes.

1.2.5 Delivered Energy Services

Figure 1.1 includes a final stage labeled "delivered energy services." Most energy demand is a "derived demand" in that it arises from consumer demands for goods and services requiring energy to produce. For example, final demand for goods in the economy creates the need for energy services (such as steam, process heat, or shaft power) as a factor of industrial production; these energy service demands in turn result in demand for electricity and combustion to drive machinery or create steam. Similarly, in the household sector, demands for warmth, comfort, or travel create the need for energy services in the form of space heating, space cooling, and mobility, which are served by electricity and stationary or mobile fuel combustion.

The concept of energy service demand provides a useful way to think about how particular energy demands affect emissions. When the demand for products changes, the type and levels of energy services (heat or work) also change. As a result, the corresponding energy consumption will change, and these energy demand adjustments will affect the type and level of greenhouse gas emissions.

1.3 STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS

The technologies described in Section 1.1 comprise the major energy-related sources of greenhouse gas emissions. As noted, the technologies may be direct emitters or may be indirectly responsible for emissions through factors associated with their use. Direct-emitting technologies include devices, such as combustion engines and furnaces, that burn fuel directly. Technologies that affect emissions indirectly include electricity-using equipment, which may be powered by electricity produced at a central fossil-fired power plant; electricity transmission and distribution equipment, which causes energy losses that must be made up by additional power generation; and factors such as automobile aerodynamics and weight that affect the load on an emitting source.

To understand the potential for reducing direct and indirect emissions, it is convenient to separate greenhouse gas releases into their more basic components. In broad terms, four factors determine the level of emissions resulting from use of a direct-emitting technology:[a]

$$\text{Emissions Level} = (\text{emissions/unit energy}) \times (1 - \text{emissions removal efficiency}) \times (\text{unit energy/unit service demand}) \times (\text{service demand level}) \quad (1.1)$$

This equation expresses the energy-related emissions produced from a particular activity or service demand in terms of factors that relate directly to the technologies used. These factors are the carbon content of the primary fuel (emissions/unit energy), the combination of technologies used to capture emissions before their release to the environment (1 - emissions removal efficiency), the efficiency of the processes for delivering energy to the point of use and conversion into the service demanded (unit energy/unit service demand), and the total level of service demanded (service demand level). Assuming these efficiencies and quantities are accurately known, the emission level for any energy-related activity can be calculated from Equation 1.1 above.

The terms in Equation 1.1 also indicate the basic strategies available for reducing the energy-related emissions. Referring to each term of the equation, the associated strategy for reducing its value is summarized below:

(a) The equation can also be used to calculate emissions from indirect emitters, although the values of the various factors actually represent the corresponding direct emitters used in supplying the energy needed.

- *Fuel Substitution* (reduce emissions/unit energy) - Non-fossil energy resources generally do not release carbon dioxide to the atmosphere, and even among fossil fuels, emission rates vary. This suggests lowering the "carbon-intensity" of fuels used to meet energy demands by substituting non-fossil or low-emission fossil fuels for high-emission fossil fuels where possible.

- *Direct Carbon Removal* (increase emissions removal efficiency) - Carbon can be extracted directly from the energy cycle to preclude its release to the atmosphere. Direct carbon removal is possible either by removing it from fuels prior to combustion or by "scrubbing" the emissions stream following combustion to capture carbon dioxide.

- *Energy Efficiency Improvements* (reduce unit energy/unit service demand) - The amount of primary energy required to provide a unit of end-use energy service can be reduced through use of more efficient energy conversion, transfer, and end-use technologies, thereby cutting total emission levels. This strategy, which is one component of "energy conservation," has potential value in both energy supply and demand applications.

- *End-Use Energy Service Demand Modification* (shift the level or type of energy service demanded) - Different mixes of demand for the final goods and services produced and consumed in the economy can lead to very different levels of energy-related greenhouse gas emissions. Changing the amount or composition of this final product demand, for example by structural shifts in economic activity from manufacturing to services, can significantly affect both the energy intensity of the economy and total greenhouse gas emissions.

The factors in Equation 1.1 (and therefore, the strategies above) are not completely independent of one another. Employing a strategy to reduce one of the factors can have either positive or negative effects on other factors. For instance, using a high-efficiency furnace to cut household energy use and emissions may also result in a higher energy service demand for household energy from consumers who turn up the thermostat, thereby reducing the gains from the efficiency improvement alone. Obviously, preferred options for implementing the strategies are those that produce a net reduction in emissions when all impacts are considered.

Although behavioral and institutional factors are also vitally important, each of these strategies can benefit greatly from use of both existing and advanced technologies. The types of actions potentially affecting each of the terms in Equation 1.1 are illustrated in Figure 1.2, which serves as a useful model for describing the technology options to implement each emission reduction strategy. The figure shows each strategy (Fuel Substitution, Carbon Removal, Energy Efficiency Improvement, and Demand Modification) along with the major categories of technology that can achieve emission reductions. The strategies and their accompanying technology categories generally apply to more than one stage of the energy-cycle framework shown in Figure 1.1. The potential for these strategies in various roles in the energy system is summarized below.

1.3.1 Fuel Substitution

The magnitude of the first term in Equation 1.1 depends on the type of primary fuel consumed in producing the energy demanded. The different fuel substitution technologies are listed in Figure 1.2: *renewables*, *fission*, *low-carbon fossil* and *nuclear fusion*. For example, consumption of a high-carbon fuel like coal tends to increase the value of this term, while use of a lower-carbon fuel like natural gas (or a renewable like hydropower) tends to reduce (or eliminate) it. Thus, for many applications, implementing this strategy is conceptually straightforward, although high cost and uncertain technical performance can still be obstacles. For instance, a significant number of industrial plants can substitute natural gas for oil or coal in dual-fuel boilers. This switching to a lower-unit-emission fuel could lead to important emissions reduction.

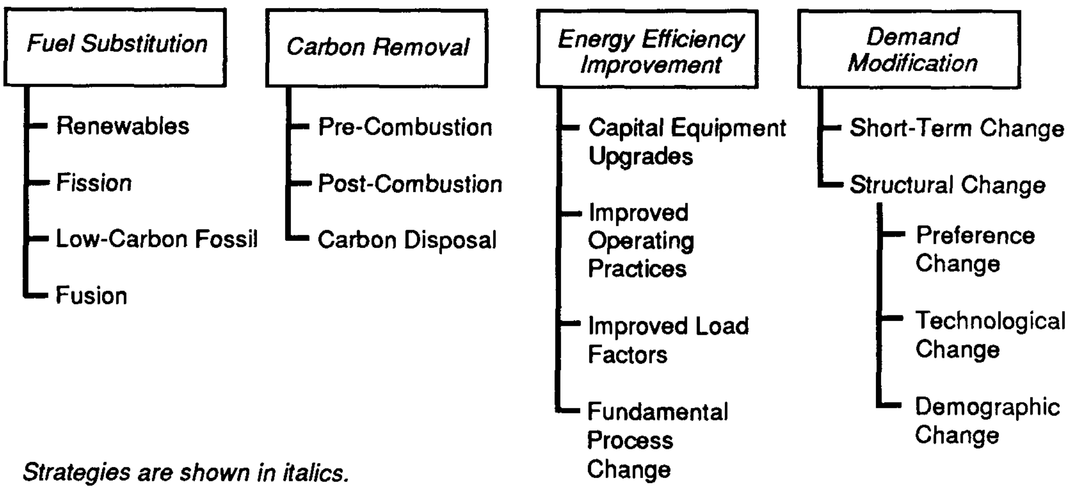

Figure 1.2. Strategies for Reducing Energy-Related Greenhouse Gas Emissions

Vehicles powered by electric batteries produce no direct emissions; rather, emissions are produced at the power-generating plant that produces the electricity to charge the battery. If electricity is generated by nuclear energy or renewables, carbon emissions are eliminated almost entirely (the first term of the equation would be near zero). An advantage in emission reduction may be obtained even for electricity generated by fossil fuel by shifting emissions from a multitude of small point sources (e.g., gasoline-powered autos) to a centralized large point source (e.g., electric power plants) because economies of scale can make fuel treatment and emission-capture technologies more economical.

1.3.2 Carbon Removal

The second term in the equation represents the cumulative emissions to the atmosphere escaping the various technologies employed to capture emissions before they are released. This factor approaches zero as the aggregate effectiveness of carbon removal processes increases. Carbon can be removed through two approaches: *pre-combustion* carbon extraction from carbonaceous fuels and *post-combustion* scrubbing of stack gases. Both approaches also require disposal of the *captured* carbon.

Most investigations of technology to remove carbon from either fuel or emissions apply to the utility sector where the needed economies of scale can be achieved. Numerous studies have been undertaken to estimate the cost and performance of a variety of carbon dioxide removal technologies for electric utility applications, with most results indicating very high cost. For instance, Steinberg (1983) estimates that collection and disposal of power-plant carbon dioxide emissions would at least double the cost of coal-fired electric power. Other estimates further indicate that removing 50% of the carbon dioxide in flue gases would reduce power plant efficiency to less than 27%, and removing 90% of the carbon dioxide would reduce power plant efficiency to less than 14% (see Chapter 9). However, some recent work indicates a more favorable potential for carbon removal in some cases. In a proprietary study for Tokyo Electric Power Company, for instance, Battelle-Northwest investigated the economic and technical effectiveness of several technologies for carbon dioxide collection, transport, and disposal for gas-, oil-, and coal-fired power plants. The cost and performance results in this study were more favorable than the above-mentioned estimates. Specific technology options currently being examined are discussed in Section 1.4.

1.3.3 Energy Efficiency Improvement

The third factor in the equation denotes the overall energy efficiency of the processes used to provide the level of service demanded by the consumer from fuel extraction to final energy end use. Thus, approaches to implement this factor include reducing losses in energy production, conversion and transfer, in addition to reducing the energy required by any equipment to satisfy a given level of final service demand. Efficiency gains can be obtained through a wide range of technologies. Some are unique to a specific energy supply or demand sector (e.g., secondary energy conversion, buildings, industry, and transportation), while others represent broad classes of improvements applying to more than one sector (e.g., efficient electric motors).

Figure 1.2 shows four measures that contribute to reducing energy used per unit service demand: capital equipment upgrades, improved operating practices, more favorable load factors, and fundamental process changes.

Equipment upgrades refer to use of advanced technology that, because of conversion improvements, requires less input energy to meet a given output level. Automobiles with high fuel economy, high-efficiency gas furnaces in industry, high-COP (coefficient of performance) building heat pumps, and high-efficiency fluidized-bed combustors for utilities all fall under this category.

Improved operations include practices such as better equipment maintenance and improved scheduling of equipment use, for example, to improve the ratio of operating to idling time.

Load factor increases refer to increasing capacity utilization, which can improve overall system efficiency. Examples occur in transportation (e.g., increasing the use of mass transit and the number of persons per light-duty vehicle or increasing freight loading) and in buildings (e.g., more people per building or multi-family buildings instead of single residences). Such load factor increases reduce the energy required "per person-mile traveled" or "per person-cubic meter heated."

Finally, *fundamental process changes* through new technology provide a long-term, but potentially very important approach to reducing emissions. Process changes (including process materials substitutions) encompass many options for achieving energy efficiency gains. Substituting a mechanical separation process for a thermal separation process, superconducting materials for conventional conductors, or lighter-weight materials for steel in automobiles illustrate the breadth of different options under this category. Many future efficiency gains will involve a substitution of this type.

1.3.4 Energy Service Demand Modification

The fourth and final factor in Equation 1.1 refers to the level of activity or amount of energy service demanded by households or businesses. Different patterns of demand for final goods and services in the economy can lead to different levels of energy use and emissions. Although the relationships between changes in final product demand and shifts in energy service demand, energy use, and greenhouse gas emissions are complex and not well understood, it is clear that the *scale* and *mix* of final demand in the economy are basic drivers for the level and type of energy used and the related emissions. This means that some types of modification to final demand have the potential to serve as an emission reduction strategy because they ultimately help to restructure the demand for energy services. Two broad factors make up this strategy: *short-term changes* and *structural changes*.

Short-term changes refer to consumer choices to accept lower levels of service in response to higher prices (e.g., lower home heating levels or less travel). Short-term changes can also include eliminating wasteful practices (e.g., turning off nonessential lighting or heating in unused building space). These changes can be easily reversed under new economic conditions.

In economic terms, *structural change* occurs over the long term and refers to fundamental consumer preference change, technological change, or demographic change. *Preference changes* include substantive changes in how the tastes or values of consumers or firms show up as purchases in the market. For example, people in households or businesses have different options to stay warm in winter--such as by wearing more clothing or turning up thermostats--and each option creates different energy service demands. *Technological change* refers to changes in how consumers or firms combine inputs like materials, labor, or capital to satisfy their needs. Technological change includes substitution, which refers to replacing an energy-intensive service with a less energy-intensive one (e.g., substituting telecommunications for travel or electronic databases for paper records). Another component of technological change is low-intensity system design, which refers to creating systems with low emissions as a design criterion (e.g., designs to cut the total material content of a manufactured good).

Finally, *demographic change* denotes items such as shifts in population growth rates, population aging, or migration of populations to more temperate climates. Also, shifts in the percentage of the population living in urban versus rural areas would have impacts on energy use and emissions.

1.4 AN OVERVIEW OF TECHNOLOGIES TO REDUCE GREENHOUSE GAS EMISSIONS

The physical means of implementing the strategies for reducing energy-related emissions generally exist in alternative technology options. Switching to a new fuel usually requires use of a different technology, for example, or at least use of a technology that has been adapted to multiple fuels. Some representative technologies that offer means of implementing each of the strategies covered in the previous section are now discussed. More detailed discussions of these and other technologies are included in the appropriate chapters in the remainder of this volume. As previously noted, some reduction strategies can apply to more than one stage of the energy cycle in Figure 1.1.

1.4.1 Extraction/Production Technology

Emissions from extraction and production of fossil fuels generally arise from methane leakage around gas pipelines, valves, pumps, and from coal mines. The principal technologies for reducing emissions in this first stage of the energy cycle include

- improved pipelines and connectors
- anti-corrosion technologies for metal fittings/components
- pumping technologies to remove gases from mines.

Recovery of these gases to mitigate losses is generally motivated by safety concerns and economics.

1.4.2 Secondary Fuel Conversion and Processing Technologies

Recent estimates suggest that about 400 GW of new or replacement electric generating capacity must come on line by 2010 to meet demand increases reliably and to replace existing capacity that will retire. Of the total required, only 65 GW will replace retired plants; the remaining 335 GW will be necessary to satisfy expected growth in electricity demands.

Along with oil use in transportation, fossil-fired electricity generation represents one of the most significant sources of energy-related carbon emissions. Therefore, electric generation technologies that reduce fossil combustion emissions, that use carbon-free fuels or that use fuels from which carbon has been removed are of great interest. Technologies that remove carbon from fossil combustion exhaust gases may also be of interest in the long term.

Fossil Electric Technology (Chapter 2)

Several emerging fossil-based technologies offer prospects for electric power generation with reduced emission levels. Some of these technologies are now in limited use in utility generating stations; others are under development with the possibility of commercial readiness before 2030.

Steam-Injected Gas Turbines. Compared with a simple-cycle gas turbine, the steam-injected gas turbine (STIG) produces considerably more power and has a higher electrical efficiency. The injection of steam directly into the combustion airflow adds high-temperature mass to drive the turbine and requires only minor modifications. Johansson et al. (1989) note a study showing that a 3.5-MW Allison turbine operating at 24% efficiency could produce 6 MW at 34% efficiency with full steam injection. Adding an intercooler between turbine compressor stages reduces compressor power consumption and allows cool air from the compressor to be routed to the turbine blades. The added blade cooling capacity permits higher turbine inlet temperatures for even greater power and efficiency than the standard STIG. Johansson et al. (1989) note a General Electric intercooled steam-injected gas turbine (ISTIG) system that operates at an inlet temperature of 1370°C and produces about 114 MW at an average efficiency of 48.5%.

Natural Gas Combined Cycle Systems. Combined cycle technology refers to the combined use of hot-combustion-gas turbines and steam turbines to generate electricity. The combined cycle technology significantly raises the overall thermal efficiency of power plants beyond that typical of conventional fossil-fueled plants using either type of turbine alone. Low carbon emissions are the result of a low-carbon fuel and a high system efficiency.

Atmospheric Fluidized-Bed Combustors. In a fluidized-bed design, coal and limestone are fed into a bed of hot particles (1400-1600°F) fluidized by upflowing air. The relatively low combustion temperature limits NO_x formation, reduces ash fusion problems, and optimizes sulfur capture by the limestone.

Pressurized Fluidized-Bed Combustors. Pressurized fluidized-bed combustion typically operates in a combined cycle mode where gases from the combustor drive a gas turbine generator, then are discharged to the stack. Water-filled coils within the bed generate steam that is used in a conventional steam turbine cycle to produce additional power. A combined cycle system permits the combustion of a wide range of coals, including high-sulfur coals. It can be used to repower oil- and gas-fired boiler units, while switching them to high-sulfur coal; to repower coal-fired power plants; and for new units. Pressurized fluidized-bed technology is estimated to have a capacity increment of as much as 40% in repowering applications.

Integrated Coal-Gasification Combined Cycle. Integrated gasification combined cycle (IGCC) is an alternative to conventional coal-fired electric power generation with post-combustion emission controls. The four major processes in an IGCC facility are 1) converting coal (via partial oxidation and gasification) into a fuel gas, 2) cleaning the fuel gas, 3) using the clean fuel gas to fire a gas turbine generator and using the hot turbine exhaust to make steam to drive a steam turbine generator, and 4) treating waste streams generated. Using advanced ISTIG turbines, overall efficiencies of 42% have been estimated for IGCC plants (Johansson et al. 1989).

Nuclear Fission Electric Technologies (Chapter 3)

Nuclear power currently provides over 20% of U.S. baseload electric generation without emitting greenhouse gases during operation. Future use of nuclear power both worldwide and in the United States will depend upon many factors, only one of which is the global warming issue. Some of the other factors are the economics of nuclear power relative to alternative generation technologies in various countries; national energy security considerations; the need to address other environmental emissions (sulfur dioxide, nitrogen oxide, other air toxics); economic and technological development of third world countries; progress in dealing with nuclear waste disposal; and continued safe operation of existing nuclear plants.

Nuclear reactors with simplified and standardized designs and passive safety features are being developed in the United States and elsewhere. These designs promise to revitalize the nuclear power industry by allowing the licensing process to be simplified and, thus, reducing the costs and financial risks associated with building nuclear facilities. Three types of advanced reactor designs are being developed: advanced light water reactors, advanced liquid metal reactors, and modular high-temperature gas-cooled reactors. The designs are in various stages of development. By the mid-1990s, utilities should be able to place commercial orders for advanced light water reactors, choosing among several designs. Some of these plants could be operating commercially by the year 2000.

Renewable Electric Technology (Chapter 4)

Primary renewable energy resources are abundant throughout both the United States and the world. They can be used to provide energy production or end-use services in many forms: as electricity, as gas or liquid fuels, and as direct heat. Renewable energy resources are diffuse; their cost of use often depends on collection techniques as much as on conversion processes.

Hydropower. Conventional and pumped storage hydropower facilities generate electricity by exploiting the kinetic energy in flowing and falling water. Conventional plants operate on water flow from storage reservoirs or free-flowing waterways. Pumped storage plants operate in a similar fashion except that the water source is pumped, usually through a reversible turbine, from a lower reservoir to an upper reservoir.

Biomass and Municipal Solid Waste. Biomass resources used for electricity generation consist of woody and fibrous primary and secondary waste materials from wood and agricultural operations, as well as municipal solid wastes from businesses and communities. Biomass is an attractive resource because of its potentially neutral contribution to carbon dioxide emissions. Although not emission-neutral, municipal solid waste is an attractive resource because 1) it is continuously generated; 2) handling is a necessary public service; and 3) using it to generate energy reduces the need for waste disposal, which is an increasing environmental problem. Landfilling of municipal solid waste creates methane as the waste materials decompose anaerobically.

Geothermal. Geothermal energy originates from the deep interior of the earth and the decay of radioactive materials in the earth's crust. Use of geothermal sources for energy purposes usually entails drilling water or steam wells for recovery. Energy uses include electricity generation and direct heat applications, such as district heating systems, industrial process heat, and crop drying.

Windpower. Wind flows are converted to useful energy through the use of wind turbines, which have been deployed in sizes ranging from 1 kW to 4 MW. Most early units have been small stand-alone applications to meet needs such as water pumping and farm power. Over the last several years, wind turbines have primarily been deployed in "wind farm" clusters.

Solar Thermal Electric. Highly concentrated radiant energy from sunlight can be used economically to produce thermal energy for electricity generation in conventional steam turbine conversion systems. The economic size range of solar thermal electric plants is 20 to 200 MW, making this technology appropriate for bulk power generation or large off-grid applications.

Photovoltaics. Photovoltaics, or solar cells, convert sunlight directly into electricity. A primary advantage of photovoltaics technology is that it is modular, i.e., it can be deployed on any scale, and thus can serve loads ranging from watts to megawatts. The technology is potentially applicable in all electricity-consuming sectors. In addition, photovoltaic cells can operate with diffuse sunlight, making them applicable in many geographical areas.

Integrated or Fuel-Flexible Energy Supply Technology (Chapters 2 and 5)

There are a number of attractive opportunities for combining separate energy supply technologies into integrated systems to provide multiple energy services at higher overall performance than stand-alone versions. Such approaches provide advantages such as fuel flexibility/independence, reduced cost, increased energy efficiency, and reduced emissions. Examples of integrated technology strategies include cogeneration, fuel cells, integrated building appliances, and integrated energy storage networks. Recovering and reusing waste heat or balancing peak and off-peak electrical or thermal loads are often key features of integrated energy systems.

Cogeneration. Cogeneration is the simultaneous production of electrical or mechanical energy and thermal energy (usually steam) from an input fuel. This sequential use of input energy for two separate output forms results in high overall energy conversion efficiencies (usually in the 60% to 80% range, annually). Careful system design permits use of cogeneration in commercial, industrial, and even residential applications. A system may supply electric power requirements as well as thermal energy for space heating, hot water, district heating, and industrial process heating. Cogeneration systems can also be designed for space cooling and refrigeration, as well as some mechanical drive needs.

Fuel Cells. A fuel cell is an energy-conversion device that converts the chemical energy of a fuel directly into electric power via an electrochemical reaction between hydrogen and oxygen. It differs from storage batteries in that battery chemical energy is stored within the cell; whereas, the fuel and oxidant are normally external to the fuel cell. Fuel cells have a long list of advantages for converting hydrocarbon fuels into electricity, possibly including simultaneous production of useful thermal energy for process heating or space conditioning needs. Electrical conversion efficiency from the raw fuel to electric power in fuel cells is high--36% to 40% for smaller units and 40% to 44% for the larger ones. Because fuel constituents are chemically separated into free hydrogen and other components while in the fuel-cell system, fuel cells may eventually prove to have further advantages regarding ease of carbon capture.

Hydrogen can be supplied by a hydrogen-rich fossil fuel or by a pure hydrogen stream. Most near-term facilities are expected to employ air for oxygen and natural gas as the hydrogen source; future technology should enable the use of synthetic fuels--especially methanol from coal or biomass.

Advanced Energy Supply and Conversion Systems (Chapter 2)

Longer-range advanced technologies have the potential to reduce emissions sometime beyond the year 2010. These technologies include advanced power cycles like the Kalina and thermoelectric conversion, but two of the most important advanced supply technologies are magnetohydrodynamic power and fusion power.

Magnetohydrodynamic Power. Magnetohydrodynamic (MHD) power generation is a method for converting thermal energy directly to electric power. The technology is based on the concept of using flowing ionized gases of liquid metals, heated by chemical or nuclear fuel, as the moving conductor in an electric generator. By using the working fluid directly, the MHD generator removes the intermediate steps of generating steam and turning a turbine. The MHD generator can use working fluids at higher temperatures than can conventional power plants, a capability which leads to increased conversion efficiencies.

Current MHD research efforts are directed toward base load (both stand-alone and retrofit) coal-fired power plant applications. MHD may also find application in industries that use significant amounts of electrical energy.

Nuclear Fusion. Nuclear fusion takes advantage of the fact that large amounts of energy are released when the nuclei of light elements (such as hydrogen) fuse to form heavier elements. The fusion reaction of great interest for energy (electricity) production is between two isotopes of hydrogen--deuterium and tritium. Fusion has two advantages over fission reactors: it uses plentiful and secure raw materials (deuterium and tritium can be obtained from seawater), and it does not produce large quantities of radioactive waste. Fusion technology is still in the early stages of development, and significant technical and economic obstacles must be overcome before commercial applications are possible. Nuclear fusion is considered a clean energy source; however, routine effluents from fusion power plants will include waste heat, chemicals, tritium, radioactive wastes, and activation products.

Fusion reactor designs of up to 4,000 MW have been proposed. Current projections indicate that commercial feasibility of fusion power plants will be demonstrated by about 2025 and that a significant contribution to the energy supply could be expected by mid-century.

Carbon Removal Technologies (Chapter 9)

Direct removal of carbon can occur before or after combustion of carbonaceous fuels. Once carbon has been captured as a gas, solid, or liquid, it must be transported and disposed of.

Pre-Combustion Carbon Removal. The notion of removing carbon before combustion has been advanced as a long-term option for reducing emissions (Steinberg and Cheng 1987). This approach results in a hydrogen-rich fuel for combustion processes. The advantage of pre-combustion versus post-combustion carbon removal is the relative ease of storing solid carbon compared with storing carbon dioxide. The difficulty of disposing of carbon after its removal and storage is a problem with either approach.

In pre-combustion removal, chemical processes break the carbon-hydrogen bonds in the fossil fuel, allowing selective combustion of hydrogen without formation of carbon dioxide. One potential approach, the HYDROCARB process, involves two steps. The fossil fuel is first hydrogenated to produce methane, which is then thermally decomposed to pure carbon and hydrogen. The carbon and hydrogen are then separated; the carbon is stored and the hydrogen is used for combustion. Net recoverable energy for this process ranges from 56% for natural gas to 24% for coal (Steinberg and Cheng 1987). With one version of the HYDROCARB process, a hydrogen economy could be efficiently based on coal because carbon dioxide emissions are cut in half. Pre-combustion carbon removal technologies are in their infancy. Many years of research and testing would be required before practical applications could be put into operation.

Post-Combustion Carbon Scrubbing. Carbon dioxide and other greenhouse gases can be collected from the exhaust gases of boilers, cement plants, landfills, natural gas pipelines, and coal mines before the gases are released to the atmosphere. Several physical and chemical separation processes have been used in the natural gas industry to separate hydrogen sulfide and carbon dioxide from natural gas. The most important of these processes are described here briefly.

Chemical Separation - the reaction of acid gases with a solvent. Two common chemical separation processes are the alkanol amine processes and the carbonate processes, both of which have been used in the natural gas processing industry.

Physical Separation - the physical absorption (or dissolution) of acid gases into a solvent. The carbon-rich solvent is then heated in a regeneration column to drive off the acid gases. Examples of physical separation processes are Rectisol and Selexol.

Membrane Processes - selective transport of fluids across a membrane under some driving force (e.g., pressure, concentration, electromagnetic field). This process has been used economically to purify gases at high pressure--principally hydrogen to date. The membrane permits specific components (solutes, solvents, or gases) to permeate, while inhibiting transport of other components.

Cryogenic Processes - refrigeration and distillation of a feed gas at high pressures (600 psig) and low temperatures (-120°F) to separate the constituents according to their different boiling points. Cryogenic processes are not commonly used to separate carbon dioxide from hydrocarbon streams unless liquefied natural gas is the desired fuel product. If the product is a gas (instead of a refrigerated liquid), one of the other processes (i.e., chemical, physical, or membrane) is more economical.

At the present time, chemical separation processes appear to be the most technically and economically feasible option for removing carbon dioxide from boiler flue gas or from cement kiln flue gas. Carbon dioxide can also be removed from the atmosphere by a variety of generally expensive means. Removing atmospheric carbon dioxide using chemical absorption processes has been estimated to require 1.5 to 2 times the energy required to remove it from power plant flue gases; the cost range depends upon the percentage of carbon dioxide removed from the flue gas.

Carbon Dioxide Disposal. A viable carbon dioxide removal system must also have provisions for transporting and storing the carbon dioxide after it is captured. There are a number of approaches; however, they have not been well characterized to date, and most of them are expensive. Moreover, uncertainty regarding the effects of permanent or long-term sequestering of carbon in land or deep ocean formations still persists.

Various transport possibilities have been proposed. Gaseous carbon dioxide could conceivably be transported via pipeline or in an appropriate container on truck or rail. Other possibilities include compressing the carbon dioxide to a liquid and then transporting it via pipeline, truck, tanker, or rail. Transport via barge or rail is feasible when the carbon dioxide is in a solid phase.

At least four methods exist for carbon dioxide disposal: storage in depleted gas wells, ocean disposal, use in enhanced oil recovery, and storage in excavated salt domes. Disposal of the carbon dioxide into the ocean as either a gas or a liquid requires about the same amount of energy, while disposal as a solid requires about twice the energy. Site availability will obviously be a key issue for each of these options, since the distance of a power plant from a disposal site would account for a large portion of the transportation cost. Disposal of carbon dioxide in the ocean could create significant problems in the global carbon cycle.

1.4.3 Energy Storage, Transmission, and Distribution Technologies (Chapter 5)

Most energy storage and transmission systems do not produce greenhouse gas emissions directly; however, their use as components in an energy conversion and transfer process contribute to overall system performance and can help lower emissions.

Energy Storage

Storage systems provide the ability to decouple energy supply from end-use demand, which is important for flexibility in the choice of fuels and primary energy sources. Energy storage systems are compatible with a variety of energy conversion processes, including many advanced energy conversion and use systems which have low or no emissions. Energy storage systems are particularly advantageous when used with renewable resources, most of which have operating characteristics that depend on the weather or time of day. In general, energy storage offers the potential to reduce emissions by reducing the need for additional energy conversion to meet a service demand. Known forms of storage fall into five major groups: electrical, thermal, mechanical, chemical, and magnetic. Their principal applications include electric vehicles, customer-side storage, building thermal, and utility load leveling.

Hydrogen

Hydrogen is attractive as a low-emission energy carrier and storage medium because, unlike the electricity generated by any energy source, hydrogen produced by such sources can be readily stored. It can thus take advantage of off-peak hydroelectric power as well as excess solar and wind energy. However, cost-effective, safe methods of storing hydrogen are needed, as current storage systems are expensive, unwieldy, and perceived to be risky.

Hydrogen can be used in fuel cells to generate electricity. In end-use applications, it can be used for heating (space heating, cooking, hot water) and transportation, including aircraft.

Hydrogen can be produced by steam reforming of methane, partial oxidation of oil, gasification of coal, or electrolysis of water. If hydrogen is produced from fossil fuels such as natural gas or oil, carbon dioxide emissions can result. The lowest emissions of radiatively important gases would be associated with non-fossil means of producing the hydrogen.

Energy Transmission and Distribution

The transmission and distribution network used to deliver electricity to end-use destinations represents a major part of any electrical utility system. Primary technology components of the network include transmission lines and transformers of various types and voltages, all of which lose some of the transmitted electricity as heat. Transformers also lose some additional power, depending on characteristics of the transformer core. These losses can be significant, particularly as transmission distance increases. Reduction of such losses with advanced transformers and transmission cables will help reduce potential power generation emissions.

Superconductivity

Several functional electricity-based power systems have been developed with low-temperature superconductors. Research to develop generators, transformers, transmission lines, motors, levitated trains, magnetic separators, and energy storage systems has demonstrated technically viable applications. Many of these superconductor applications exhibit large economic savings, even for the liquid-helium-cooled versions; and several have been developed through the prototype stage. Estimates of commercial availability for high-temperature superconductors capable of bulk power applications range from 5 to 20 years, with unknown probabilities of success.

1.4.4 Energy End-Use Technologies (Chapters 6, 7, and 8)

The basic approaches for reducing emissions in end-use applications are efficiency improvements and fuel substitution. However, describing the potential gains for each end-use application is difficult. Unlike most supply technologies, where a few relatively distinct system technologies predominate, a vast number of end-use technologies exist for both improving efficiency and fuel switching. Several recent studies (e.g., Carlsmith et al. 1990) project that average savings from end-use efficiency improvements could be 10% of expected year 2010 energy consumption, assuming aggressive conservation efforts using currently cost-effective technology. Such gains could have important implications for reducing greenhouse gas emissions. Moreover, as indicated below, even more savings from advanced technology are possible.

End-use technologies are discussed either as generic technologies, which can apply to more than one end-use sector, or as sector-specific systems. Since the demand modification strategy applies most directly to end-uses, the role of technology to implement these approaches is also presented here.

Generic Technologies

Several generic technologies represent a large potential for energy efficiency gains because of their widespread use in end-use sectors and, in some cases, as part of the energy supply system.

Motors. Electric motors are used extensively throughout the industrial and building sectors. Much of the energy use typically associated with other types of equipment actually can be traced to an internal motor. The electricity consumed in refrigeration equipment, for example, is the electricity fed to the motor that drives a compressor. While improved compressor design can reduce the load on the motor, final energy consumption remains with the motor.

Even for state-of-the-art motors, as many as 37 opportunities to improve efficiency have been identified by the Rocky Mountain Institute (Shepard et al. 1990). Improvements in motor technology typically involve using efficient materials or motor components that minimize electrical losses. For example, one developing technology that may help reduce motor electricity consumption is superconducting materials for motor components. Such improvements are generally transferable to all motors of similar design. Even though the percentage of improvement is small for an individual motor (perhaps improving efficiency from 98% to 99%, for example), the large potential impact stems from the number of motors that could be improved.

Internal Combustion (Piston) Engines. Piston-driven engines are most commonly used in motive power applications (e.g., in transportation vehicles) and in situations where a self-contained, portable power supply is needed (for industry or utility needs). A lesser but not insignificant application is shaft power in industry, particularly where cogeneration of power and steam can be used.

Engine efficiency improvements (power out/fuel energy in) are possible in many forms. Several improvements in automotive applications have allowed tremendous gains in the ratio of power output to combustion chamber capacity during recent years.

Improved engines having greater energy efficiency within anticipated emissions constraints are now being developed. The fuel-efficient DISC (direct-injection stratified-charge) engine is likely to have difficulty meeting future NO_x standards. Some other designs offering relatively near-term impact on fuel efficiency include diesel and two-stroke engines.

Compared with gasoline engines, diesel engines have relatively high fuel efficiency and operate on lower-grade fuels. To overcome projected problems with future emission standards, especially NO_x and particulates, techniques to lower emissions are being investigated. The low-heat-rejection (or adiabatic) diesel is attractive for replacing engines with conventional liquid cooling systems.

Two-stroke engines promise lower fuel consumption because of charge dilution, reduced pumping loss, and less engine friction. Two-stroke engines also contain high power-to-weight ratios, so that a much lighter engine can be used in a given situation (primarily of value in motive power applications).

Lighting. Lighting has extensive application in the commercial, residential, and industrial sectors. Most lights in residences are standard, low-efficiency (15 to 17 lumen/watt) incandescents. Significant electricity and cost savings can occur if high-efficiency light sources are substituted for higher wattage bulbs. Fluorescent bulbs, for example, have performance of 40 to 60 lumen/watt. Compact fluorescent bulbs typically cost 10 times more than incandescents but last 10 times longer and use 25% of the electricity. Lighting in commercial and industrial applications is generally of higher efficiency than residential lighting, although much improvement is still possible in these sectors. Further upgrades to high-pressure sodium or mercury vapor lighting can offer even greater savings than fluorescents.

Lighting controls reduce energy consumption by providing the minimum amount of artificial light necessary to perform a given task. With lighting systems, artificial lights can be dimmed in response to daylight; lights can be turned off when occupants are absent; and lighting in individual areas can be fine tuned. Four types of energy-saving lighting control measures are important in the near term: occupancy scheduling, lumen maintenance, fine tuning, and load shedding.

Advanced approaches to lighting include energy-efficient core ballasts, electronic (solid-state) ballasts, improved compact fluorescent bulbs, and improved task lighting concepts.

Boilers. A boiler consists of a pressurized system that generates heat to vaporize water and produce steam. Heat is typically generated using some conventional fuel (including nuclear fuels); however waste-heat and renewable-energy-powered boilers are becoming more common. Although other fluids are sometimes vaporized in the boiler, water is by far the most common fluid used because of its favorable thermodynamic, environmental, and economic characteristics.

Commercial boilers produce from a few hundred pounds of steam per hour to more than 6 million pounds per hour, and pressures range from 0.5 pounds per square inch (psi) to 5000 psi for power generation boilers. Superheated temperatures in the latter pressure ranges can be as high as 1100°F. Most boilers have efficiency curves that rise with increasing steam flow to a maximum near their full rated load, then drop off. A typical new boiler would range in efficiency from about 82% to 92% depending on load (Turner 1982). Efficiencies also change with deposition of soot and scale and with excess air in the combustion feedstream.

Energy Management/Controls. A number of energy management systems are commercially available today for use in buildings, industry, and transportation equipment. New concepts being developed will vastly upgrade existing capabilities and expand potential applications. Current systems are directed at automatic control of one or more individual pieces of equipment. In residential buildings, for example, the heating system can be programmed to lower temperatures when no one is home or to run the dishwasher at night.

Three general tiers of control automation are known: smart products, intelligent sub-systems, and integrated total automation systems. Full automation technology is exemplified by buildings applications in which integrated control of all major devices and systems in the structure is provided according to the schedules and use patterns of the occupants, over a cycle of weeks and months, even of seasons. The intelligent home is adaptive, accounting for changing conditions (e.g., weather or patterns of appliance use). If the windows are repeatedly opened, the heating system responds and automatically resets itself to a lower temperature. The integrated communication channels that make these advances possible can also enhance the efficiency and economy of load management in both supply and demand sectors.

Transportation Energy End-Use Technology (Chapter 6)

The transportation sector dominates petroleum use in the United States and is an almost exclusive user of petroleum over other fuels, a situation which is expected to continue for most of the near and mid term. Virtually all types of transportation emissions can be cut by increasing energy efficiency and by fuel substitution. Energy efficiency is increased by the following:

- improving vehicle fuel economy
- increasing load factors (e.g., more mass transit)
- improving the operation of transportation systems and upgrading traffic management practices.

Fuel substitution implies use of alternative fuels, including advanced liquids, gases, and electricity. Numerous improved vehicle technologies are attractive for use in light and heavy cars and trucks, as well as aircraft applications to reduce greenhouse gas emissions. Many are considered cost-effective for near-term use (Carlsmith et al. 1990).

Alternative Fuels for Transportation. In the mid and long term, alternative fuels will probably become strong contenders for significant use in the transportation sector, primarily for low-occupancy vehicles. The principal candidates are reformulated gasoline; diesel fuel; alcohols (M85 - 85% methanol/15% gasoline, M100 - neat methanol, and ethanol); liquefied petroleum gases or LPG (mostly propane); compressed natural gas (90+% methane); and electricity.

Alcohol fuels, including ethanol or methanol from biomass, are technically feasible now, but have no supporting fuel supply and vehicle infrastructure. Some technical problems, including environmental questions, also remain.

Current electric vehicles have only limited range and are, thus, attractive only in niche markets. Electric vehicles will not be widely used without significant improvements in battery technology. Three near-term battery technologies capable of 100- to 150-mile range are lead-acid, nickel-iron, and sodium-sulfur. Each has its own technical hurdles. Hybrid vehicles, which use both a battery-electric system and a small engine for charging, are another option.

In the long term, hydrogen is also a possible transportation fuel; it has been burned in spark-ignition engines. Storage is, however, a major problem. Gaseous, liquid, or solid storage forms have not yet provided the needed technical performance.

Vehicle Fuel Efficiency Increases. Raising total (powered and unpowered fuel rates) vehicle fuel economy depends on three main factors: 1) a number of key vehicle characteristics (vehicle mass, tire rolling-resistance coefficient, and aerodynamic drag), 2) powertrain efficiency (average brake thermal efficiency of the engine plus average efficiency of the drivetrain), and 3) the nature of the average driving cycle (e.g., how much is power-mode versus unpowered idling).

A number of technological options available in the new vehicle market promise future fuel efficiency gains. Engine technologies are a major target for efficiency gains (previously discussed in this chapter under "Generic Technologies"). In addition to piston-driven engine designs, gas turbine engines are receiving attention for their potential application to vehicles. Other approaches to improving vehicle fuel efficiency include electronic transmission control, front-wheel drive, better aerodynamics, materials substitution for lower weight, and improved accessory designs.

Increased Transportation Load Factors. By increasing the load factor (passenger-miles per vehicle), mass transit systems offer significant potential for energy savings. Although many current surface mass transit systems and vehicles are now operational, future introduction of high-speed, magnetically levitated (Maglev) vehicles may make mass transit even more attractive in the mid to long term. Although its competitiveness in the market is not yet known, such a system could replace some highway traffic and commercial aircraft flying short routes, particularly in highly congested areas. However, technical obstacles will probably preclude significant Maglev for more than a decade. Availability of cost-effective high-temperature superconducting materials will undoubtedly increase the attractiveness of both Maglev vehicles and magnetically propelled ships.

Improved Transportation Operations. Many possibilities exist for better traffic management and reduced fuel consumption and emissions. Examples include high-occupancy-vehicle lanes and computerized traffic control systems. In addition, fully automated highways have also been proposed, although many technical, financial, and behavioral obstacles must be overcome before such options will be realistic.

Buildings Energy End-Use Technology (Chapter 8)

Electricity is the dominant fuel in both the residential and commercial buildings sectors. In terms of end-use services, space heating, water heating, and refrigeration account for almost 70% of residential end-use energy. In the commercial sector, space heating, lighting, and air conditioning are the largest energy end uses. Though not insignificant, building energy use is generally a smaller percentage of the overall consumption in the industrial sector. General improvements in site and shell technologies and other relatively generic systems (e.g., HVAC) have potential impacts for buildings in all sectors.

Fuel Substitution in Buildings. Fuel substitution in buildings encompasses the following actions:

- substituting low-carbon for high-carbon fossil fuels (natural gas for coal)
- substituting cleanly produced electricity for fossil fuels
- substituting biomass fuels (or other non-fossil primary energy) for fossil fuels
- increasing use of cogeneration in buildings.

Building Efficiency Gains. Efficiency gains for buildings can occur in both the building shell (building design, windows, and insulation) and the conversion equipment within the building. The main technologies for these components are listed below.

Refrigerator-Freezers. Almost 100% of all U.S. households have refrigerators. The baseline model for the energy and cost analysis is a top-mount auto-defrost refrigerator with an 18-cubic-foot capacity and an average energy use of 947 kWh per year. Compressors (including the electric motor) account for approximately 75% of refrigerator energy use. Compressor energy use can be reduced by 1) installing more efficient compressor designs or 2) reducing demand for compression by improving the insulation.

Space Heating. Natural gas is the dominant space heating fuel in all regions of the country (almost 55% of heated commercial floor space is heated by natural gas, 23% by electricity, and 12% by fuel oil). Gas-fired warm-air furnaces are the most common type of residential space heating (heat pumps for electrically heated houses are discussed below under residential air conditioning). The energy efficiency options for gas furnaces include intermittent ignition devices, two-stage burners, induced draft, and a condensing heat exchanger. Condensing furnaces, which have entered the residential space heating market in large numbers recently, are the most efficient with an annual fuel utilization efficiency (AFUE) rating of up to 97%.

Air Conditioning and Heat Pumps. Residential air conditioning is accomplished with room air conditioners, central air units, or heat pumps. Almost 60% of all U.S. residences have air conditioning, and half of those residences have central units. Reversible heat pumps have slightly lower efficiencies than comparable central units because both coils must be able to operate as evaporators and condensers. Air conditioner efficiency can be increased by improving the heat transfer of the heat exchangers, improving fan and compressor efficiencies, switching to electronic expansion valves, and using multiple or variable speed compressors.

About 80% of commercial floor space is air conditioned; 91% of cooled commercial floor space uses electricity for air conditioning and 6% uses natural gas (i.e., gas absorption chillers). Small cooling loads (under 135 kBtu/hr) are met using electrically driven air conditioners. The main large load technologies are electrically-driven chillers (conventional refrigeration cycle), gas-fired absorption chillers (heat-operated refrigeration equipment) and evaporative cooling (temperature reduction of an air stream by evaporating water). Economizer cycles can be used to reduce space cooling loads, but they do not allow precise humidity control.

Efficient Building Design. Demand for energy use in buildings can be reduced through intelligent building design. One form of intelligent design is capitalizing on natural resources to minimize the demands on conventional energy systems. Passive solar designs can frequently eliminate the need for heating during part of the heating season. Combining buildings of similar function, as in office buildings, shopping malls, and townhouses and apartments, minimizes exposure to the external environment and allows sharing of thermal resources (heating and cooling energy).

Windows. The basic types of residential windows in use today are single-glazed, double-glazed, and double-glazed with a low emissivity (low E) coating. With low emissivity coatings reducing radiative losses, conduction becomes the main heat loss mechanism in a double-glazed window. Windows can also be filled with heavier-than-air inert gases (e.g., argon) to reduce the glass-to-glass thermal conductivity. Future windows may use vacuums or silica aerogel fills to reduce the thermal conductivity of the window.

Large commercial buildings have significant internal heat gains and low surface-area-to-volume ratios and therefore generally require more cooling than heating. Lighting also adds a heat load in commercial buildings. Daylighting can reduce both lighting and cooling bills if the solar gain is controlled.

Insulation. Standard insulating materials work by trapping an air layer in a porous material. There are two predominant types of insulation in buildings today: fiberglass and styrofoam.

Water Heating. Water heating is second to space heating in terms of residential energy use. The predominant fuel types for residential water heating are natural gas (54.4%) and electricity (35.3%). Pulse combustion and flue gas condensation are furnace technologies that could be applied to water heaters, but are not yet commercially available.

Savings from design options depend heavily on the use patterns. Water heating energy can be reduced by decreasing water use. Low-flow showerheads and more efficient clotheswashers and dishwashers will cut water use.

Improving Building Operations. A variety of automatic controls can be used to improve energy using operations in buildings. Examples include lighting and room occupancy sensors, heating equipment controls, and controls for time-of-day appliance use. Improved maintenance of building equipment will also minimize energy consumption.

Industrial Energy End-Use Technology (Chapter 7)

The industrial sector includes manufacturing, mining, agriculture, and construction. Manufacturing is the largest energy consumer, constituting roughly 29% of U.S. energy use. End-use energy services for industry include steam, process heating, machine drive, electrolytic processes, and feedstocks.

For a given level and mix of industrial energy service demand, energy-generated carbon dioxide emissions can be reduced by substituting low-carbon for high-carbon fuel and by increasing industrial energy efficiency. Energy efficiency is improved through process equipment upgrades, better operating practices, and fundamental process changes. Process equipment change generally involves capital investment and aims to improve multiple process features. Operating practice improvement includes better housekeeping and energy management. Although motivated primarily by broader concerns about production efficiency and cost, fundamental process change (e.g., direct steel making) can also significantly increase energy efficiency.

Industrial Fuel Substitution. Fuel source changes include substituting

- natural gas for coal
- electricity for fossil fuels (nonfossil or natural-gas-based)
- biomass fuels (or nonfossil primary energy) for fossil fuels.

The potential for substituting natural gas for oil or coal in industry is limited. Most oil-based combustion, for example, is now at remote sites (e.g., in forest products). At present, increased electricity substitutions are attractive for carbon dioxide reductions only in end uses where the relative efficiency of electricity is about three (or more) times higher than that of the fuel for which it substitutes (Ross 1990).

Cogeneration, usually co-production of steam and electricity, can enable substantially improved efficiency in the joint production of heat and shaft power. Economical application of cogeneration requires fairly steady heat loads, such as the steam loads in papermaking. One excellent example, now in the development stage, is replacement of boilers and steam-turbine generation at kraft pulp mills (black-liquor recovery systems) with gas turbines, which will produce about three times more electricity without fossil fuel input (Fulkerson and Reister 1989).

Industrial Energy Efficiency Improvements. Industrial energy efficiency gains occur in three basic ways: upgrades of process equipment, improved housekeeping, and fundamental changes in material conversion processes.

Process equipment changes are sometimes made directly to improve energy use, but usually result from other productivity improvements and generally require significant capital investment. Some recent energy upgrades include the steel (ladle heaters), aluminum (efficient electrodes), chemical (separations), pulp and paper (drying), and textile (process automation) industries. These equipment changes also have other benefits that improve overall productivity.

Although better housekeeping operations are of great importance for industrial energy carriers such as steam and compressed air, as well as for lighting and HVAC, they can probably only contribute another 5% to energy use reduction (Ross 1990). Installation of automated energy management systems, typically requiring expensive rewiring in existing plants, is a prime example of new technology for this approach.

Fundamental process change is a long-range phenomenon of largely unknown potential since dramatic process changes tend to occur slowly. However, significant changes can revolutionize industries, as illustrated by the following four examples of fundamental process change: float-glass process, basic oxygen steelmaking, induction heating of metals, and surface heating with electromagnetic beams.

Some examples of fundamental process change that may be achieved in the near future in the chemicals, paper, and food-processing industries are the following (Ross 1990):

- improved separation processes based on membranes, adsorbing surfaces, critical solvents, freeze concentration, etc.

- new and improved catalysts for chemical processing

- continued improvements in the processing and forming of materials

- biological processing of organic chemicals

- dry papermaking

- ethylene chemistry based on natural gas feedstocks and biomass feedstocks for organics.

Several near-term process changes possible in the metals industry may help reduce emissions. Examples include the following:

- near net shape casting

- surface treatment with electromagnetic beams

- direct and continuous steelmaking

- coal-based aluminum smelting.

Achievement of these changes will require significant research, invention, development, and major investments.

Integrated or Multi-Sector End-Use Technology

Considering end-use sectors separately has the disadvantage of not accounting for cross-sectoral efficiency opportunities. Considerable savings in energy use and emissions can, for example, result from community-level technologies that integrate the functions or activities in multiple sectors. The clearest example is district heating and cooling, although some cogeneration or storage network applications are also important.

District heating and cooling is delivery of hot or chilled water or steam from a central plant or a thermal source through pipes to customers for space heating and cooling use. District systems can be an attractive alternative to the operation of single-building heating and cooling. The technology offers an established way to conserve scarce fuels, improve air quality, and increase the fuel efficiency of power plants. Effective heating and cooling systems can be developed to use renewable fuels, thus reducing the consumption of oil and gas in space conditioning applications.

Despite an important role in Scandinavia and other European countries, district thermal applications have not enjoyed widespread use in the United States, partially because of high initial capital costs. As the technology gains acceptance and its cost declines, one of the major potential markets for district services in the United States will be the space cooling market.

1.4.5 Technology to Modify Energy Service Demand (Chapter 10)

The advent of demand-side energy management in utility planning strategies signifies a recognition that cutting required energy services can be as effective as adding to supply in matching supply and demand. Various demand-side opportunities typically involve efficient technologies that do not directly change the demand for service, but rather satisfy the same level of demand more efficiently with less energy. Efficiency changes can alter demand, but the effects are difficult to estimate.[a]

A somewhat different approach to demand-side management involves actual reductions in demand, that is, changes in the level of service demanded by consumers (regardless of how efficiently or inefficiently that service is delivered). Demand reduction is commonly associated with energy conservation as the concept of "doing without." While doing

(a) A good example is the "conservation buy-back" phenomenon, in which, for instance, cost or energy savings from a more efficient residential furnace may lead consumers to turn up the thermostat, thus demanding more heat and reducing possible energy savings.

without is one possible approach to demand reduction, this concept is generally incongruous with the goal of attaining a higher standard of living and is easily reversed at the discretion of the consumer.

Other opportunities for demand-related effects on emissions exist, including ones that do not necessarily lead to reductions with undesirable impacts to standard of living. They involve a more permanent alteration or "modification" of energy-using systems that change the energy demanded by virtue of different final product (goods or services) demand. These final demand changes often are associated with structural change in the economy (see Chapter 10). In fact, technologies and concepts that lead to energy service demand restructuring may not even be normally thought of in terms of energy use. The energy benefits may be secondary and possibly even unknown to consumers. Some example technologies that bring about restructuring in demand include energy management and monitoring systems, recycling and waste minimization, telecommunications, and design of efficient community systems.

Energy Management and Monitoring Systems

Energy management systems were described under the "Generic Technologies" section earlier in this chapter. Such systems can be deployed to monitor use of facilities or equipment; for example, to shut down unnecessary system operations. Motion indicators that control facility functions (e.g., lighting, door access) and office equipment or home appliances with idle or "power saver" modes are examples of demand-reducing technologies that are in widespread use.

Recycling and Waste Minimization

Reuse of previously processed materials reduces the demand for new materials and supplants a significant portion of the energy required to process those materials from raw inputs. Materials wasted in the production process (either by becoming scrap or by being converted into waste requiring disposal) increases demands for energy in the process. New technologies to recover valuable constituents of waste streams from all sectors of the economy not only save raw materials and disposal costs but also save significant amounts of energy. Eliminating procedures that generate wastes is an even better strategy because reprocessing costs are also avoided. Waste minimization and recycling are receiving international attention as important approaches for addressing energy and environmental concerns.

Telecommunications

The impacts of substituting electronic communications for travel in transportation energy consumption will not be lost on the economy as the utility of these substitutions increases. Already the advent of facsimile machines is having a profound effect on the number of mailings and other deliveries required on a worldwide basis. Teleconferencing allows staff at different locations to speak together (and in some cases, see each other) for meetings, avoiding travel altogether. Telecommuting, or working at home via computer and modem communications instead of traveling to a central office, has significant potential for reducing future traffic congestion and may substantially reduce consumption of transportation fuel over the next several decades.

Efficient Community Systems Design

Designing efficient community systems has the potential for reducing energy demand over the mid to long term. Strategic placement of shopping centers in a community, for example, minimizes the distance residents of the community must travel. Optimal planning of service routes (e.g., bus, garbage collection, mail delivery) through communities saves time as well as energy. In these examples, the efficiency of the vehicles making the trip is not changed, but rather the length of the average trip (or cumulative demand on the aggregate system) is reduced. High-density building design, interspersed with urban trees to cut heating and cooling loads, can reduce energy use over comparable dispersed land use patterns by significant margins.

Computer-aided design of community systems could lead to many such improvements in the future.

1.5 TECHNOLOGY COST AND PERFORMANCE DATA

This section presents a summary of the technical and cost characteristics of key technologies discussed in this volume. Table 1.3 contains data for fossil and nuclear electricity technologies; Table 1.4 contains characteristics for life-extension/repowering technologies; and Table 1.5 contains data for renewable electric technologies. In Appendix A, end-use technologies are characterized using cost curves. The data in Tables 1.3, 1.4, 1.5, and Appendix A are the technology characteristics used for the National Energy Strategy (NES) analysis and for analysis in Volume II of this study.

In some cases, the data presented in these tables differ from technology performance and costs presented in Volume I. These differences arise because considerable uncertainty exists regarding technical and economic assumptions used for emerging technologies that have not yet been commercialized; moreover, this uncertainty increases as the expected date of commercialization for a technology moves farther into the future. Although different authors may have used slightly different assumptions in producing technology estimates, in all cases, the differences are within acceptable ranges of uncertainty.

1.6 FACTORS THAT INFLUENCE THE IMPACT OF TECHNOLOGY ON EMISSIONS REDUCTIONS

At any given time, a combination of technological, economic, institutional, informational, and behavioral factors will interact to determine energy use and the related levels of greenhouse gas emissions. Determining the role of these factors, let alone simply projecting future levels of energy use, is a very difficult matter. In fact, extensive analysis of even high-quality historical energy consumption data has revealed great difficulty in clearly determining the role of any single causal factor (DOE 1989).

What is clear, however, is that achieving emissions reductions will require taking advantage of the natural turnover of existing energy capital stock. As older, less efficient capital units are retired from the stock, the opportunity exists to replace these units with state-of-the-art technologies with lower emissions. If this opportunity is missed, however, it may be missed for decades because many types of energy capital last 40 years or longer. A similar opportunity for "injecting" state-of-the-science technology into the capital stock also arises as population increases, economic growth, and other pressures create a demand for expansion. If new power plants, cars, and homes are to be built and used to provide services for a larger and wealthier population (for example), the opportunity to do so in a relatively low emission manner is an important policy consideration.

The turnover rate of the existing energy capital stock and the expansion of that stock from addition of new units depend on a number of factors, but the average age of existing facilities and the typical expected lifetime of individual units are two basic components. Table 1.6 provides a summary of the average ages and the expected lifetimes for significant energy-consuming classes of U.S. capital stock by energy-using sector. This information was obtained from a survey of the literature on capital stock service lives and age frequency distributions.[a] Although this information is of varying quality and reliability, the data indicate that some end-use technologies (e.g., automobiles) tend to turn over relatively rapidly, while others (e.g., buildings and electric power plants) may last half a century or longer.

Tables 1.7 and 1.8 provide age distributions for passenger cars and trucks and for coal- and natural-

(a) A. K. Nicholls et al. 1991. "Energy-Using Capital Stock Service Lives: A Survey of the Literature." Draft paper, Pacific Northwest Laboratory, Richland, Washington.

Table 1.3. Fossil and Nuclear Electricity Technologies: Technology Costs and Characteristics

Technology	Capital Cost[a,b] (1989$/kW) 2000	2010	2020	O&M Cost[c] (mills/kWh)	Commercial Year[d]	Heat Rate (Btu/kWh)	Load Use	Capacity Factor[e]
Coal Steam	1,355	1,355	1,355	4.3	--	11,000	Base/Int	0.65
Coal Steam w/flue gas desulfurization	1,535	1,535	1,490	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
Atmospheric Fluidized-Bed Combustor	1,300	1,300	1,300	10.2	1,990	9,750	Base	0.70
Pressurized Fluidized-Bed Combustor	1,440	1,200	1,200	13.0	1,996	8,400	Base/Int	0.70
Integrated Gasification Combined Cycle	1,415	1,280	1,280	8.9	1,994	9,220	Base/Int	0.70
Steam Injected/ Intercooled Steam-Injected Gas Turbine	600	600	600	2.1	1,990	7,260	Base/Int	0.70
Gasification Steam-Injected Gas Turbine	1,455	1,240	1,025	6.4	2,005	8,530	Base/Int	0.70
Gas Fuel Cells	860	705	705	10.9	1,997	6,450	Inter	0.47
Coal Fuel Cells[f]	1,335	1,335	1,235	10.9	2,025	7,130	Base/Int	0.80
Light Water Reactor	1,785[g]	1,785[g]	1,785[g]	26.6[h]	--	10,800	Base	0.65
Advanced Light Water Reactor[i]	1,490	1,375	1,375	8.9	1,996	10,200	Base	0.75
2nd Gener. Nuclear[i]	1,775	1,480	1,480	13.0	2,000	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, Volume II of this study.

(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 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 6000 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 to reflect the historical cost of installing new capital equipment in response to new or modified Nuclear Regulatory Commission requirements.

(i) New nuclear orders are assumed to require changes in policy and are therefore not included in the Current Policies Case; they are included in the NES Actions Case. Cost excludes $170/kW decommissioning cost.

Source: DOE 1991, Table A-19, p. 92.

Table 1.4. Life-Extension/Repowering Costs and Characteristics[a]

Technology	Capital Cost[b] (1988$/kW)	O&M Cost (mills/kWh)	Commercial Year	Heat Rate (Btu/kWh)	Construct Time (years)
Coal Steam	235	4.3	1,990	10,400	3
Oil/Gas Steam	155	5.0	1,990	9,500	3
Nuclear	580	11.2	1,990	10,200	3

(a) Full-life extension is assumed for all fossil plants in excess of 200-MW capability; life extended capacity equals 340 GW by 2010.

(b) Costs do not include costs of compliance with new source performance standards.

Source: DOE 1991, Table A-20, p. 93.

Table 1.5. Renewable Electricity Technologies: Technology Costs and Characteristics

	1990	2000	2010	2020	2030
Photovoltaics					
Capital cost (1989$/kW)[a]	---	3620	2130	1385	1170
O&M cost (mills/kWh)	---	2	2	2	1
Capacity factor	---	28%	28%	28%	28%
Solar Thermal					
Capital cost (1989$/kW)[a]	2130	1600	1600	1830	1830
O&M cost (mills/kWh)	11	9	9	8	8
Capacity factor	37%	37%	37%	43%	43%
Wind Farms					
Capital cost (1989$/kW)[a]	1100	1000	965	915	850
O&M cost (mills/kWh)	18	12	9	8	8
Capacity factor	20%	28%	29%	30%	31%
Geothermal					
Capital cost (1989$/kW)[a]	2215	2110	2025	1915	1790
O&M cost (mills/kWh)	26	19	13	21	9
Capacity factor	81%	85%	90%	95%	95%
Biomass Electric					
Capital cost (1989$/kW)[a]	1600	1600	1600	1600	1600
O&M cost (mills/kWh)	9	9	9	9	9
Capacity factor	70%	70%	70%	70%	70%
Heat rate (Btu/kWh)	13000	13000	13000	13000	13000

(a) Represents the overnight construction costs.

(b) Solar thermal costs reflect the penetration of new technologies after 2010.

(c) Geothermal and biomass electric are base-load technologies; others are intermediate or peak load.

Source: DOE 1991, Table A-24, p. 94.

Table 1.6. Average Ages and Expected Lifetimes for Significant Energy-Consuming Components of the U.S. Capital Stock

Capital Stock Component	Average Age of the Stock (Years)	Expected Lifetime (Years)
Electric Utility Sector		
Coal-Fired Electric Generating Plant	26.7	45
Gas-Fired Electric Generating Plant	30.3	45
Oil-Fired Electric Generating Plant	31.8	45
Transportation Sector		
Passenger Cars	7.6	12
Trucks	7.9	16
Commercial Jets	12.8	25
Diesel Locomotives	15.2	25
Buildings Sector		
Single-Family Homes	29.0	80
Multi-Family Homes (5 or more units)	22.4	65
Office Buildings	25.0	36-90
Health Care Buildings	20.0	48-90
Gas Furnace	12.5	19-23
Electric Forced-Air	10.1	23
Electric Heat Pump (heating application)	5.5	23
Electric Water Heater	6.7	13
Refrigerator	9.8	18
Industrial Sector		
Integral Horsepower Motors	7.6	18
Generators	9.0	18
Gas Internal Combustion Engine	4.2	14
Diesel Internal Combustion Engine	4.7	14

Source: A. K. Nicholls et al. 1991. "Energy-Using Capital Stock Service Lives: A Survey of the Literature." Draft paper, Pacific Northwest Laboratory, Richland, Washington.

Table 1.7. Age Frequency Distribution of the Stock of Automobiles and Trucks (as of 1989)

	Automobiles[a]		Trucks[b]	
Age (years)	Vehicles (thousands)	Percent of Total	Vehicles (thousands)	Percent of Total
1 or less	16,771	14	8,015	15
2 - 5	40,825	33	17,016	32
6 - 10	35,022	29	11,349	21
11 - 15	20,299	16	9,719	18
16 and older	9,835	8	7,098	13
Total	122,752	100	53,197	99

(a) ORNL 1991, Table 3.9, Pages 3-18.
(b) ORNL 1991, Table 3.19, Pages 3-30.

gas-fired electricity plants over 100 megawatts in capacity. For automobiles, the median service life is 12 years. That is, an automobile has a 50/50 chance of still being in circulation after 12 years. The present age frequency distribution for automobiles reveals that nearly 50% of all automobiles are 5 years old or less. The implication is that in 7 to 12 years, about half of the vehicles currently under 5 years of age (coming to nearly 29 million) will be retired and presumably replaced. The conclusion to be drawn is that even with the newest cars, there is substantial opportunity for technology replacement in the short to medium term. There is slightly less opportunity with trucks. As with cars, nearly 50% of all trucks are 5 years old or less. But because trucks have median service lives that are 4 years longer than cars, it will take relatively longer for these trucks to be retired and, hence, replaced.

Table 1.8 indicates that about 30% of all coal-fired power plants are 21 years or older, while nearly 60% of all gas-fired plants are 21 years or older. Because both types of plants have expected service lifetimes of 45 years (in the absence of life extension), a relatively larger proportion of gas-fired than coal-fired units is nearing retirement. This implies that there is a somewhat greater opportunity for upgrading the efficiency of the gas-fired stock in the near term than the coal-fired stock, everything else equal.

Table 1.8. Age Frequency Distribution of the Stock of Coal- and Natural-Gas-Fired Steam Electric Power Plants (Greater than 100 MW in Capacity)[a]

	Coal		Gas	
Age (years)	Units	Percent of Total Capacity	Units	Percent of Total Capacity
0 - 10	146	27	2	2
11 - 20	222	41	85	41
21-30	210	20	126	42
31 and Above	220	12	96	16
Total	798	100	309	101

Note: Percentage totals may not sum to 100 due to independent rounding.

(a) Calculated from data in DOE 1988.

Tables 1.6 through 1.8 provide a starting point for developing an estimate of the potential rate of greenhouse gas reductions resulting from the introduction of new technologies into the energy capital stock. Obviously, a much more rigorous approach is needed to assess the potential rate with sufficient accuracy, including age frequency distributions for all important types of capital, estimations of the potential for life extension, and perhaps most importantly, sufficient understanding of the barriers to technology adoption, by type of capital.

Information about the rate of technology turnover provides an idea of the ***potential*** for greenhouse gas reduction from new technology, but the near-term ***feasibility*** of new technology penetration into the stock is largely a function of the various barriers to new technology adoption. These barriers may include economic considerations such as first cost affordability and performance, as well as institutional, legal and informational factors. For example, while the stock of cars turns over at a relatively rapid rate, this fact by itself does not address the feasibility of actually replacing standard internal combustion vehicles with, for example, electric vehicles.

Clearly, a number of market factors will need to be evaluated--performance, ability of the infrastructure to deliver the fuel, availability of information--to determine the rate at which this new technology might actually enter the vehicular stock. Such market assessments, along with information about capital turnover rates, will allow the most accurate identification of the opportunities for emissions reductions.

1.7 OUTLINE OF THE VOLUME

The remainder of this volume contains technology characterizations to provide more detailed performance and cost data on the major classes of technology discussed in this chapter. The volume begins with energy supply and transfer technologies. Chapter 2 presents the fossil-fueled technologies, including both liquid and gaseous fuel production, as well as electricity generation. Synthetic fuel production, such as coal-gasification or liquefaction, is not covered. Chapter 3 discusses nuclear fission technology used in electricity production. Chapter 4 covers renewable technologies, including electricity and biomass fuels production, and direct heating. Chapter 5 discusses energy storage, transmission, and distribution technologies, primarily for electricity, although liquid and gaseous fuels are also treated.

Energy end-use conversion and use technologies are covered in the next three chapters. Chapter 6 begins the end-use technology discussion with transportation technologies. Chapter 7 presents the industrial sector technologies. Chapter 8 covers residential and commercial buildings.

The last chapters cover use of environmental controls to remove carbon or carbon dioxide before it is released into the atmosphere (Chapter 9) and finally, technologies for restructuring end-use energy demand (Chapter 10).

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2.0 FOSSIL ENERGY PRODUCTION AND ELECTRICITY GENERATION TECHNOLOGIES

This chapter focuses on oil, gas, and coal production activities and electric utility consumption of these fuels. Also discussed are associated emissions of greenhouse gases and new power generation technologies that may help to reduce these emissions. The related activities that may give rise to emissions are described; the data sources from which emission estimates might be obtained are reviewed; and preliminary values for emission factors that might be used in modeling efforts or long-term projection studies are estimated. The chapter is organized in three sections. Section 2.1 describes the outlook for energy supplies from oil, gas, and coal; Section 2.2 describes sources of greenhouse gases related to oil, natural gas, coal, and electric utilities; and Section 2.3 provides a summary of greenhouse gas emissions resulting from these activities.

2.1 OUTLOOK FOR ENERGY SUPPLY

Studying the effects of greenhouse gas emissions involves not only identifying the sources and the current levels of emissions but also the projected use of these sources well into the future. This section discusses the expected supply and use of oil, natural gas, and coal fuels and the resulting greenhouse gas emissions.

2.1.1 The U.S. Situation

In 1985, domestic oil, natural gas, and coal production accounted for more than 65% of the primary energy supplied to (consumed by) the U.S. economy. Energy imports, almost exclusively oil, accounted for 10% of this supply. Figure 2.1 is a plot

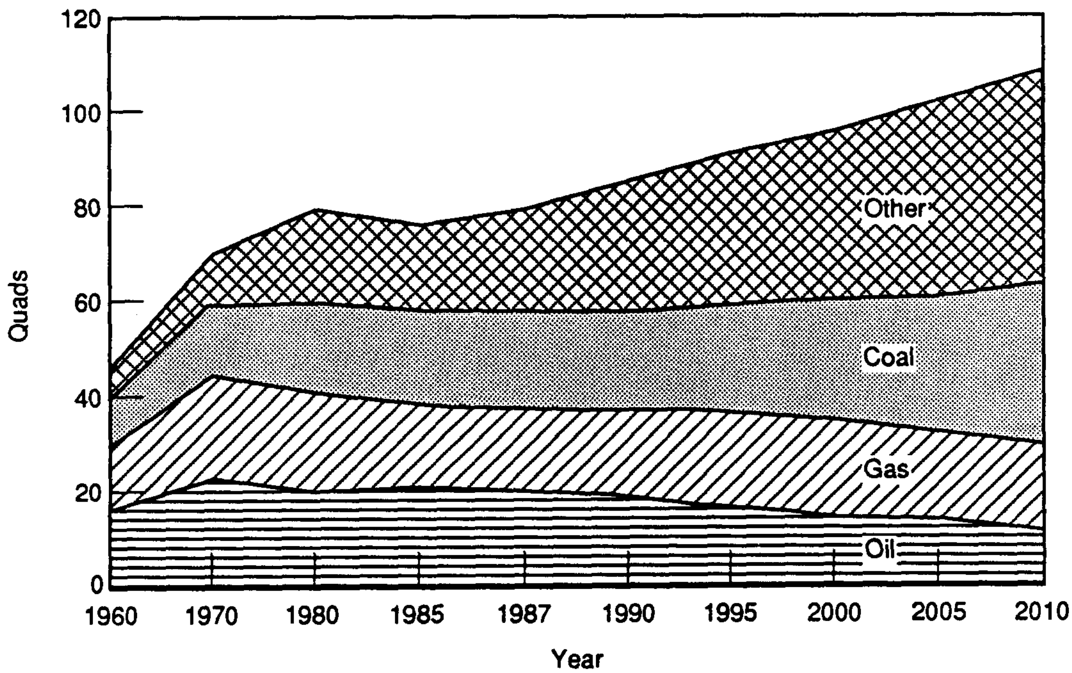

Figure 2.1. Outlook for Energy Supply Activity

showing the total energy supplied to the economy from 1960 and projected through 2010, assuming no changes in current policies. The relative volumes of oil, natural gas, coal, energy imports, and other energy sources are also shown. The "other energy sources" category is composed of nuclear and renewable energy sources. The projections are from the National Energy Policy Plan Projections prepared by the Office of Technology Policy of the DOE. Table 2.1 supplements this figure by showing the amounts of energy supplied for each source in quadrillion Btu (quads).

Energy consumption in the economy is expected to increase by 36% between 1987 and 2010, from 78.9 to 107.6 quads. Projections indicate that the total energy supplied domestically will increase by 19% in this same time period, from 67.7 to 80.7 quads. Because the total energy to be supplied domestically is not expected to increase as fast as the total energy demand, the percentage of total energy supplied by imports will increase from 14.2% to 25.0% for this time frame.

Over 90% of these imports are expected to be oil. Oil production in the United States is expected to drop steadily while oil imports are projected to double. However, natural gas production in the United States is projected to increase somewhat in the 1990s and then return to its 1987 level by 2010. Coal production is expected to increase by 67% over its 1987 level. The projections indicate that by 2010, domestic oil and natural gas together will account for less than 26% of all energy consumed, while coal will make up more than 31%. Estimated fossil energy reserves in the United States are shown in Table 2.2. Their expected duration at current production rates is also shown. Relative availability of these resources will be a major criterion in selecting from among alternative fossil energy technologies.

From an emissions standpoint, greenhouse gas emissions from oil production in the United States should decrease as reserves are depleted. However, consumption of oil is expected to increase through imports. Thus, the refined and transported volume will increase, thereby increasing the potential for greenhouse gas emissions from these sources. For coal and natural gas, the expected increases in production will increase the potential for the emission of greenhouse gases, especially for coal if its production level increases by 67% as is projected.

2.1.2 World Energy Situation

The world is currently dependent on fossil fuels to supply over 88% of its total primary energy and to generate over 60% of its electricity (DOE 1990a).

Table 2.1. Energy Supply and Demand Outlook

Year	Oil	Gas	Coal	Nuclear	Renewable	Total Domestic Supply	Primary Energy Demand	Imports[a]
1960	16.4	12.7	10.8	--	2.9	42.8	45.1	2.7
1970	22.9	21.7	14.6	0.2	4.1	63.5	67.9	5.8
1980	20.5	19.9	18.6	2.7	5.4	67.2	78.2	12.1
1985	21.2	16.9	19.3	4.2	6.3	67.9	76.8	7.7
1987	19.8	16.8	20.1	4.9	6.0	67.7	78.8	11.3
1990	18.5	17.7	20.5	5.9	6.1	68.9	84.0	15.2
1995	15.8	19.7	22.6	6.1	7.1	71.4	90.2	18.8
2000	13.9	19.4	25.5	6.2	8.4	73.4	95.1	21.7
2005	12.6	17.8	29.2	6.2	9.9	75.7	100.6	25.5
2010	11.4	17.1	33.7	6.2	12.3	80.7	105.7	26.9

(a) Imports may not exactly equal supply minus demand, adjustments from stock changes will make up the difference.
Source: National Energy Policy Plan Projections, preliminary data dated January 1989.

Table 2.2. Fossil Fuel Resources in the United States

Fossil Fuel	U.S. Reserves[a] (Quads)	Estimated Production Life (yr)[b]	Estimated Consumption Life (yr)[c]
Coal	5758	255	302
Natural Gas	1411	78	73
Petroleum & Natural Gas Liquids	1080	61	32

(a) Includes estimates of future discoveries.
(b) At 1990 rates of production.
(c) At 1990 rates of U.S. consumption. Values assume 100% of U.S. demand is supplied by U.S. reserves and there are no exports. Values are shown for purposes of comparison only.
Source: Derived from DOE 1990b, 1989, 1991.

Table 2.3 lists estimates of the world reserves of fossil energy resources and estimated duration of these resources based on current (constant) rates of production. While new resources are likely to be discovered, the increasing rate of fossil fuel use by both developed and (especially) developing countries will tend to counteract the effect of additional reserves and could reduce these estimated lifetimes significantly. As fossil fuel reserves are depleted, advanced fossil technologies with their higher operating efficiencies will play an increasingly important role in the development of lesser-developed countries.

Table 2.3. Fossil Fuel Resources in the World

Fossil Fuel	World Reserves[a] (Quads)	Estimated Life (yr)[b]
Coal	22400	325
Natural Gas	13000	190
Petroleum	5750	40-50

(a) Includes estimates of future discoveries.
(b) At current rates of world production.
Source: Derived from DOE 1990c and WEC 1989.

2.2 DESCRIPTION AND CHARACTERIZATION OF ACTIVITIES

The following subsections contain descriptions of activities related to the production of fossil fuels and the use of these fuels to produce electricity. Detailed discussion of end-use technologies (for direct use of fossil fuels in the industrial, residential/commercial, and transportation sectors) can be found in the appropriate chapters elsewhere in this volume.

2.2.1 Oil

The fuel cycle of oil extends from the discovery of crude oil thousands of feet below the surface of the earth to the delivery of refined products to users. The operations included are drilling, production, refining, storage, and transportation. Figure 2.2 is a diagram involved in these operations result in the emission of greenhouse gases, primarily methane and carbon dioxide, either fugitively or through combustion. The following section discusses technologies involved in oil operations and the potential for and magnitude of greenhouse gas emissions.

Drilling

The first phase of oil operations is drilling for reserves. The greenhouse gas emissions of major

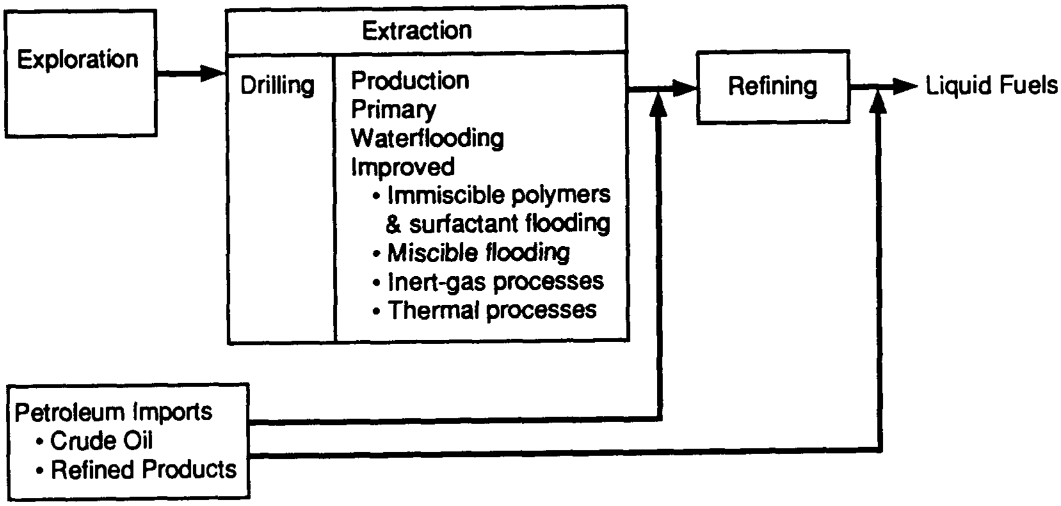

Figure 2.2. Crude Oil Resource Development

concern in this phase are carbon dioxide and methane. There are several potential sources for emissions during drilling. First, large combustion engines are used to hoist and rotate pipes and to pump the drilling fluid used to drill the well. Compared with other industrial processes, however, the total amount of fuel consumed in drilling is small, resulting in minor gas emissions from combustion. The second potential source of greenhouse gas emissions is the drilling fluid system. Drilling fluid (known as "mud") is circulated continuously through the drill pipe to the bore cutting surface where it lubricates the drilling bit and carries the drilling by-products to the surface. The drilling fluid is typically exposed to the atmosphere at the surface. This exposure allows hydrocarbon gases (predominantly methane) that enter the well below the surface to escape into the atmosphere. However, drilling systems are designed to minimize the amount of hydrocarbon gases entering the system. Otherwise, if a significant amount of hydrocarbons did enter the well, control could be lost, and the well could blow out, resulting in an uncontrolled release of hydrocarbons to the atmosphere. A blowout is the largest potential source of greenhouse gas emissions in drilling, providing not only a threat of fugitive methane emissions but also a major threat of fire. Nevertheless, less than 0.05% of all wells drilled blow out, and as technology continues to advance, the number of blowouts is expected to decrease.

Producing and Treating

After an oil well has been drilled and economically exploitable reserves discovered, the well is completed and production commences. The production process involves lifting the fluid out of the ground and transporting, treating, and storing the oil within the field. Potential sources of greenhouse gases from oil production include the use of combustion engines and the fugitive emission of methane. Combustion engines are often employed to power the mechanical pumps used to remove the fluid from the reservoir and to inject water or other fluids as necessary for improving recovery. Combustion engines emit carbon dioxide and air pollutants. As for fugitive methane emissions, natural gas and water typically are produced to some degree with the oil. The produced fluid is then treated in the field to remove natural gas and water. Inefficiencies in this process (i.e., valve and vessel leakage) provide opportunities for methane to escape to the atmosphere.

Fuel Use and Emissions from Oil Production

Data on the magnitude of greenhouse gas emissions for each one of the above oil production technologies are not available on an individual process basis. However, data from the National Acid Precipitation Assessment Program (NAPAP 1989) inventory and the National Energy Accounts (NEA 1989) are available for these activities. Preliminary information indicates that most of these emissions come from oil production and treating and that very few come from the drilling process. The NEA contain estimates of the amount of fuel burned in the petroleum production process. These estimates can be used to estimate the amount of carbon dioxide emitted. Approximately 172 trillion Btu of energy were used in producing crude oil in the United States in 1985. Based on carbon dioxide emission factors for the various fuel types, estimated carbon dioxide emissions from petroleum production in 1985 would have been 11.9 million tons.

Refining

From the field, oil is taken to the refinery where it is processed into a variety of products. As in oil production, the major greenhouse gases that are emitted in refining are methane and carbon dioxide. Fugitive methane emissions result mostly from leaks in seals and valves; whereas, carbon dioxide emissions result from combustion used in the many phases of refining. The major stages in refining include distillation, sulfur removal, cracking, and reformation. Figure 2.3 is a schematic of the refining process. The crude oil is initially passed through a distillation tower where it is heated, releasing various products at different heights of the tower. Depending on their components, these products may pass through desulfurization, cracking, and reformation processes. The energy efficiency of the total refining process is approximately 90% to 95%, varying with the age of the refinery. Leaks in valves and seals at numerous places in the refinery allow fugitive emissions of methane, and the large amount of combustion that takes place for heating and treating the various

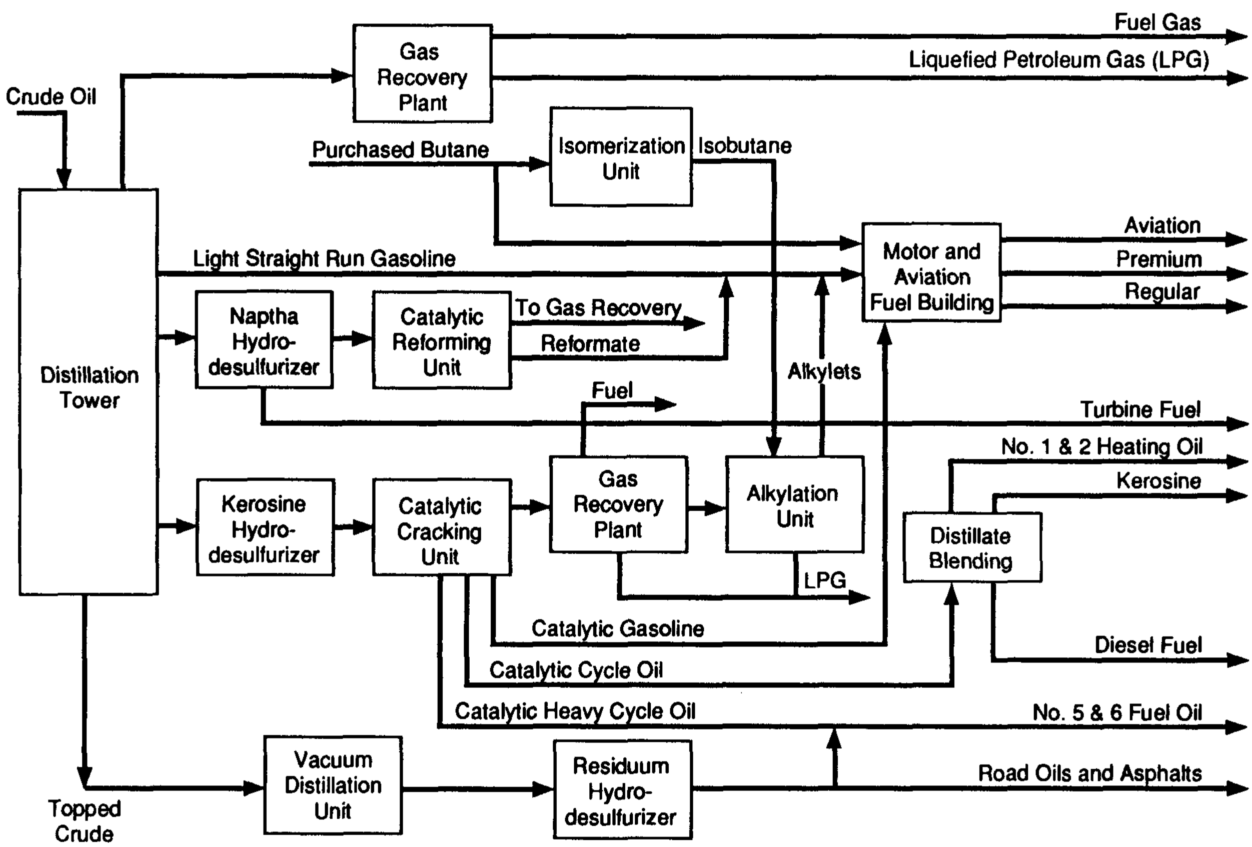

Figure 2.3. Schematic of the Refining Process

products emits carbon dioxide. Any measures that reduce throughput correspondingly reduce the incidence of these emissions. The largest source of carbon dioxide emissions is in the cracking process, where the larger-molecule heavier oils are converted (cracked) into those with smaller molecules (e.g., gasoline, diesel fuel, etc.). In this process, large amounts of coke are formed and then burned as a catalyst in the cracking process, resulting in large emissions of carbon dioxide.

Because procedures for reporting emissions are more stringent in the refining process than in the production process, the estimates for carbon dioxide inventory data indicate that fugitive methane emissions from refining are greater than those from any other technology discussed in this section. For 1985, an estimated 123,000 tons of methane escaped in the refining process; however, this number may also be in error, and there is a need for further research to determine a more reliable value. As for fuel use, NEA data suggest that petroleum refining is by far the largest user of fuel of any primary energy technology (i.e., excluding electricity generation) discussed in this chapter--approximately 2,900 trillion Btu in 1985. Considering that approximately 28,000 trillion Btu were input, this yields an overall refining efficiency of approximately 90% (about 10% of the input energy was used for fuel). This number is consistent with the average efficiency of the refining process as reported by industry experts. Using fuel-specific emission factors, this energy consumption resulted in roughly 221 million tons of carbon dioxide being emitted during 1985. As is true of carbon dioxide, most methane emissions from refining operations are a result of the catalytic cracking process.

Transportation, Storage, and Transfer

Transportation, storage, and transfer activities are covered in Chapter 5.

2.2.2 Natural Gas

The fuel cycles of natural gas and oil are somewhat similar. Different production, treatment, and storage activities, however, cause major differences in greenhouse gas emissions. Figure 2.4 shows the steps involved in developing the natural gas resource. The low physical weight of natural gas reduces the need for combustion processes at the production stage, and the simpler molecular structure reduces the complications of the treating process. The amount of combustion needed is less than that required for treating oil; thus, less carbon dioxide is emitted in this fuel cycle. On the other hand, natural gas is harder to control during storage, and it primarily consists of methane. Therefore, fugitive methane emissions resulting from natural gas operations are much larger than those from oil production, treatment, and storage. The following sections discuss the technologies involved in developing natural gas into a fuel source and the

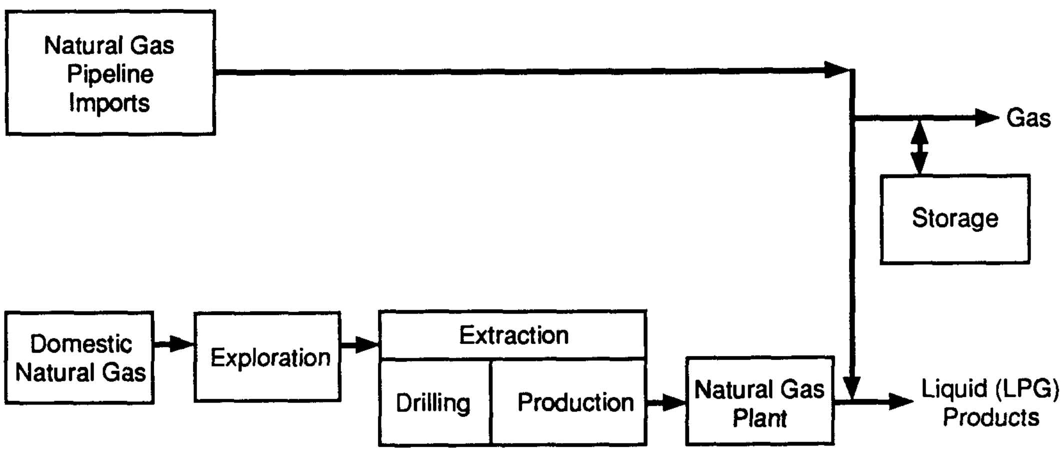

Figure 2.4. Natural Gas Resource Development

resulting greenhouse gas emissions. Figure 2.5 diagrams the natural gas fuel cycle and shows 1987 estimated volumes of gas in the various phases.

Drilling

The basic drilling functions for gas wells are essentially identical to those for oil. The blowout rate of gas wells is somewhat higher than that of oil wells, but is still less than 0.2% of all wells drilled.

Producing and Treating

The production process for natural gas is simpler than that for oil because less mechanical energy is required and recovery efficiencies are higher, thereby reducing the need for secondary and enhanced oil recovery techniques. (Enhanced oil recovery as a means of carbon dioxide disposal is described in Chapter 9.) Natural gas is recovered by the energy of the reservoir until this energy level is too low to push gas to the surface. At this point, if the gas is dry, a compressor is installed to aid in the production. Because of the relatively infrequent use of mechanical energy, combustion and its related carbon dioxide emissions are not a major issue in natural gas production. The major source of greenhouse gas emissions in natural gas production is the fugitive emission of methane. Emissions from natural gas before its treatment are difficult to estimate, however, because of difficulty in trying to obtain an accurate measure of what is being produced from beneath the surface. Typically, some amount of liquid (oil, liquid gas, or water) is produced with natural gas. This multiphase fluid flow makes it hard to accurately measure the amount of natural gas produced.

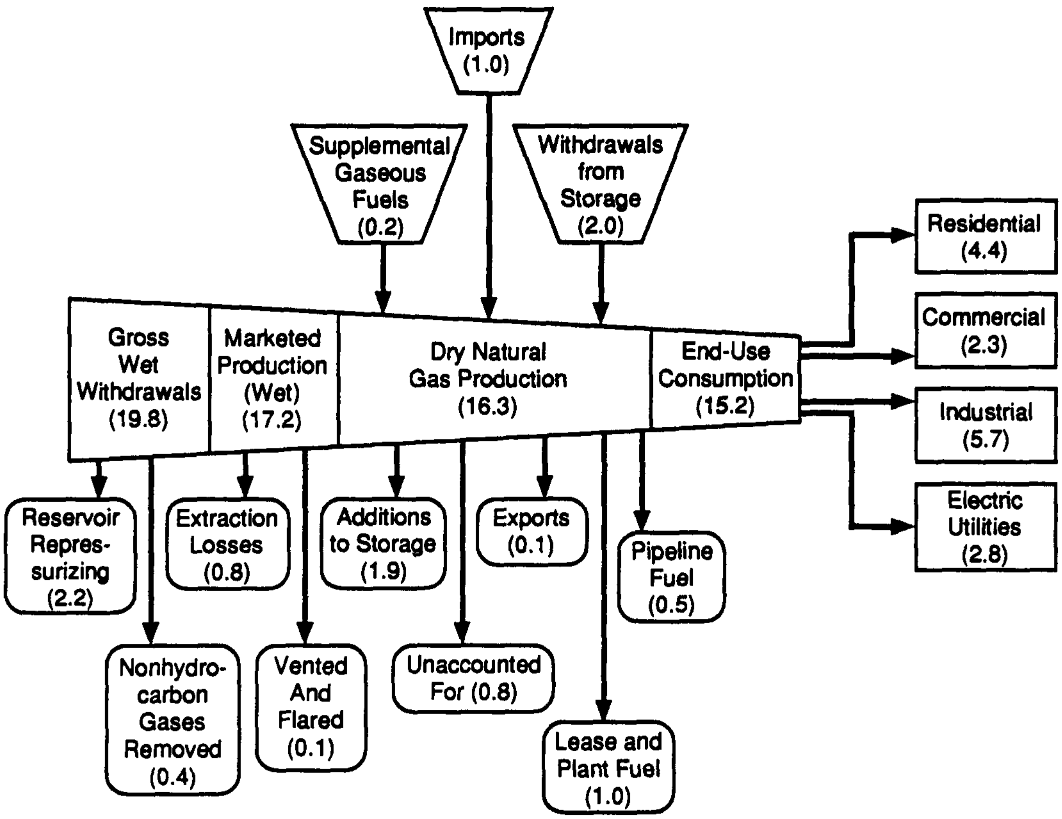

Figure 2.5. Supply and Disposition of U.S. Natural Gas - 1987
(Numbers in parenthesis are trillion cubic feet.)

Without an accurate measurement, it is impossible to know exactly how much natural gas has been lost before it reaches the treatment facilities. Losses before treatment are, however, thought to be low.

Once natural gas is brought to the surface, it is passed through treatment facilities to remove the impurities. The gas is then transported by pipeline to a processing plant, where the gas is further processed into the final products, typically dry gas and liquid hydrocarbons. The numerous pipe connections, valves, and vessel seals provide places where methane can escape. Fisher[a] quotes a gas utility study that estimated natural gas leakage from a new, well-maintained distribution system may be as much as 0.14% of throughput. One potential approach to reducing gas leakage from pipelines is the use of anti-corrosion technologies for metal fittings and components that help to maintain the integrity of seals. General maintenance and monitoring of existing distribution components also minimize methane emissions. Technologies that perform or aid in these duties thereby help to reduce emissions. Also, at the gas processing plant, a large amount of combustion is used to treat the gas, resulting in carbon dioxide emissions. Chapter 5 contains a more detailed discussion of technologies for reducing pipeline emissions.

2.2.3 Coal

As with oil and natural gas, the fuel cycle of coal is a multi-stage process with the potential for greenhouse gas emissions at each stage. As is shown Figure 2.6, the development of coal as a fuel resource has basically four stages: 1) exploration, 2) mining, 3) beneficiation (preparation), and 4) transportation. Emissions from all stages are minimal with the exception of coal mining. The potential for emissions and technologies involved in reducing emissions from coal mining are discussed in this section. Again, emissions of methane and carbon dioxide are the predominant concerns.

Mining

There are two basic types of coal mining: surface and underground. In the past, underground mining accounted for most of the coal produced domestically. However, surface mining has become more popular

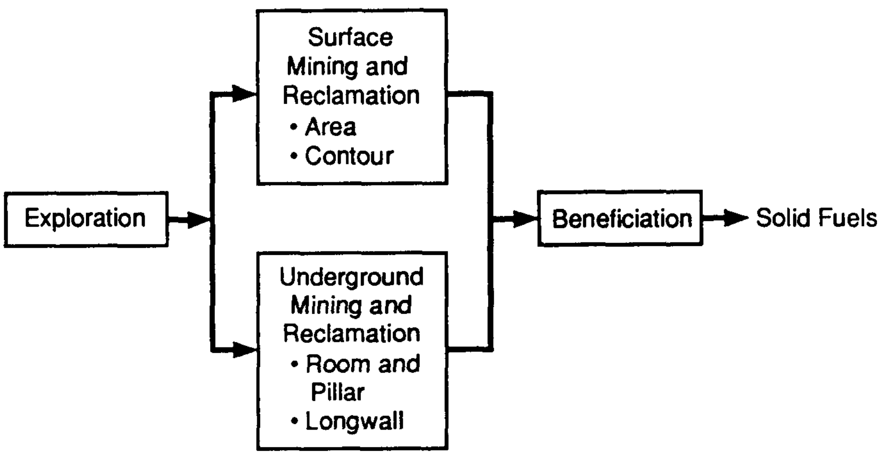

Figure 2.6. Coal Resource Development

(a) Fisher, D. 1990. Draft Report. *Options for Reducing Greenhouse Gas Emissions*. The Stockholm Environment Institute, Stockholm, Sweden.

in recent years and now accounts for most of domestic coal production. In surface mining, coal reserves near the earth's surface are recovered through some type of excavation technique. Most often, heavy equipment such as tractors and bulldozers is used to recover this coal. Surface mining also involves preparing the surface and restoring it after mining is complete. In both instances, similar heavy equipment is used. Because this equipment is typically powered by internal combustion engines, the potential for carbon dioxide emissions exists.

The technology involved in underground mining is somewhat different. Building access roads and installing facilities on the surface is similar to that of surface mining. The next step involves boring a tunnel to the coal reserves. Once the target is reached, support structures are built and mining commences. Typically, electrically powered machinery is used in the mine to cut and transport the coal to the surface. The use of internal combustion engines is avoided because of the potential for producing flammable gases. Thus, the potential for carbon dioxide emissions from underground mining is smaller than that for surface mining, although some emissions do occur if the electricity is fossil-fuel generated.

2.2.4 Coal Bed Methane Emissions

All coal seams contain some methane. Generally, deeper seams contain more methane than shallow seams. In addition, methane content is a function of coal rank. High rank coals average 200 to 500 cubic feet of methane per ton of coal, while low rank coals have less than 200 cubic feet per ton. In 1985, the Bureau of Mines estimated that 180 mines liberated 100,000 standard cubic feet of methane per day each, with some liberating much greater quantities; the total quantity of methane liberated by these 180 mines was 303.9 million standard cubic feet per day. The total methane content of major coal seams is shown in Table 2.4.

In the past, ventilation was the most common method of assuring that the mine atmosphere was nonexplosive. In the past 10 years, however, the use of methane drainage systems to produce fuel gas has increased substantially. Methane is recovered by drilling wells into the coal seam. Different drilling techniques, along with hydraulic fracturing, are used to increase the methane flow. The project capital costs are strongly dependent on the well depth and the quantity of fracturing fluids used.

Table 2.4. Methane Content of Major Coal Seams

Seam	Trillion Cubic Feet
Piceance Basin	110
Northern Appalachian	61
Central Appalachian	48
Powder River Basin	39
Green River Region	31
San Juan Basin	31
Western Washington	24
Illinois Basin	21
Warrior Basin	18
Raton Mesa	18
Total	401

The methane is pumped from the wells into a collection header and then to the surface cleanup facility. The pumps lower the pressure within the coal formation, thus promoting the flow of methane through the fractures. The raw gas consists chiefly of methane and water, although the gas from some coal seams will contain carbon dioxide. The coal gas does not contain hydrogen sulfide.

The surface facility removes liquid water and any particulate matter and then compresses the methane to pipeline pressure (200 to 800 psig). The compressed gas is dehydrated to pipeline quality in a glycol system. If the raw gas contains carbon dioxide, such as in the case of gas from the San Juan Basin (which contains over 5% carbon dioxide), the compressed gas is fed to a membrane separator to remove the carbon dioxide. The compressed, high-Btu gas product is then metered into an adjacent natural gas pipeline.

Potential for Methane Reduction

This process reduces methane releases from coal seams by recovering the methane for use as fuel. Of the estimated 401 trillion cubic feet of methane contained in the major coal seams shown in Table 2.4, approximately 22% (90 trillion cubic feet) can be economically recovered. Obtaining an economic return on this gas is a relatively new development that may encourage greater recovery of future emissions.

2.2.5 Electric Utilities

Initial efforts at characterizing greenhouse gas emissions from utilities that use fossil-fuel technologies have focused on carbon dioxide and NO_x. Several fossil-fuel-based technologies were selected for this work. These selections represent options that are now used in the electric utility sector or are currently under development.

Three pulverized-coal-fired (PCF) technologies have been selected. The first plant serves as a reference case for the other options and is based on the assumption that no NO_x or sulfur dioxide controls have been incorporated into the plant. The other two plants are assumed to have been equipped with low NO_x burners to keep NO_x production at a reasonably low level. The second plant incorporates a conventional, wet limestone flue gas desulfurization (FGD) system. Use of limestone as the sorbent will increase the carbon dioxide emissions, as this gas is released when the limestone is calcined. In addition, the FGD system itself uses electricity, lowering overall efficiency and increasing carbon dioxide emissions per unit of *delivered* electricity (to consumers). The third PCF plant uses the advanced NOXSO process, which is capable of removing up to 97% of the sulfur dioxide and 70% of the NO_x emissions without increasing the carbon dioxide emissions to the extent seen with conventional limestone-based FGD systems.

Three advanced coal-based technologies are also included. These are the integrated coal-gasification combined cycle (IGCC) with the Shell gasification option (which is assumed to be representative of the available options) and atmospheric and pressurized fluidized-bed combustors (AFBC and PFBC).

Preliminary results for carbon dioxide and NO_x emissions are summarized in Table 2.5. Values are given both in terms of pounds per million Btu of heat input and pounds per million megawatt hours (MWh) of net electrical generation. The latter values allow for a more direct comparison of the options. The carbon dioxide emissions are estimated on the assumption of complete combustion with no production of carbon monoxide.

Nitrous oxides and methane can be released from various points along the fossil-fuel cycle. Quantifying these emissions is very difficult and estimates have indicated a very wide range of values. Short discussions on the emissions of these gases are included in Appendixes A and B.

Table 2.5. Estimated Carbon Dioxide and NO_x Emissions from Selected Fossil Technologies

	Heat Rate	CO_2 Emissions		NO_x Emissions	
Technology	Btu/kWh	lbs/MMBtu	lbs/MWh	lbs/MMBtu	lbs/MWh
Uncontrolled PCF	9,500	207	1,970	1.0	9.5
PCF/Wet FGD	9,850	213	2,100	0.5	4.9
PCF/NOXSO	9,850	207	2,040	0.1	1.0
IGCC	8,730	207	1,810	<0.1	<0.9
AFBC	9,750	221	2,150	0.2-0.3	2.0-2.9
PFBC	8,710	229	1,990	0.1-0.1	0.9-1.7
Oil Steam	9,460	181	1,710	0.6-0.9	5.7-8.5
Gas Steam	9,580	115	1,100	0.6-0.9	5.7-8.6
NGCC	7,570	115	870	0.2-0.3	1.6-2.4
STIG	8,100	115	930	0.2-0.3	1.7-2.4
ISTIG	7,260	115	830	0.2-0.3	1.5-2.2

For the PCF options and the advanced coal-based technologies, the carbon dioxide emissions are dependent on the amount of sorbent used, which in turn is dependent on the amount of sulfur in the coal. For purposes of producing the information shown in Table 2.5, the coal used in these technologies is assumed to be a midwestern bituminous coal with a heating value of 10,100 Btu per pound and a 4% sulfur content.

Oil- and gas-fired steam units are also included even though the number of these units in operation is declining with time. This information will allow current emission rates to be estimated consistently. Other natural-gas-fired units are the natural gas combined cycle (NGCC) and the aircraft-derived advanced turbines using steam injection (STIG) along with versions of STIG that employ intercooling (ISTIG). The STIG and ISTIG options can also be fitted with gasifiers to produce the fuel gas that is burned in the gas turbines. The coal and gas technologies listed in Table 2.5 are discussed in more detail in the following sections.

Pulverized-Coal-Fired Technology

In conventional coal combustion technology, various types of high- and low-sulfur coals are pulverized to a fine powder and are blown into the boiler and ignited. Steam lines in the boiler absorb heat by raising steam that is then converted to electricity through turbines. Some of the ash products of combustion are removed from the base of the boiler, while as much as 80% become particulates in the exhaust stream, requiring removal through technologies such as electrostatic precipitators.

Adding an auxiliary wet-limestone-based, flue-gas desulfurization system to the exhaust stream for control of sulfur emissions (typically 90% effective) results in a small efficiency penalty and an increased heat rate, with a corresponding increase of carbon dioxide emissions. Modern low-NO_x burners minimize emissions of NO_x through carefully designed burner configurations and controlled combustion conditions. The net operating efficiency of a conventional coal plant with wet FGD is typically in the range of 30% to 35% (DOE 1990a).

The NOXSO process is currently in the demonstration phase of development, but is included here for completeness. In the basic process, flue gas passes through a fluidized-bed adsorber downstream of the electrostatic precipitator. Sulfur and nitrogen compounds are adsorbed by spherical beads that are later regenerated elsewhere in the system as the cleaned flue gas passes to the stack. NO_x is recycled to the boiler while the SO_2 is converted to elemental sulfur that has potential market value. The process is expected to achieve SO_2 reductions of 97% and NO_x reductions of 70% and is currently under demonstration at Ohio Edison's Niles Station.

Integrated Coal-Gasification Combined Cycle

Integrated gasification combined cycle (IGCC) is an alternative to conventional coal-fired electric power generation with post-combustion emission controls. Gasification of coal allows pollutant carriers to be removed from the fuel before its combustion in the power plant. Emissions of sulfur and nitrogen oxides and particulates from IGCC facilities are projected to be significantly lower than for existing technologies. Nitrogen and sulfur contained in the gasified fuel are in such forms that they can be attached to adsorbents much more easily than oxides in the flue gas.

The four major processes in an IGCC facility are 1) converting coal into a fuel gas, 2) cleaning the fuel gas, 3) using the clean fuel gas to fire a gas turbine generator and using the hot turbine exhaust to make steam that drives a steam turbine generator, and 4) treating waste streams generated. The first step involves partial oxidation and gasification of the coal into hydrogen and carbon monoxide and other mineral components. The reactor used in the gasification step consists of one of three basic designs: fixed bed (or Lurgi), fluidized bed, or entrained flow. Fixed-bed reactors are tubular pressure vessels which maintain a uniform coal charge that progresses from the top of the vessel to the bottom, where the gasification agents are introduced and ash products are removed. Fluidized-bed reactors feed coal from the bottom of the unit and feed gasifying agents at a velocity sufficient to fluidize the bed. Entrained-flow gasifiers feed gasification agents and very fine-grained coal from the sides of the bed into a very hot reaction chamber so that combustion and gasification start spontaneously and are completed within seconds or even fractions of a second. The fixed and fluidized beds generally operate between 900°C and 1300°C (1650°F to 2370°F), while the entrained bed operates at 1500°C (2730°F) and higher.

Cleaning the fuel gases typically employs passage through cyclones to separate coarse dusts and subsequent washing with various physical and chemical scrubbing processes. The other processes in an IGCC facility, firing the generators and treating the waste streams, are similar to conventional plants.

IGCC plants require 15% less land area than pulverized coal plants with FGD and produce only about 40% of the solid waste produced by a comparable pulverized coal plant. Investment costs are estimated to be slightly lower for IGCC than for conventional plants with FGD. Repowering is a viable IGCC option, where a gasifier, gas stream cleanup unit, gas turbine, and waste heat recovery boiler are added to replace the existing coal boiler. Johansson et al. (1989) quote a study that estimated overall efficiency of 37.9% for a combined cycle station using the existing turbines. This study also estimated that a higher efficiency of 42.1% could be achieved through use of advanced ISTIG gas turbines. Calculated capacity increments in repowering applications can be as high as 230%.

Atmospheric Fluidized-Bed Combustors

In a fluidized-bed design, coal or other fuels and limestone are fed into a bed of hot particles at 800°C to 950°C (1470°F to 1740°F) that are fluidized by upflowing air. The upflowing air creates a two-phase, gas/solid system. One phase consists of solid particles together with the gas just necessary to suspend them; the second phase consists of the excess gas passing through the bed as bubbles. The required particle size is generally about 10 mm (or slightly less), which means that coal must be granulated (versus finely pulverized for other combustion technologies). If the bed is heated to a temperature above the ignition temperature of the fuel to be used, combustion can be sustained by continuing the flow of fuel into the bed while maintaining a temperature substantially below that of a normal flame temperature. Airflow through the bed removes heat from the reacting fuel at such a speed that the temperature does not increase. The relatively low combustion temperature limits NO_x formation, reduces ash fusion problems, and optimizes sulfur capture by the limestone in the bed.

Fluidized beds are exceptionally fuel flexible, and even fuels with extremely low calorific values can be used. In practice, limitations of the hardware used for fuel feeding and ash removal provide the constraints on fuel use (Johansson et al. 1989).

The two major types of atmospheric fluidized-bed technologies are the dense or bubbling bed and the dilute or circulating atmospheric fluidized-bed (CAFB). In the circulating bed, particles pneumatically carried out of the bed are captured by a subsequent trap and returned to the bed for further decomposition. Circulating atmospheric fluidized-bed technology has good potential for both the industrial and utility sectors in repowering existing coal-fired plants (the boiler could be easily coupled to a conventional steam plant) or for construction of new facilities. In repowering applications, CAFB has a capacity increment of approximately 15%.

Pressurized Fluidized-Bed Combustors

In pressurized fluidized-bed combustion (PFBC), the fluidized bed is contained within a pressure vessel operating at a pressure generally between 6 and 15 atmospheres. The pressurized system allows use of a combined cycle where exhaust gases from the boiler drive a gas turbine generator before discharge to the stack. Water-filled coils within the PFBC bed generate steam that is used in a conventional steam turbine cycle to produce electricity. An unusual feature of the combined cycle PFBC is that steam from the boiler is the primary source of electricity (approximately 80%) and is independent of the gas going to the gas turbine, rather than being generated downstream from the gas turbine as in other combined cycle designs. Combustion in the bed occurs at about 850°C (1560°F). With typical steam conditions at about 540°C (1000°F) and 177 atmospheres, the PFBC cycle operates with a net efficiency of 42% to 44% (Johansson et al. 1989).

Combined cycle PFBC permits the combustion of a wide range of coals, including high-sulfur coals. A low fluidization velocity (about 1 m/s) and a relatively deep bed (about 4 m) lead to gas residence times in the bed of around 4 seconds. This long residence time leads to high combustion efficiency and high sulfur capture. Like AFBC, PFBC can be used to repower oil- and gas-fired boiler units, to repower coal-fired power plants, and to build new construction. In repowering applications, PFBC is estimated to have a capacity increment of 40%.

Oil-Fired and Gas-Fired Steam Generation

Oil- and gas-fired electricity plants use the same basic unit processes as conventional coal technology. The chemical energy in the fuel is converted to heat energy in the boiler, the output of which is used to drive a steam generator. The plants may incorporate similar environmental control equipment, including electrostatic precipitators, sulfur dioxide scrubbers, and other waste treatment systems. These plants also operate at similar efficiencies of 30% to 35%.

Natural Gas Combined Cycle

Combined cycle technology refers to the combined use of hot-combustion gas turbines and steam turbines to generate electricity. Steam is generated with the exhaust from the gas turbine and is then used to drive a steam turbine. Electricity is produced by both steam turbines and gas turbines, although about two-thirds of the total power is typically generated in the gas turbine portion of the plant.

Use of combined cycle generation significantly raises the overall thermal efficiency of power plants beyond conventional fossil-fueled plants using either type of turbine alone. A combined cycle efficiency of 45% can be achieved, for example, in 200-MW plants costing $520 per kW (Johansson et al. 1989). Combined cycle plants fueled by natural gas or distillate oil are also simpler than other fossil technologies because they require no gas cleanup systems.

Steam-Injected Gas Turbines

Recent technological innovations allow gas turbines to compete in cogeneration markets characterized by variable heat loads and to compete with baseload electric utility technologies. High-pressure steam injection at the fuel combustor greatly increases the exhaust stream heat capacity and mass flow through the turbine. Compared with a simple-cycle gas turbine, the steam-injected gas turbine STIG) produces more power and has a higher electrical efficiency. The only extra work required to take advantage of steam injection is compressing the steam to boiler pressure. The General Electric (GE) LM-5000 is an aircraft turbine with an electrical output of 33.1 MW and an efficiency of 33% when operated as a simple-cycle gas turbine burning natural gas. With full steam injection, the output increases by 60% to 52.5 MW and the efficiency to 40%.

Intercooling between the two compressor stages reduces the amount of work required in compressing the air flow to the burner. Using a portion of the compressed combustion air to cool the turbine blades allows the turbine inlet temperature to be raised from about 1211°C to 1370°C, boosting the output to about 110 MW at 47% efficiency and an installed capital cost of about $400/kW for the GE LM-5000. The estimated efficiency for the intercooled steam-injected gas (ISTIG) turbine is higher than that of advanced combined cycle plants, while the capital costs are lower. The ISTIG will produce less expensive electricity for natural-gas-fueled plants (Fulkerson et al. 1989).

The STIG and ISTIG have several advantages. STIG and ISTIG units are less complex than combined cycle units (while both systems have a gas turbine and heat-recovery steam generator, a STIG does not have a steam turbine, condenser, or cooling tower). Pollution controls are less costly for a STIG than those for a combined cycle unit. NO_x emissions, a problem with conventional turbine systems because of high combustion temperatures, are greatly reduced by steam injection. The small size of the STIG unit provides more flexibility in capacity expansion. ISTIG plants have yet to be demonstrated commercially.

Fuel Cells

Fuel cells are an advanced electricity technology currently in the demonstration phase of development. Fuel cells convert the chemical energy in a fuel to electricity through electrochemical reaction. The operation of fuel cells is similar to that of a chemical battery except that the fuel and oxidant (usually streams enriched in hydrogen and oxygen) are derived from outside of the cell, rather than contained internally. Fuel cells have significant possibilities for future use of fossil-derived fuels such as gas from coal gasification. The fuel cell itself only requires feedstreams of hydrogen and oxygen which it then converts to water, so that methods to remove and sequester carbon from fossil fuels before their use will minimize carbon emissions.

Fuel cells are generally classified by type of electrolyte. Current types include alkaline, phosphoric acid, molten carbonate, solid oxide, and proton exchange membrane fuel cells. Each type of fuel cell has different operating characteristics and requirements. Phosphoric acid, molten carbonate, and solid oxide fuel cells are under consideration for utility application. Phosphoric acid fuel cells (PAFCs) are the most commercially advanced form, although their performance record is still insufficient to warrant large-scale production. An 11-MW phosphoric acid fuel cell unit is currently under demonstration by Tokyo Electric Power Co. The high operating temperatures of molten carbonate and solid oxide fuel cells (600°C to 700°C and 1000°C, respectively) make them highly suitable for cogeneration applications, and they are able to reform hydrocarbon fuels (break the fuel down into elemental hydrogen and other constituents) directly in the cell rather than in an external reformer. Fuel cells are expected to operate in efficiency ranges between about 36% and 50% (Fulkerson et al. 1989).

Magnetohydrodynamic Power Generation

Magnetohydrodynamic (MHD) power generation is another advanced power generation technology that is a possible user of gaseous fuels derived from fossil resources. This technolgoy involves the flow of a conducting fluid (generally a gas or plasma) through a magnetic field. In the open-cycle magnetohydrodynamic generator, high-temperature (2500°C) combustion products from a fossil fuel are seeded with an element of low ionization potential (e.g., potassium) until enough free electrons are present to provide sufficient electrical conductivity. The interaction between the combustion flow and the fixed magnetic field through which it is directed generates an electromotive force. Magnetohydrodynamic power generation is still in the research and development stage, but could potentially raise the thermal efficiency of a steam-turbine generator to which it was coupled to about 50% to 60% (Fulkerson et al. 1989).

Estimated Costs for Selected Fossil-Fuel Technologies

Capital and operating costs for the selected fossil-fuel technologies are summarized in Table 2.6. All costs are based on a 500-MW plant and are expressed in 1988 dollars.

For those technologies based on coal, the estimates are based on the use of a bituminous coal having 3.5% sulfur with an sulfur dioxide removal capability of 90%. Use of other coals would have a small (5% to 10%) impact on the capital and fixed operating and maintenance (O&M) costs of the power plant. However, the impact of the variable O&M costs could be larger because of the cost of sorbent and waste disposal.

Table 2.6. Capital and Operating Costs of Selected Fossil Technologies

Technology	Capital Cost ($/kW)	Fixed O&M ($/kWyr)	Variable O&M (mills/kWh)	Development Stage
Uncontrolled PCF	1,300	16.0	3.0	mature
PCF/Wet FGD	1,475	25.1	5.8	mature
PCF/NOXSO	1,400	37.1	2.6	demonstration
IGCC (Shell)	1,420	29.2	3.3	demonstration
AFBC	1,300	21.1	6.9	commercial
PFBC	1,440	36.4	9.4	demonstration
Oil Steam	900	5.2	5.1	mature
Gas Steam	820	4.3	4.2	mature
NGCC	615	6.5	1.8	demonstration
STIG	600	2.0	1.0	commercial
ISTIG	600	2.0	1.0	commercial

2.3 GREENHOUSE GAS EMISSIONS SUMMARY

The primary greenhouse gases emitted from the fossil-energy production system discussed here are carbon dioxide and methane. The findings thus far regarding emissions of carbon dioxide and methane from oil, natural gas, and coal technologies are described in Sections 2.3.1 and 2.3.2.

Nitrogen oxide (NO_x) emissions are related to the global warming issue through their ability to absorb outgoing thermal radiation from the earth and through their role as a chemical precursor to stratospheric ozone destruction. The main oxide of concern is nitrous oxide (N_2O) because of its long atmospheric lifetime. NO_x emissions are already the subject of control because of their concurrent role in the formation of acid rain. Discussion of NO_x (focusing on N_2O) emissions from fossil fuel technologies is included as Appendix B.

2.3.1 Carbon Dioxide

Carbon dioxide emissions from primary oil, gas, and coal technologies (excluding electricity generation) were determined by gathering NEA data for fuel use and then applying the appropriate emission factors. Table 2.7 summarizes carbon dioxide emissions from the various technologies in 1985. More detailed tables for each technology are provided in Appendix D; those tables show the amount of each fuel type used and the appropriate emission factor. Table 2.7 shows that petroleum refining accounts for almost 65% of the total fuel used by these technologies and approximately 70% of the carbon dioxide emissions. Estimated carbon dioxide emissions from refining activities in 1985 were 221 million tons, compared with 7.6 million tons from coal mining activities. The total carbon dioxide emissions from these processes was estimated to be 317 million tons in 1985.

Table 2.7. Carbon Dioxide Emissions for 1985 by Industry Sectors (based on NEA data)

Technology	Energy Used (trillion Btu)	Estimated CO_2 Emissions (million tons)
Coal Mining	148.79	7.59
Crude Oil Production	171.62	11.94
Natural Gas Production	854.29	51.17
Natural Gas Liquid Production	423.38	24.66
Petroleum Refining	2900.14	221.04
Miscellaneous (Coal and Oil)	0.52	0.52
Total	4498.74	316.93

2.3.2 Methane Emissions

Estimates of methane emissions associated with the use of oil and gas are extremely uncertain. Several studies have been completed or are under way that attempt to estimate methane leakage rates from the natural gas system in the United States. All these studies emphasize the high level of uncertainty, especially associated with venting losses at the point of extraction. Early estimates of methane emissions, which have been based on so-called "unaccounted for" gas, have ranged from 2% to 4% of total gas use. However, since "unaccounted for" gas is actually a bookkeeping adjustment that includes such items as metering and accounting errors, it does not provide an accurate measurement of actual methane losses. More recent estimates by Pacific Gas & Electric, Pipeline Systems Incorporated, and an ongoing study for the Environmental Protection Agency (Burklin et al. 1991) suggest a range of 1% to 1.5% of total gas use.

The IPCC workshop on methane emissions (1990) cites a study by Pipeline Systems Incorporated (1989) that suggests methane emissions from the natural gas system for 1988 may be on the order of 3 million metric tonnes per year or about 1% of total gas use. These estimates are summarized in Table 2.8 and compared to the preliminary EPA assessment. The largest source of emissions is leakage during normal operations, arising primarily from valves and flanges and pneumatic instruments. Pipeline purging and blowdown also release methane. Leakage from upsets/mishaps is also a significant source of fugitive methane emissions, arising principally at the wellhead. Finally, small leaks in distribution piping are important but highly uncertain. Because of the range of estimates of natural gas loss, a reasonable range of estimates for national methane emissions would be 2 to 6 million tons per year. Methane losses from other components of the oil production system and from oil and gas combustion are small (probably <100,000 tons per year). Table 2.9 presents a more detailed description by point and area source.

Recent research suggests that global methane emissions from oil and gas use are between 20 and 50 million tons in a typical year (Bolin et al. 1986; Sheppard et al. 1982; Lashof and Tirpak 1990; Cicerone and Oremland 1988). Thus, it can be concluded that the United States is responsible for, perhaps, 5% to 10% of worldwide emissions from oil

Table 2.8. Methane Emissions from the Natural Gas System in the United States (thousand metric tonnes/year)

	Normal Operations	Routine Maintenance	Upsets and Mishaps	Total	Percent of Total Production	
					PSI	Burklin[(a)]
Withdrawal and Field Separation	117	<1	1,000	1,117	0.34	0.18
Gathering, Processing, Transmission	948	551	96	1,595	0.48	0.61
Distribution	374	5	47	426	0.13	0.37
Total	1,439	556	1,143	3,138	0.95	1.2

(a) Burklin et al. 1991, data for 1991.

Source: Pipeline Systems Incorporated (1989) as cited in IPCC Workshop report (1990), data for 1988.

Table 2.9. Fuel Cycle Emissions for Oil (Steam) Power Plant

Activity	Emissions, lb/MWh CO_2	NO_x	N_2O	CH_4
Exploration & Development				0.06
Extraction				0.08
Refining	149	0.6		0.08
Transportation, Storage, etc.	40	0.1		0.04
Power Plant	1710	7.1	0.34	0.02
Total	1899	7.8	0.34	0.28

Heat rate: 9460 Btu/kWh

and gas operations. For perspective, global methane emissions from all source types are thought to be in the range of 440 to 640 million tons per year (Cicerone and Oremland 1988; IPCC Workshop Report 1990). Some further discussion of global methane emissions, related methane chemistry, and emissions from selected fossil power plant technologies is included in Appendix C.

2.3.3 Summary Fuel Cycle Emissions from Selected Fossil Energy Technologies

Information on the emissions/releases of various greenhouse gases for selected electricity generation technologies is summarized in Tables 2.9 through 2.13. The objective of these tables (which should be

Table 2.10. Fuel Cycle Emissions for Atmospheric Fluidized-Bed Combustion Power Plant

Activity	Material Inputs Units	Amount	Emissions, lb/MWh CO_2	NO_x	N_2O	CH_4
Coal Mining						
Electricity	kWh/ton	20	19.5			
Diesel Oil	bbl/ton	0.015	6.8			
Residual Oil	bbl/ton	0.002	1.1			
Coal	ton/ton	0.0005	1.0			
Methane (Release)	Cu ft/ton	100				2.16
Coal Preparation						
Electricity	kWh/ton	2.6	2.5			
Transportation						
Diesel	bbl/ton	0.025	11.3			
Power Plant						
Limestone	tons/ton	0.31	124			
Output			2060	2.4	1.5	0.04
Total			2226.2	2.4	1.5	2.2

Basis: Heat rate: 9750 Btu/kWh
Coal: U.S. avg 10,000 Btu/lb
Transportation: Rail 480 km

Table 2.11. Fuel Cycle Emissions for Natural Gas Combined Cycle Power Plant

<table>
<tr><th></th><th colspan="4">Emissions, lb/MWh</th></tr>
<tr><th>Activity</th><th>CO_2</th><th>NO_x</th><th>N_2O</th><th>CH_4</th></tr>
<tr><td>Exploration & Development</td><td></td><td></td><td></td><td>1.08</td></tr>
<tr><td>Extraction</td><td></td><td></td><td></td><td rowspan="2">1.52</td></tr>
<tr><td>Processing, Transmission</td><td>45</td><td rowspan="2">0.3</td><td></td></tr>
<tr><td>Distribution</td><td>27</td><td></td><td>0.41</td></tr>
<tr><td>Power Plant</td><td>870</td><td>2.0</td><td>0.16</td><td>0.10</td></tr>
<tr><td>Total</td><td>942</td><td>2.3</td><td>0.16</td><td>3.11</td></tr>
</table>

Heat rate: 7570 Btu/kWh

viewed as preliminary) is to show the relative contribution to greenhouse gas emissions of the various components of the coal, oil, and natural gas fuel cycles for different fossil fuel electric technologies.

Although these preliminary estimates suggest that the combustion stage of the cycle is most significant, they also suggest that other parts of the fuel cycle should be more carefully examined so as to better estimate the greenhouse gas emissions for the entire fuel cycle.

More complete evaluation will allow for more thorough comparisons among options and, ultimately, will lead to more defensible guidelines and policies regarding greenhouse gases.

Table 2.12. Fuel Cycle Emissions for Integrated Coal-Gasification Combined Cycle Power Plant

	Material Inputs		Emissions, lb/MWh			
Activity	Units	Amount	CO_2	NO_x	N_2O	CH_4
Coal Mining						
Electricity	kWh/ton	20	18.0			
Diesel Oil	bbl/ton	0.015	6.3			
Residual Oil	bbl/ton	0.002	1.0			
Coal	ton/ton	0.0005	1.0			
Methane	Cu ft/ton	100				2.0
Coal Preparation						
Electricity	kWh/ton	2.6	2.3			
Transportation						
Diesel Oil	bbl/ton	0.025	10.5			
Power Plant						
Airborne			1903	0.9	0.14	0.04
Total			1942.1	0.9	0.14	2.04

Basis: Heat rate: 9010 Btu/kWh (Avg.)
Coal: U.S. avg 10,000 Btu/lb
Transportation: Rail 480 km

Table 2.13. Fuel Cycle Emissions for Pulverized Coal Power Plant

Activity	Material Units	Material Amt	Emissions, lb/MWh CO_2	NO_x	N_2O	CH_4
Coal Mining						
Electricity	kWh/ton	20	19.7			
Diesel Oil	bbl/ton	0.015	6.9			
Residual Oil	bbl/ton	0.002	1.1			
Coal	ton/ton	0.0005	1.0			
Methane (Release)	Cu ft/ton	100				2.18
Coal Preparation						
Electricity	kWh/ton	2.6	2.5			
Transportation						
Diesel	bbl/ton	0.025	11.4			
Power Plant						
Limestone		0.12	49.0			
Output			2080.0	5.0	0.14	0.04
Total			2171.6	5.0	0.14	2.22

Basis: Heat rate: 9010 Btu/kWh (Avg.)
Coal: U.S. avg 10,000 Btu/lb
Transportation: Rail 480 km

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3.0 NUCLEAR ENERGY TECHNOLOGY

The principal application of nuclear reactors is for electrical generating stations, although nuclear reactors also have the potential for use in producing steam or hot water for industrial processes or for district heating and cooling systems. Nuclear power has the potential to reduce the emission of greenhouse gases because it does not require combustion to produce electrical energy. There are 111 commercial nuclear power plants operating in the United States today that produce approximately 20% of our electrical energy. In addition, there are currently eight plants with construction permits from the U.S. Nuclear Regulatory Commission (NRC), two of which are actively under construction. All licensed plants are light water reactors, which are cooled by ordinary water. However, because of a decrease in the rate of growth of electricity demand and concerns about safety, disposal of high-level radioactive waste, and large cost overruns that have weakened the financial status of some utilities, there have been no new orders for nuclear power reactors in the United States for more than a decade. Allowing for licensing by the NRC and construction time, the earliest a newly ordered nuclear power reactor could begin operation is near the turn of the century.

In this chapter, we describe the nuclear technologies that could play an important role in avoiding greenhouse gas emissions in the next century, if technology development continues and if policies are implemented that are favorable to the use of nuclear power. Three technologies are described:

- advanced light water reactors, which use ordinary water as a coolant and represent improvements of technology currently in place

- advanced liquid metal reactors, which are sodium-cooled reactors that have passive safety features and may have the potential to consume a portion of the long-lived radioactive waste generated by current reactors and to breed additional fuel

- modular high-temperature gas reactors, which are helium-cooled; are capable of efficient, high-temperature operation; and have passive safety features for reactor shutdown and decay heat removal.

Following the technology descriptions, we discuss barriers to increased use of nuclear power technologies.

3.1 ADVANCED LIGHT WATER REACTORS

This section describes the advanced light water reactor technology and its potential to reduce greenhouse gas emissions. Development needs and commercialization issues are then discussed. Finally, some quantitative performance and cost data are presented, followed by a discussion of the market potential of this technology.

3.1.1 Technology Description

Energy is produced in nuclear reactors from the nuclear fission of certain heavy nuclides (e.g., U-235 and Pu-239) induced by collision with neutrons. In light water reactors, a matrix of uranium dioxide rods (slightly enriched in U-235) is cooled by ordinary water. The water coolant also acts as a moderator; that is, it slows down high-speed neutrons produced by the fission process so that they can be readily absorbed by the uranium and primarily cause additional fission (rather than undergoing nonfission capture by U-238). Light water reactors are either pressurized water reactors, or boiling water reactors, depending on whether the water coolant is allowed to boil.

The matrix, or core, of a light water reactor is contained in a pressure vessel. The pressure vessel and some associated equipment are located in a containment building. The cladding on the fuel rods, the pressure vessel, and the containment building form three lines of defense against offsite releases of radioactivity.

The next generation of nuclear reactors that will be available for order will be improved light water reactors with enhanced safety features, greater operating efficiencies, and improved economics compared with current reactors. Improved light water reactors also differ from the current generation in that they will not be customized for each installation as has been the practice in the past, but rather will be constructed from a few standardized designs.

The major domestic reactor vendors have developed improved light water reactors that are fairly far advanced. These designs can be placed into two categories: evolutionary and mid-sized. The first category includes improved versions of existing large (1300 MWe) reactors that have enhanced safety features and other operational improvements. Design improvements include increased safety margins, simplified piping and valving, advanced digital instrumentation and control, and reduced operation and maintenance requirements. The second category includes advanced, 600-MWe reactors that use a significant amount of technology from existing light water reactors but add passive safety features not found in existing reactors. These features include very large inventories of cooling water stored above the core, gravity-fed and non-mechanically operated emergency core cooling systems, and other safeguards. These passive safety systems use the physical properties of materials and gravity to remove heat automatically in the event of an accident or breakdown. This reduces the likelihood of operator error and provides for prompt emergency response. Should the reactor temperature approach limits for safe operation, the reactor is shut down and damage is prevented without relying on external power supplies or operator action.

The NRC is currently conducting design certification proceedings for four plant designs:

- the General Electric (GE) Advanced Boiling Water Reactor (1300 MWe)
- the Combustion Engineering (CE) System 80+ (1300 MWe)
- the Westinghouse AP-600 (600 MWe)
- the GE Simplified Boiling Water Reactor (600 MWe).

The AP-600 is based on the latest pressurized water reactor technology, with significant simplifications in design, construction, and operation and the use of more passive safety systems. Onsite prefabrication and extensive use of modularized design and fabrication/construction are expected to result in simpler, less costly construction and a shorter construction schedule, compared with current light water reactors. The Simplified Boiling Water Reactor incorporates many of the advanced design features of the Advanced Boiling Water Reactor. In addition, its smaller size and reduced core power density allow the recirculation pumps to be eliminated, such that normal heat removal is accomplished by natural circulation.

During nuclear reactor operation, nuclear fuel is both consumed and produced. Nuclear fuel (fissile nuclides) is created through neutron capture by a fertile nuclide (e.g., U-238), creating an unstable nuclide that decays to a fissile nuclide (e.g., Pu-239). If a reactor burns more nuclear fuel than it creates, it is a converter; if it creates more fuel than it burns, it is a breeder. Light water reactors are converters, and in converters, only about 1% of the uranium is consumed.

At present, domestic supplies of uranium appear to be adequate to support expansion of nuclear power. Based on a future with nuclear plant life extensions and new nuclear plant orders, the National Energy Strategy (NES) forecasts 195 GWe of nuclear capacity to be operating by the year 2030. Reasonably assured uranium resources, plus estimated additional resources at $50/lb, could support that capacity for the entire 60-year life of new plants, as well as the life of existing plants. Additional uranium resources at higher prices could be available in the future.

In the very long term, the availability of uranium could become an issue in the use of nuclear power. A nuclear option consisting only of converters (e.g., light water reactors) would provide electricity for only a limited number of years because the supply of uranium could become exhausted. The lifetime of a converter-only option can be extended if fissile plutonium produced in irradiated fuel rods is reprocessed and recycled back into light water reactors in the form of uranium-plutonium oxide fuels. This option was under serious consideration in the 1960s and early 1970s when electricity demand was growing at an annual average rate of 7%. The slowdown in demand experienced in the past two decades, coupled with economic and nuclear proliferation concerns, led to the U.S. decision to reject this option. Other countries, such as France, the United Kingdom, and Japan, continue to consider reprocessing as a viable option for extending uranium resources. To extend the use of nuclear power, it would be possible to develop breeder reactors for operation in conjunction with light water reactors, thereby increasing the potential use of uranium by a factor of 50 to 70.

3.1.2 Potential for Greenhouse Gas Emissions Reductions

Energy-related greenhouse gas emissions are associated primarily with combustion processes. Because nuclear power reactors produce energy from nuclear fission, rather than from combustion, they do not produce any greenhouse gases during operation. Thus, as a major baseload electric generation technology, nuclear power can play an important role in reducing emissions of greenhouse gases as well as of other air pollutants, such as sulfur dioxide, nitrogen oxides, and air toxics.

The future use of nuclear power both worldwide and in the United States is dependent upon a number of factors, only one of which is global warming and other air pollution issues. Other factors include the economics of nuclear power relative to alternatives in various countries, national energy security considerations, economic and technological development of third world countries, progress in dealing with nuclear waste disposal, and continued safe operation of existing nuclear plants.

Parts of the nuclear fuel cycle are electricity-intensive, particularly the gaseous diffusion process for enriching uranium in the U-235 isotope to the level required by current light water reactors. If this electricity is provided by non-emitting sources, the maximum emissions-reduction benefit of nuclear power is realized.

3.1.3 Development Needs

Advanced light water reactors are currently in the design and design certification stage. Key research and development issues center around safety-related design, construction, and operating requirements and procedures. However, because the development of next-generation light water reactors does not require extensive or bold technological advances over the current generation of light water reactors, it is not expected to require prototypes or significant levels of federally funded research and development.

The advanced light water reactor development program is a coordinated effort among DOE, the utility industry, and reactor manufacturers, with the certification cost shared by government and industry. The goal is to establish conditions so that industry will order and build nuclear power plants by the mid-1990s that would begin operation by the turn of the century.

3.1.4 Cost and Performance Data

Construction costs for evolutionary advanced light water reactor plants are expected to be in the \$1300 to \$1400/kW range. Costs for mid-sized passive advanced plants are expected to be in the \$1400 to \$1500/kW range. Operating costs for these plants are anticipated to be lower than those of today's nuclear generation units because the systems are simplified (fewer components) and the units are standardized (minimum customization and maximum use of standard operating and maintenance procedures). In 1989, nuclear operation and maintenance costs averaged $0.016/kWh, and nuclear fuel costs averaged $0.008/kWh. The advanced light water reactor plants are expected to have fuel costs somewhat lower than this and operation and maintenance costs considerably lower than this.

The fuel used in the advanced pressurized water reactor is uranium dioxide. The enrichment of the fuel varies from 2.5% to 4.4% by weight in a typical pressurized water reactor based on current designs. A typical heat rate value for current light water reactors, 10,200 Btu/KWh, is thought to be attainable, and possibly improved, in the advanced light water reactors.

U.S. reactors have experienced a wide range of capacity factors, with values of approximately 55% to 85% for most plants and an average in the 60% to 65% range. This average capacity factor appears to be increasing. It is expected that a value of approximately 75% can be sustained as mandated shutdowns, unnecessary reactor scrams, and refueling outages are minimized.

3.1.5 Market Potential

Because of their high capital costs, nuclear power plants are used as baseload units and not as peaking or cycling units. According to the analyses supporting the NES, the demand for electricity is expected to continue to grow. It could account for close to 50% of the primary energy consumed in the United States by 2030. It is expected that between 1990 and 2010, about 200 GWe of electric generating capacity will be added in the United States, even with increased energy conservation and demand-side management. By 2030, a substantial amount of additional capacity will be needed to meet an anticipated increase in demand from projected economic growth and to replace retired capacity. Of the 200 GWe required by 2010 and the additional requirements through 2030, up to 85% represents baseload capacity. The importance of lowering fossil fuel emissions will make nuclear energy increasingly attractive for providing this capacity. However, before nuclear power can become a viable option, significant issues with respect to licensing, nuclear waste, safety, and economics must be resolved.

3.2 ADVANCED LIQUID METAL REACTORS

This section describes the advanced liquid metal reactor technology and its potential to reduce greenhouse gas emissions. Development needs and commercialization issues are then described. Finally, some quantitative cost and performance data are presented, followed by a discussion of the market potential of this technology.

3.2.1 Technology Description

The only liquid metal reactor operating in the United States is the second Experimental Breeder Reactor (EBR-II), which has been operating in Idaho for at least two decades. A demonstration fast breeder reactor, the Clinch River Breeder Reactor, was designed during the 1970s, but the project was cancelled in 1983. The Fast Flux Test Reactor near Richland, Washington, is a metal-cooled fast reactor, but the heat removed from the reactor system is exhausted to the atmosphere rather than used to generate electricity.

The advanced liquid metal reactor is a sodium-cooled fast reactor that could provide favorable safety and environmental features. These are provided by the physical properties of the sodium coolant (large heat capacity and high heat-transfer rate), the low pressure of the reactor systems, and the relatively high operating temperatures. The high temperature results in greater efficiency, so that less waste heat is discharged to the environment. The low pressure enhances operating safety. Design features in the system allow convection cooling to be effective when the plant is shut down.

The advanced liquid metal reactor currently being developed is based on the concept of an Integral Fast Reactor system. This system consists of a metal-fueled fast reactor closely coupled to a compact spent fuel reprocessing and refabrication facility. Using this system, the long-lived transuranic actinides (such as plutonium, americium, and neptunium) created by the reactor can be reprocessed for use as fuel in other reactors. In addition, a concept is being studied that would recycle the actinides in spent fuel from light water reactors into the Integral Fast Reactor fuel cycle. The National Academy of Sciences is studying the efficacy of such a concept.

While there is no U.S. program to develop a breeder reactor, it is technically feasible to use advanced liquid metal reactor technology to extend uranium resources by breeding fuel. Breeding would be accomplished by surrounding the reactor core with a blanket of fertile material, such as U-238. With the use of breeder reactors, it is estimated that the uranium resource utilization could be increased by a factor of 50 to 70 over nuclear generating facilities consisting solely of converters.

3.2.2 Potential for Greenhouse Gas Emissions Reductions

Advanced liquid metal reactors would produce little or no greenhouse gas emissions during operation. If spent fuel from advanced liquid metal reactors and light water reactors is recycled, the emissions associated with the advanced liquid metal reactor fuel cycle could be lower than those associated with the light water reactor fuel cycle. The savings would result from a decreased need to mine, transport, and enrich uranium. The advanced liquid metal reactors also have the potential to breed additional fuel, if breeder development is pursued, and thereby to extend the potential use of nuclear power and the accompanying displacement of fossil-fuel-related greenhouse gas emissions.

3.2.3 Development Needs

Development needs for the advanced liquid metal reactor technology are to

- design and demonstrate the technology
- develop and demonstrate the Integral Fast Reactor fuel-cycle technology
- develop waste management technology, including Integral Fast Reactor fuel cycle waste stream processing and packaging for disposal
- determine the technical and economic feasibility of burning actinides from light water reactor spent fuel by separating and recycling to the advanced liquid metal reactor.

The overall goal of the advanced liquid metal reactor development program is to achieve technical and economic feasibility and acceptable system performance of the Integral Fast Reactor system by 2007 to 2010 and to be able to deploy commercial advanced liquid metal reactors after 2010. A second goal is to determine the technical feasibility of using a pyrometallurgical method to process light water reactor spent fuel and, if feasible, complete the design and construction of a full-scale prototype module to demonstrate the commercial potential of the process.

Private industry would need to construct and operate a commercial-sized prototype plant to obtain certification of that design from the NRC. To support this certification, efforts are needed in the following areas: 1) fuel and core performance; 2) safety analysis; 3) plant control systems; 4) validation of analytical tools used in design development and safety analysis; 5) systems and components performance; 6) materials; 7) codes and standards; and 8) processing, packaging, and preparing wastes for shipment to storage and disposal sites. Government and possibly international support will be needed to support these activities should a decision be made to proceed.

Before the advanced liquid metal reactor could be used to recycle and possibly burn actinides, new fuel processing and fuel fabrication systems and facilities would have to be in place. These facilities could either be integrated with reactor systems at selected site complexes or centrally located at larger complexes that serve a greater number of advanced liquid metal reactors. When fully in place, the metal fuel cycle system could separate actinides from advanced liquid metal reactor spent fuel and fabricate fuel assemblies, permitting recycle of the assemblies in advanced liquid metal reactors.

As a consequence, a key aspect of the advanced liquid metal reactor research and development effort is the development of the Integral Fast Reactor fuel cycle and associated facilities for recycling advanced liquid metal reactor spent fuel. Required supporting tasks include 1) establishing licensability of the process and facilities through interactions with NRC; 2) developing capital cost data; 3) obtaining operation and maintenance data; 4) collecting equipment performance data; 5) identifying the type, composition, and volume of waste streams that are generated; and 6) establishing the methods to prepare the wastes generated for shipment to storage and disposal sites.

The Integral Fast Reactor processing technology has the potential to extract actinides from light water reactor spent fuel. Major activities required for developing and assessing the process and facilities for recycling light water reactor spent fuel through the advanced liquid metal reactor are to 1) demonstrate the technical feasibility of the pyrometallurgical method for processing light water reactor spent fuel and 2) establish the economic feasibility of processing light water reactor spent fuel for recycling through advanced liquid metal reactor plants.

Commercialization of this technology will require a larger private investment than commercialization of advanced light water reactors because extensive development and demonstration projects are required. Advanced liquid metal reactor technology is in the design and development stage. There is limited operational experience with this technology in the United States or internationally. To bring the technology to commercial acceptance would require significant expenditures by industry and government to complete the research, development, and demonstration needed for the entire Integral Fast Reactor fuel cycle. It is currently assumed that, in view of the long-term potential of this technology, the government would fund a portion of this effort.

Recycling actinides has significant ramifications. In order for the advanced liquid metal reactors and their associated fuel conversion and fabrication facilities to be licensed and deployed, a change is required from the current once-through fuel cycle to a reprocessing fuel cycle that would entail substantial private sector capital investment. Also, public concerns over proliferation and diversion resistance issues would have to be addressed. Other ramifications include the requirement to find a site for and license the first light water reactor spent fuel processing facility, as well as the need to transport highly radioactive and thermally hot fuel for reprocessing. Again, the National Academy of Sciences is evaluating the merit of this concept.

3.2.4 Cost and Performance Data

For advanced liquid metal reactors to be commercially viable, their generating costs will have to be in the same range as those projected for the next generation of mid-sized advanced light water reactors. Research and development efforts are focused to achieve cost competitiveness with advanced light water reactors.

The fuel for one advanced liquid metal reactor concept is expected to be uranium, plutonium, neptunium, americium, zirconium (10%) metal pins. The composition of the metal pins will vary from cycle to cycle until an equilibrium cycle is reached. For a 900-MWt core design, the equilibrium cycle loading of fissile nuclides (U-235, Pu-239, and Pu-241) has been estimated at approximately 1,600 kg. The fissile loading per year is approximately 350 kg.

It is anticipated that advanced liquid metal reactors could have heat rates as low as 8,720 Btu/kWh, which represents a slight improvement over that estimated for earlier liquid metal reactor designs. Based on experience with the EBR-II, which had an average capacity factor of 71.2% over the period from 1976 to 1986, it is expected that the advanced liquid metal reactor could achieve an annual capacity factor of 75%.

3.2.5 Market Potential

While advanced liquid metal reactors could be ordered after 2010, this will only occur if current research and development efforts are successful and the cost of producing electricity using this technology is competitive with alternatives. In addition, a strong, established vendor/supplier infrastructure must be established; currently, the primary support for this technology comes from the federal program. It is unlikely that an advanced liquid metal reactor will be a viable alternative to advanced light water reactors until after the turn of the century.

3.3 HIGH-TEMPERATURE GAS REACTORS

This section describes the high-temperature gas reactor technology and its potential to reduce greenhouse gas emissions. Development needs and commercialization issues are then described. Finally, some quantitative cost and performance data are presented, followed by a discussion of the market potential of this technology.

3.3.1 Technology Description

Two commercial high-temperature gas reactors were constructed and operated in the United States. The first was the 40-MWe Peach Bottom Unit 1, which operated between 1967 and 1974. The second was the 300-MWe Fort St. Vrain plant, which began operation in 1979 and was shut down in 1989. Two high-temperature gas reactors were also operated in Germany, and 40 gas-cooled reactors, not of the high-temperature gas reactor type, are operating in the United Kingdom.

The modular high-temperature gas reactor design is an advanced reactor technology capable of high-temperature operation using a ceramic-based, coated particle fuel system; a graphite moderator; and helium coolant. The fuel system can hold fission products within the coated particle at very high temperatures, thus allowing the system to operate at a level that makes the plant more efficient. This system uses uranium fuel that is enriched in U-235 to slightly less than 20% by weight.

Modular high-temperature gas reactors can be divided into two types: near-term and advanced. The near-term designs would use steam cycle technology and build upon the Peach Bottom, Fort St. Vrain, British, and German gas-cooled reactor experience. Advanced modular high-temperature gas reactors would have reactor outlet temperatures in the 850°C to 950°C range, while near-term designs would have outlet temperatures of 700°C.

The high heat capacity of the graphite in a modular high-temperature gas reactor is an important safety feature because the critical time period within which heat removal must be established in case of an emergency is much longer. The use of helium, an inert gas, also provides advantages: 1) it does not react with other materials in the reactor system; and 2) it does not carry impurities that can be activated by radiation in the reactor core. Together these materials and the system design provide passive safety, improved operational safety, and reduced investment risk. The modular high-temperature gas reactor also has the potential for cogeneration applications with only modest modifications to the turbine plant and plant control system. In addition, it has the potential for use in direct-cycle, gas-turbine systems that could achieve high efficiencies and provide direct process heat (e.g., for synthetic natural gas or hydrogen production). Such systems could reject heat through dry cooling systems, thus divorcing site selection from the requirement for cooling water.

3.3.2 Potential for Greenhouse Gas Emissions Reductions

The operation of modular high-temperature gas reactors would not produce greenhouse gas emissions. Indirect greenhouse gas emissions could result from the fuel-production processes (e.g., enrichment) for the modular high-temperature gas reactor, as is also the case for light water reactors. Because of its high temperature operations, the advanced modular high-temperature gas reactor could possibly provide a means to produce synthetic natural gas or even hydrogen gas with reduced emissions of greenhouse gases.

3.3.3 Development Needs

Two critical aspects of the modular high-temperature gas reactor concept that require research, development, and demonstration are the fuel performance and the capability for passive heat removal from the core and pressure vessel. The advanced design may require substantial materials development. The gas-turbine concept would benefit from transfer of technology from the U.S. aerospace industry.

The DOE is currently developing a New Production Reactor for defense applications. The gas-cooled version of this reactor has technical attributes similar to those of modular high-temperature gas reactors. As such, the modular high-temperature gas reactor development program expects to reap technological benefits from the New Production Reactor program, if the gas-cooled reactor is selected as the New Production Reactor concept for further development. If technology transfer from this program is available and is well coordinated, and if development proceeds as planned, modular high-temperature gas reactors could be deployed commercially after the year 2000.

3.3.4 Cost and Performance Data

The reference design for the modular high-temperature gas reactor is for a plant having four modular, helium-cooled, 350-MWt reactors producing a net plant output of 538 MWe. The fuel is uranium oxycarbide enriched to 19.9% (by weight) U-235. The initial core loading contains 1,726 kg of uranium and 2,346 kg of fertile thorium oxide.

This technology is still in the design and development phase. However, economic studies conducted in 1986 indicate that development efforts should focus attention on lowering costs. Cost reduction studies are under way to examine the impacts of increasing power levels (from 350 to 450 MWt), removing thorium from the fuel, and modifying design margins that may be overly conservative. If research and development efforts are successful, it is expected that modular high-temperature gas reactors could achieve power generating costs that are competitive with advanced light water reactors in the post-2010 time frame. The economic competitiveness of these reactors may also be improved by taking advantage of their potential to produce process steam for industrial applications.

The expected heat rate for the reference design is 8,886 Btu/kWh (38.4% net efficiency). It is anticipated that the capacity factor could reach 80%.

3.3.5 Market Potential

Through the end of this century, it appears that advanced light water reactors will most likely dominate the market as the nuclear option for generating electricity. The reason for this is that advanced light water reactors are further along in design, have more support from vendors and the federal government, and are currently being certified by the NRC. The modular high-temperature gas reactor lacks a strong, established high-temperature gas reactor vendor/supplier infrastructure. Its primary support comes from the federal program. It is unlikely that a modular high-temperature gas reactor will be a viable alternative to advanced light water reactors until the next century. Market entry for modular high-temperature gas reactors will depend upon their cost competitiveness with advanced light water reactors and non-nuclear power plants, generating capacity needs, and electrical demand.

3.4 BARRIERS TO INCREASED USE OF NUCLEAR ENERGY TECHNOLOGY

Despite projections of a growing need for power in the 1990s and beyond, there have been no nuclear power plant orders in the United States since 1978. Four obstacles to expanding nuclear power were identified during the National Energy Strategy (NES) hearing process: 1) nuclear waste disposal, 2) public concern about safety, 3) plant licensing procedures, and 4) plant economic performance.

3.4.1 Nuclear Waste Disposal

The two components of the waste management system, a monitored retrievable storage facility and a high-level radioactive waste repository, are needed under all future energy projections whether or not any new nuclear plants are ordered. However, nuclear waste disposal has been identified as a major obstacle to the expansion of nuclear power. Increasing the use of nuclear power will require implementing a system for the safe, permanent disposal of spent nuclear fuel and high-level radioactive waste in a way that addresses public concerns. However, site-selection efforts for a permanent repository have met with strong opposition from potential host states.

The waste management system now being implemented by DOE addresses radioactive waste management issues and includes the following objectives: 1) placement of commercial spent fuel in a permanent repository beginning in 2010 if the candidate site currently under investigation (Yucca Mountain, Nevada) is found suitable and is licensed by the Nuclear Regulatory Commission; 2) placement of defense-generated solidified, high-level waste in the same repository beginning in 2015, and 3) initial acceptance, in 1998, of spent nuclear fuel at a licensed monitored retrievable storage facility located at a volunteer site. A negotiated agreement with a volunteer host state or tribe for a monitored retrievable storage facility is being sought by the Nuclear Waste Negotiator to present to the Congress by 1992 for review and approval. It is expected that site selection and submission of a license application to the Nuclear Regulatory Commission for the monitored retrievable storage facility by 1995 would demonstrate progress on solving the waste management problem and would be a basis for the start of new nuclear plant orders.

To facilitate the development of a waste management system, the NES would modify the Nuclear Waste Policy Act of 1982 in several ways. The proposed legislation would enable the Secretary of Energy to obtain the environmental permits needed to carry out the necessary site characterization activities at the Yucca Mountain candidate repository site. The legislation would also eliminate current linkages between the schedules for the monitored retrievable storage facility and the repository, thereby allowing the monitored retrievable storage facility to start operation independent of the schedule for the high-level waste repository.

3.4.2 Nuclear Safety

There is continuing public concern about the safety of nuclear power plants, particularly in light of two serious accidents, at Three Mile Island (U.S.) and Chernobyl (U.S.S.R.). While the two reactor designs are very different and the severity and consequences of the accidents were also considerably different, public perception has been affected by these accidents. In the past, public officials' concerns about the ability to evacuate the neighboring population after an accident have delayed the licensing of some facilities.

Government and industry have made significant efforts to incorporate the "lessons learned" from the Three Mile Island accident into operational practices and advanced reactor designs. These efforts have resulted in, among other things, improved operator training, frequent operator requalification, review and revision of regulatory practices, development of more broadly based quality assurance programs, and the establishment of rigorous international standards for nuclear power plant operations. Advanced reactor designs will be simpler and have better engineered safety systems and advanced control systems. These features will both further reduce the possibility of accidents and simplify nuclear power plant operation and maintenance.

Government and industry (through the Nuclear Power Oversight Committee) have also recognized the need to improve communications with the public regarding nuclear safety and other issues, including the safety of nuclear waste treatment, transportation, storage, and disposal.

3.4.3 Plant Licensing Procedures

As cited during the NES hearing process, reform of the NRC licensing process is required if nuclear power is to be a viable option for future electrical generating capacity in the United States. Uncertainty in the outcome of the licensing process, i.e., in whether an operating permit will be granted after the plant has met construction permit requirements, has created economic risks for utility investors and customers. Because of uncertainty concerning the NRC's ability to change procedures under current law, some regulatory changes may be needed to facilitate NRC licensing reform. Legislation was introduced in 1991 to improve the current licensing process.

3.4.4 Plant Costs

Market entry for advanced light water reactors will depend on their cost competitiveness with nonnuclear generating options. In the past, some utilities that were constructing nuclear power plants experienced large cost overruns that weakened their financial status. The cost of constructing a new nuclear power plant is affected by many factors, only one of which is regulatory uncertainty. Other factors that have led to significant cost overruns include changes in licensing requirements over the construction period, delays due to litigation, and poor quality control during construction. These factors must be addressed to ensure that nuclear power plant construction costs can be predicted with reasonable accuracy. Design standardization and regulatory streamlining would be expected to reduce cost overruns; however, the history of cost problems with nuclear power plants could hinder new plant orders. On the other hand, the argument can be made that, while costs have increased, industry and NRC experience with backfitting and quality control has been incorporated into the cost estimates, such that the uncertainty in the estimates has decreased.

The cost of fossil-fired-fuel generation is being affected by growing environmental concerns, including concerns over emissions of greenhouse gases and acid rain precursors. Requirements to install costly control technologies to limit emissions from fossil-fired plants would raise the cost of these plants, which could make nuclear power plants more cost competitive with fossil units.

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4.0 RENEWABLE ENERGY TECHNOLOGIES

Renewable energy resources are enormous and abundant throughout both the United States and the entire world. These resources can be used to supply energy in many forms: electricity, gas, heat, or liquid fuels. Renewable energy sources currently provide about 8% of annual U.S. energy needs.

Expanded use of renewable energy technologies can displace fossil-fuel use and, in many cases, associated by-product emissions, including carbon dioxide and other greenhouse gases. Being largely dependent on ongoing natural forces, renewable energy resources tend to be diffuse, with the cost of their use often depending on collection techniques as much as on conversion processes. While the capital costs of deploying renewable energy technologies can be large per unit of energy delivered, operating costs are generally low.

In this chapter, we describe renewable energy technologies that either play an important role today in avoiding greenhouse gas emissions or that can be important in the very near future if the technologies continue to progress and, at the same time, policies are adopted to hasten their deployment.

4.1 TECHNOLOGY DESCRIPTIONS

The renewable energy technology descriptions are presented by resource or technology type within general end-use form categories. The electricity-producing technologies, ordered by current energy contribution, are presented first, followed by biofuels and solar heating technologies. Cost and performance projections for the renewable energy technologies are provided in Appendix E.

4.1.1 Hydropower

Hydropower facilities exploit the kinetic energy in flowing or falling water to generate electricity. Most hydropower facilities are incorporated into dams or other impoundment structures that capture and store water from streams and rivers. A smaller number of facilities operate in a run-of-river mode in which water flow is not restricted.

The principal advantages of using hydropower are the large domestic resource base; the renewable, nonpolluting nature of the generation; the very low operating costs; and the ability of these systems to respond quickly to utility load swings. Hydropower plants also have much higher availabilities (~95% on average) than do thermal generating plants. Disadvantages include the environmental impacts resulting from stream or river impoundments and the potential for conflict among competing users of the water resource.

Hydropower technology can be categorized into two types: conventional and pumped storage. Conventional plants operate on the flow of water from storage reservoirs or free-flowing waterways. The water is directed down through an intake tube to turn a turbine connected to a generator. The water continues through and is released into a lower waterway.

Pumped storage plants operate in a similar fashion except that instead of tapping free-flowing water, the water resource is pumped, usually through a reversible turbine, from a lower reservoir to an upper reservoir. Pumped storage facilities are net energy consumers (i.e., more energy is required for pumping than is generated by the plant [typically 1.25 to 1.4 kWh required for each kWh generated]); however, these plants are valuable to a utility because they operate in a peak power production mode when electricity is most costly to produce. Pumping to replenish the upper reservoir is performed during off-peak hours using the least costly utility generation sources. This process generally provides additional benefits to the utility by increasing the load factors and reducing the cycling of its baseload units.

Hydropower development in the United States dates back more than a century. As late as the 1930s, hydropower provided 30% of the nation's total installed capacity and 40% of the electric energy generated. Since then, the growth in thermal-based capacity has far outstripped that of hydropower; hydropower (both conventional and pumped storage) represented only 12% of U.S. capacity in 1988. At the same time, growth of hydropower capacity has been slowing. Hydropower generating capability increased by 22.7 GW during the 1960s and by 21.3 GW during the 1970s, but increased only 12.2 GW in the 1980s. Furthermore, over 40% of hydropower capacity additions since 1972 have been pumped storage facilities, indicating that conventional hydropower additions have been on an even steeper decline.

It is generally perceived that the prime conventional hydropower resource sites have already been developed and that new hydropower developments will add only small increments to capacity. However, both the U.S. Army Corps of Engineers (the Corps) and the Federal Energy Regulatory Commission (FERC) have estimated that substantial hydro resources remain undeveloped. The Corps estimated in 1983 that 46.0 GW of additional capacity could be economically and environmentally developed at existing and undeveloped sites (19.5 GW and 26.5 GW, respectively), while FERC has more recently (1988) estimated that the total undeveloped conventional capacity alone amounts to 76.1 GW. If developed, this capacity could more than double the current capacity. The American Public Power Association estimates that less than 3% of U.S. dams produce electricity, an estimate which suggests a large retrofit potential.

In addition, FERC has identified sites with the potential for "many million kilowatts" (or many GW) of pumped storage capacity, beyond the 17.1 GW of stated potential already in the planning stages. Stream flow is not as important a consideration in pumped storage development as is topography. The essential requirement is topography allowing the development of two reservoirs that are close to each other and that have a high head differential. Given the need for only a few days storage at most, the reservoirs can be much smaller than those of conventional hydropower impoundments.

Some additional potential can be realized at existing generation facilities through the refurbishment and upgrading of older turbines and generators. For instance, by the early 1990s, the Bureau of Reclamation will have added 10% to its 13 GW of hydropower generation capacity through a program of rewinding and upgrading existing units. These upgrades can be performed for well below $100/kW. At present, the total upgrade potential of the nation's existing hydropower facilities is not known.

Obstacles to further hydropower development are primarily environmental and political. Hydropower impoundments can flood large areas of land and, thus, come into conflict with existing uses, such as agricultural, grazing, wilderness, and recreational uses. Impoundments can also interfere with fish spawning runs. Claims already in place on stream flow and water use also complicate water impoundment. A solution to this problem may lie in development of a formal capability and procedures to resolve conflicts over environmental and resource access values, as well as of criteria and methods to objectively assess the costs and benefits of hydroelectric development.

Current Deployment Status

As of 1989, installed hydropower capacity was 90 GW: 71.2 GW and 16 GW of utility-owned conventional and pumped storage capacity, respectively, with another 1.9 GW of nonutility-owned capacity. The average annual generation capability of this existing capacity is just over 300 billion kWh. Actual generation may vary significantly from the average capability because of year-to-year variation in precipitation patterns and, thus, water availability, and also because of competing demands on the water resource.

Key Issues

Continued federal involvement or research and development investment will be needed to

- research mitigation of adverse environmental impacts, such as on fish and wildlife resources and on dam safety issues
- identify the generation potential and development feasibility at existing nongenerating water impoundments
- examine utilization practices at existing hydropower facilities and opportunities and methodologies to achieve greater output
- verify resource opportunities for additional pumped hydropower sites
- review engineering and other technical opportunities to increase the efficiency of hydropower plant operations
- review the pricing basis for federal hydropower sales and assess the implications of different pricing strategies for additional hydropower development.

4.1.2 Biomass Electric

Biomass resources used for electricity generation consist of woody and fibrous primary and secondary waste materials from wood and agricultural production and processing, as well as municipal solid wastes generated by businesses and communities.

The principal advantages of using biomass resources for electricity supply are that they are renewable resources with fairly widespread availability; the conversion systems are relatively small scale and modular and can operate as baseload, dispatchable power plants; and combustion aids in mitigating waste disposal problems. The sulfur content of biomass is negligible; therefore, biomass combustion does not contribute to acid rain. Furthermore, recycling paper, glass, plastics, and metal products, performed in conjunction with municipal waste collection and combustion, can conserve energy resources required for the primary manufacture of these energy-intensive materials. Disadvantages include the lower energy density of biomass resources, which places localized constraints on economic collection and transport, and the environmental impacts of the combustion process. However, adverse air emissions can be mitigated through use of either emission control technologies or gasification processes.

Conventional wood resources consist of wood in excess of the needs of the traditional forest products industry. This wood is available either from thinning commercial stands or from clearcutting to allow planting improved stands. This resource is estimated at 6.5 quads annually at present.

Agricultural and forestry wastes represent the portion of plants and trees that remain after the economically more valuable portions have been separated. Primary residues include stalks, leaves, bark, and limbs left in the field after harvesting; secondary residues are wastes produced at a processing facility, such as wood scraps, sugarcane, bagasse, rice hulls, or food processing wastes. Secondary wastes have the advantage of incurring small or no transport costs because they are a byproduct of the primary processing. The waste resource is estimated at 2.0 quads annually.

Municipal solid waste is the solid waste generated from households, commercial, and institutional operations, and some industrial production. Municipal solid waste is an attractive resource because 1) it is continuously generated, 2) it is recovered and delivered as an essential public service, and 3) its use for electricity production reduces the need for disposal, which is an increasing environmental problem. Eighty percent of the dry weight content of municipal solid waste is made up of organic materials, about 67% of which is natural lignocellulose. The annual municipal solid waste resource in the United States is estimated to represent 2.5 quads.

Landfilling municipal solid waste creates methane as the waste materials anaerobically decompose. Although this so-called landfill gas represents an additional energy resource that can be tapped, only part of this resource can be recovered, and some methane is eventually emitted to the atmosphere. Thus, direct use of municipal solid waste in combustion processes is a more effective control on waste-related greenhouse gases than is landfilling.

The principal energy conversion mechanism for wood and agricultural materials is direct combustion to provide heat and electricity. The cogeneration of heat and electricity is a common conversion mechanism in industry. The pulp and paper and wood products industries are the primary industrial users of biomass materials for energy and are second only to the chemicals industry in the level of self- and co-generation of power. The food processing industry also uses a significant amount of biomass-derived waste materials for energy.

Commercial conversion technologies used to exploit the municipal solid waste resource include direct combustion (mass burn) to produce steam or heat, source separation of materials that conserve energy when recycled, production of a solid fuel [refuse-derived fuel (RDF)] that can be combusted, and recovery of methane gas generated in composting landfills.

Mass burn facilities use the waste resource on an as-delivered basis, with minimal front-end sorting. These plants can be of the water-wall (excess air) or modular (starved air) type. Water-wall units are conventional power plant boilers with a grate or rotary combustor to dry and combust the waste. Modular systems are essentially gasifiers with the gas produced in a primary chamber and combusted in a secondary chamber, typically a waste heat boiler. Refuse-derived fuel production employs extensive front-end sorting of the waste (typically using shredders and air classifiers) to remove metals and other noncombustibles. This process results in a material with a higher heating value than primary waste but also with a higher cost.

The history of municipal solid waste combustion has been marked by operating problems because of the particular nature of the municipal solid waste resource. Slagging can occur in the boilers if glass is present in the waste. Extensive slag buildup fouls the boiler components and reduces heat transfer as well. Also, explosions can occur in shredders. However, technologies are being developed and applied to address these problems, and many existing plants continue to operate satisfactorily.

Issues constraining greater use of biomass resources (exclusive of municipal solid waste) in electricity generation pertain to the cost of the delivered resource. To be transported economically, wood resources must generally be procured within a 50-mile radius of the conversion plant. Most current generation capacity is based on the use of readily accessible waste resources; thus, the resource is already available at very low cost. If conversion plants are to compete with advanced coal and natural gas technologies, the biomass-based feedstocks, in general, must be available for less than $2.00/MMBtu. At high levels of penetration, competition might bid up biomass resource costs. Thus mechanisms must eventually be established to ensure low-cost resources. One potential longer-term solution is the development of dedicated farms of high productivity, short rotation woody crops for feedstock production. However, in the shorter term, substantial opportunity exists for greater use of biomass resources that are currently underused.

Environmental and institutional issues often present obstacles to deployment of biomass plants and, in particular, municipal solid waste combustion plants. In some cases, the need to have the resource nearby dictates that plants be built close to load centers, a situation that can lead to conflicts over siting and operation.

Current Deployment Status

Deployment of biomass-based generating plants has been pursued primarily by nonutility, industrial entities. As of the end of 1988, 6600 MW of nonutility-owned, biomass-based generation capacity was in operation. Of this total, two-thirds used cogeneration technology. Wood-fired systems accounted for 74% of the total capacity, followed by municipal solid waste (17%), agricultural waste (5%), and landfill gas (4%). Another 1000 MW or more of utility-owned, biomass-fired capacity is also in operation.

Key Issues

Areas requiring continued federal involvement or research and development investment include the following:

- production research on biomass energy crops (overlaps with biofuels needs)
- research and development on municipal solid waste gasification/combustion systems
- identification and development of techniques and equipment to improve the quality of municipal solid waste gas
- research on waste recycling/preparation of refuse-derived fuel
- development of front-end handling and storage systems for biomass electric systems
- research into management of the urban wood resource
- research and development on biomass-fired gas turbine/combined-cycle technology
- validation of biomass-to-gas electric systems using aeroderivative turbines
- research on alternatives to field, slash, and other open-burning methods.

4.1.3 Geothermal

Geothermal energy originates from the deep interior of the earth and the decay of radioactive materials in the earth's crust. Although in some places this heat comes to the earth's surface in natural vents of hot water or steam, the use of this resource for energy purposes usually entails drilling water or steam wells to convey the geothermal heat to the earth's surface. Energy uses include electricity generation and direct heat applications, such as geothermal heat pumps, district heating systems, industrial process heat, and crop drying.

The principal advantages of geothermal energy are the tremendously large domestic resource base, the modularity and short construction lead times of geothermal systems, and the relatively small environmental impacts. In addition, power plants based on geothermal energy can deliver baseload energy. Disadvantages include the broad variation in geothermal reservoirs, resource temperatures, composition, and other characteristics that necessitate a large number of different approaches to drilling, heat extraction, environmental control systems, heat exchanger designs, and energy conversion. Thus, resource development strategies must often be site-specific. Potential environmental side effects can include noxious air emissions, such as hydrogen sulfide; waste disposal requirements; and land subsidence and seismicity.

However, a variety of extraction and utilization technologies are available to meet site-specific requirements of resource temperature, chemical composition, and depth. In addition, some site-specific conditions that seemed especially problematic a decade ago have yielded to technological solutions. For example, gas emissions can now be controlled; trace toxic metals can be removed from solid waste; and the potential for subsidence and seismicity problems can be reduced.

Most of the high-temperature geothermal resource suitable for power generation is located in the western states, including Hawaii and Alaska. However, low-to-moderate temperature fluids are currently being used for direct heat applications in 44 states.

The geothermal resource is categorized into four different types:

1. hydrothermal, which is hot water or steam at temperatures ranging from 90°F to >680°F

2. geopressured, which is moderately hot water (212°F to >400°F) under high pressure containing dissolved methane

3. hot dry rock, which is impermeable hot rock

4. magma, which is molten or partially molten rock (>1400°F).

To date, only the hydrothermal resource has been commercially developed, largely because it is more accessible and amenable to conventional drilling and conversion processes. The advanced technologies needed to economically extract the heat or other forms of energy from geopressurized brines, hot dry rock, and magma now are being developed for future commercial application.

The basic components of a geothermal energy conversion system are 1) production wells, through which the geothermal resource is brought to the surface; 2) a conversion system, which converts the geothermal energy to useful energy; and 3) reinjection wells, through which the spent geothermal fluids are disposed of or recycled back into the reservoir.

Three primary electric power conversion technologies may be employed, depending on the temperature and makeup of the hydrothermal resource: 1) dry steam, 2) flash steam, and 3) binary. The first technology is used where the resource naturally occurs as dry steam. Conventional turbine generators of standard materials are employed with the natural steam, replacing the boiler used in conventional steam generator systems. However, once the steam is condensed, gaseous and solid impurities become more concentrated and the condensate becomes more corrosive. Thus, more expensive materials, such as stainless steel, are needed to protect subsequent system components.

Flash-steam technology is employed when the resource occurs as a high-temperature liquid (>375°F). In this case, the liquid is allowed to flash to steam under reduced pressure. The steam (generally about 15% to 22% of the brine) is separated from the remaining liquid and used to drive a turbine generator. Because corrosive, noncondensable gases are liberated in the flashing process and high levels of dissolved solids may be present in the liquid, the materials used and the design of the system become critical in eliminating scaling and corrosion problems. The economics of flash-steam plants can be improved by using a dual-flash cycle, which can produce as much as 20% to 30% more power than a single-flash system at the same fluid-flow rate.

Lower temperature hydrothermal liquids (200° to ≤375°F) are more suited to binary cycle units. This technology, which is less common in commercial operation, uses the heat of the geothermal liquid to vaporize a secondary working fluid (with a lower boiling point) for use in the turbine.

The total hydrothermal resource (>90°C), both identified and undiscovered, to a depth of 6 kilometers, is estimated to exceed 12,000 quads. The vapor-dominated resource represents only a small fraction of the total hydrothermal resource, pointing out the necessity to further develop the hot-water technologies to tap a significant portion of this potential. The resource bases for the other geothermal types (geopressured, hot dry rock, and magma) are even larger.

The economic development and exploitation of a geothermal reservoir depend primarily on an understanding of the reservoir's properties. The overall hydrogeological characteristics of the system largely control the circulation of the geothermal fluids under natural conditions and during exploitation. The thermodynamic and geochemical properties of the formation fluids govern the processes occurring in the reservoir. Finally, the management of the reservoir, through selection of well sites and rates of flow, provides control over these processes and will affect the economic life of a geothermal field.

The geothermal industry has made great strides in locating and developing hydrothermal reservoirs. However, the lack of techniques to locate and characterize fractures in underground rock formations significantly inhibits the industry's ability to consistently tap the areas of greatest fluid productivity. As a result, many reservoirs have not reached full production potential because they cannot be sufficiently characterized to allow development of cost-effective exploitation strategies. Reliable techniques are similarly lacking for identifying hydrothermal systems in regions where cool groundwater masks the underlying heat. And, although injection of spent geothermal fluids back to the subsurface is now practiced in virtually all power plant operations, premature cooling of the fluids in the production zone may result from poorly located injection wells.

Hydrothermal well costs have declined significantly at some geothermal fields; the most economical are estimated to be about 1.5 times as expensive as comparable oil and gas drilling. At other fields, high well costs can constitute a major deterrent to increased development. A major reason for this difference is that geothermal drilling often occurs in granite rocks, which are harder than the sedimentary geologic formations typical of oil and gas deposits. Finally, large-scale, binary-cycle electric power conversion technology is still marginally economical for commercial use. Further technological improvements are needed to fully exploit the moderate-temperature reservoirs.

Current Deployment Status

As of 1989, over 2,000 MW of installed geothermal dry-steam capacity had been developed at The Geysers resource area in California. However, The Geysers is one of very few known dry-steam resource areas in the United States, making substantially greater development from this resource highly uncertain. In addition, it appears that The Geysers field has reached its production limit. About 800 MW of flash-steam and binary capacity has been developed in the western United States outside of The Geysers. Much of this additional development has occurred very recently, signifying a move toward exploiting the liquid-dominated hydrothermal resource as the dry-steam resource becomes fully developed. Geothermal energy currently accounts for about 8% of utility-generated electricity in California.

For direct uses of geothermal energy, the total installed capacity in the United States was 1,700 MWt in 1988, providing about 0.017 quads of energy. The fastest growing market segment is residential-scale groundwater heat pumps with about 66,000 systems installed. In addition to the heat pumps, about 1,000 direct-use geothermal projects, including a number of commercial greenhouses, fish hatcheries, and district heating systems, currently operate in 44 states.

Key Issues

Areas requiring continued federal involvement or research and development investment include the following:

- development of improved technologies and procedures for locating, delineating, characterizing, evaluating, and managing reservoirs
- achievement of significant performance improvements in hard rock drilling technologies
- achievement of performance improvements in binary-cycle electric power conversion technologies for moderate-temperature resources
- determination of the technical feasibility and economics of extracting and using chemical, thermal, and mechanical energies contained in geopressured fluids

- determination of the dynamic characteristics and projected longevity of typical geopressured reservoirs under production conditions

- determination of the feasibility of operating large-scale underground heat extraction systems necessary to exploit the hot dry-rock resource

- development of technology to access and extract energy from moderately deep (i.e., 10,000 to 20,000 feet) magma bodies.

4.1.4 Windpower

Windpower technology converts wind flows to useful energy through the use of wind turbines. Wind turbines have been deployed in sizes ranging from 1 kW to 4 MW. Historically, wind turbines have been used for small stand-alone applications such as water pumping and farm power needs. Over the last several years, wind turbines have experienced the largest deployment in clusters of so-called "wind farms." Individual turbine sizes in wind farms have ranged from 18 kW to 600 kW; however, most turbines installed to date have been in the 100-kW size range. Most recently, turbine installations have been larger, above 200 kW.

The principal advantages of wind energy are its renewable, nonpolluting nature and its modularity and short construction lead times. Most regions of the country have significant wind resources. One important disadvantage pertains to the intermittent nature of the wind resource. In the absence of storage or other significant system response capabilities, this intermittency can make matching wind turbine output to utility daily load profiles problematic. However, this situation can be partially alleviated through spatial considerations in siting where the natural diversity of the wind resource across a region can be used to advantage. Also, the extent to which intermittency is an issue is site- and utility-dependent. Environmental disadvantages relate primarily to visual and auditory aesthetics and land and habitat disturbance.

A wind turbine system contains five basic subsystems: 1) a rotor, usually consisting of two or three blades, which is the energy conversion device; 2) a drive train, generally including a gearbox and generator; 3) a tower and foundation that support the rotor and drive train; 4) various turbine supporting systems including controls and electrical cables; and 5) "balance-of-station" subsystems, which, depending on the application, might include ground support equipment or interconnection equipment.

There are two basic technical approaches to wind turbine design: 1) horizontal-axis machines, in which the axis of the rotor's rotation is parallel to the wind stream and the ground and 2) vertical-axis (Darrieus) machines, in which the axis of rotation is perpendicular to the wind stream and the ground. Most turbines in commercial use today are of the horizontal-axis type.

Many variations in horizontal-axis wind turbine configuration are possible. For example, yawing mechanisms are designed to keep the rotor oriented properly in the wind stream. Some machines simply have a tail vane or rudder to control yawing motion; others (typically larger machines) have active yaw drive systems controlled by microprocessors. On most of the recently installed horizontal-axis machines, the blades are located on the upwind side of the tower; others are downwind. Some machines have fixed-pitch blades that reduce design complexity; others have variable-pitch blades that aid in starting and stopping and regulate power output by changing the angle at which blades cut through the air. Rotors that are attached to the hub using flexible couplings are known as teetered rotors, which can help reduce cyclic loading.

Wind turbine technology relies on complex aerodynamic phenomena. When the wind flows through the area swept by the rotor, certain physical interactions between the wind and the rotor blade occur. For steady-wind conditions (i.e., when the wind is moving at a constant speed and direction), the rotor airfoil shape is designed to create lower pressure on one surface and higher pressure on the other. The net pressure differential creates aerodynamic lift, the primary force acting on the rotor, causing it to turn. The rotating blades drive the gearbox and generator.

Rarely, however, is the wind a steady, homogeneous flow across the turbine's rotor area. In reality, the wind near the earth's surface can be extremely turbulent (i.e., characterized by rapidly changing speed and direction). Fluctuating aerodynamic forces from nonuniform, unsteady wind conditions cause the blades to flex unevenly, which in turn creates cyclic stresses in the blade structure that can lead to fatigue failures in the blades, rotors, and other machine components. These structural stresses caused premature fatigue failures that adversely affected the performance and reliability of the first generation of wind turbines and increased the cost of operating and maintaining them. Average rotor lifetimes were less than 5 years rather than the projected 20 to 30 years. However, since then, the industry has improved component lifetimes and reliability dramatically through both technology and aggressive preventive operation and maintenance practices.

Although fluctuating aerodynamic forces and their interaction with wind machines are not well understood, further knowledge is being gained through research sponsored by the Federal Wind Program in cooperation with industry. Other problems, such as blade soiling and array losses from terrain, wake, and turbulence effects, also contributed to poor performance in earlier machines. Airfoil design and other technology advances hold promise for mitigating these adverse impacts.

Current Deployment Status

At present, over 14,000 wind turbines are installed and operating on California wind farms, representing about 1,500 MW of capacity. In 1990, these turbines generated an estimated 2.5 billion kWh of electricity or 2% of California's annual electricity needs. In 1990, 175 MW of capacity was installed, an amount far below the 1985 peak year capacity installation of about 400 MW. California wind turbine installations have dropped since 1985 largely because wind energy tax credits expired and favorable utility standard-offer contracts were suspended. Also, the industry turned to refurbishing older machines that had experienced reliability problems.

Given the end of high-avoided-cost utility power purchase contracts in California, wind energy will have to compete at cost equivalence with conventional generation alternatives. Achieving the required reductions in energy cost will require increases in performance through the use of advanced technology, including design tools, advanced airfoils, site tailoring, and improved operating strategies.

Key Issues

The primary area requiring continued federal involvement or research and development investment is advanced turbine technology that incorporates the knowledge gained from the operational experience of earlier designs. Advanced technologies would incorporate variable-speed generators, power electronics, advanced airfoils, and adaptive controls. These changes are expected to help increase energy output by up to 50% over current wind turbine designs.

Areas requiring continued federal involvement or additional research and development include the following:

- Science/Basic Research - Develop an improved understanding of the basic physical processes of the wind resource with particular emphasis on processes affecting wind turbine performance and reliability (wind turbine dynamics). This effort would include work in atmospheric fluid dynamics, aerodynamics, structural dynamics, and mathematical models to predict the influence of these factors on alternative designs.

- Components - Develop the technology base necessary for industry to achieve major improvements in machine cost, performance, and lifetime, with particular emphasis on advanced concepts offering the potential for cost-effective operation under dynamic operating conditions. This effort would include development of advanced airfoils, controls, drive trains, and systems concepts.

- Systems - Continue research support in the areas of technology assessment, electrical systems analysis, environmental impact analysis, and wind data collection and verification.

- Operations - Continue operation and testing of existing machines to validate the technology base and solve operational problems and transfer that knowledge to industry.

4.1.5 Solar Thermal Electric

Solar thermal electric technology uses highly concentrated radiant energy from sunlight to produce thermal energy that, in turn, generates electricity in conventional steam turbine conversion systems. The economical size range of solar thermal electric plants is 20 to 200 MW, which makes this technology appropriate for bulk power generation or large off-grid applications.

The principal advantages of solar thermal electric systems pertain to its use of a secure, domestic energy resource; its relatively low environmental impact; and its relative modularity and short construction lead times. One important disadvantage of this application is its geographic limitation to regions with a high direct normal solar radiation resource, such as the southwestern United States, although enhanced transmission capabilities could help lessen the importance of this constraint. The intermittent nature of the solar resource can also be a drawback, although this problem can be overcome either by thermal storage systems or by combining the solar thermal electric system with a conventional fuel-based system in a hybrid configuration.

The basic elements of a solar thermal electric system are 1) the tracking concentrators, which are used to capture and focus the sun's energy; 2) the receiver, which converts the energy to heat in a working fluid; 3) the piping, which carries the flow of heated fluid; and 4) the conversion device, which converts the heat in the fluid to electricity.

Solar thermal electric systems can incorporate any of three primary concentrator concepts: 1) central receivers, 2) point-focus parabolic dishes, and 3) line-focus parabolic troughs. All three concepts employ the same principle of reflecting and concentrating sunlight and are distinguished by the various mirror geometries and receivers used. Groups of parabolic dishes and troughs, where each reflector module has its own receiver, are called distributed receiver systems.

Central receiver systems use fields of two-axis tracking mirrors called heliostats to reflect the sunlight onto a single tower-mounted receiver. Research and development on central receiver components and systems has resulted in significant cost reductions. These cost reductions have been achieved primarily through reduced component costs, improved designs, and operational experience. Individual heliostat costs have decreased from more than $1,000/m^2 to less than $150/m^2, while the reflectivity of mirror surfaces has increased from 70% for early systems to over 90% today. Stretched membrane heliostat concepts, which substitute lighter weight polymer-based reflective materials for the early glass/metal configurations, show significant potential for further cost reductions. Research has also shown that improved system performance and lower costs can be achieved with heat transfer fluids such as molten salts that have better heat transfer characteristics than water and that can also be used for storage. To date, however, these advanced concepts have not been tested in a commercial-scale system, although demonstration units have been tested.

Parabolic dishes use a two-axis tracking concept and focus the sunlight onto receivers/engines located at the focal surface of each dish. Dish modules, in the range of 10 to 25 kWe, can be used in stand-alone or large multimodule systems. Current parabolic dish designs are evolving toward higher operating temperatures to take advantage of higher engine efficiencies. Solar-to-electric conversion efficiencies of 30% have been achieved in 25 kWe modules. Parabolic dishes are able to provide these higher temperatures because of their high solar flux concentration capability. Similar to the central receiver technology, dish systems will also benefit from recent advances in stretched membrane and other low-cost concentrator technologies.

Parabolic troughs use single-axis tracking collectors that concentrate sunlight onto a receiver tube positioned at the focal line of each trough. Individual trough modules can be combined in rows to meet large capacity needs. The parabolic trough technology is the most commercially developed of the three major solar thermal technologies. Parabolic trough systems have also shown significant cost reductions and performance improvements. Today's collectors have raised the optical performance to 77% peak efficiency by increasing concentrator accuracy and incorporating highly specular silvered glass reflector technology.

Current Deployment Status

Through 1988, the following systems had been deployed:

- Central Receiver - A 10-MWe federally funded demonstration system (water/steam) using 1818 glass/metal, computer-controlled heliostats. Southern California Edison Company operated this system in Barstow, California, from 1982 to 1988; the system is currently shut down.

- Parabolic Dish - A 3-MWt (400-kWe) federally funded cogeneration system has been in operation since 1982 in Shenandoah, Georgia. A field of 114 dish collectors (aluminized reflector film technology along with some higher reflectivity silver film) heats a silicone-based fluid to provide process heat, air conditioning, and electric power in a central conversion system.

  A 5-MWe privately funded system constructed at Warner Springs, California, used 700 dishes (incorporating lightweight stretched acrylic reflective film facets) to produce steam for a centrally located turbine-generator. This system is not in operation at this time.

- Parabolic Trough - Nine privately funded plants, totaling 354 MWe, are in operation, with an additional 300 MWe under utility contract through 1993. Other plants are being negotiated. Located at three sites in the Mojave Desert in California, these plants are solar thermal/natural gas hybrids with the natural gas contribution limited to 25% under the regulations of the Public Utilities Regulatory Policies Act of 1978.

Key Issues

Areas requiring continued federal involvement or research and development investment include the following:

- development of improved and lower-cost optical materials and concepts for concentrators and receivers

- development and validation of high-efficiency, reliable 5- to 25-kWe heat engines for dish applications

- development of lower-cost, higher-efficiency energy transport and storage

- assessment of innovative concepts and applications

- adaptation of conventional balance-of-plant components to the solar environment

- analysis, design, and testing to verify performance and reliability of central receiver molten salt systems

- evaluations of complete systems at utility user locations.

4.1.6 Photovoltaics

Photovoltaics, or solar cells, convert sunlight directly into electricity. A primary advantage of photovoltaics is that it can be deployed at any scale (i.e., few economies of scale accrue to larger sizes). Thus, it can serve loads ranging from watts to megawatts. Because size is not a constraint, the technology is potentially applicable to all electricity-consuming sectors. Photovoltaic technology can operate with diffuse sunlight, making it applicable in many geographical areas. Photovoltaic systems require few, if any, moving parts and thus require very little maintenance. Being a nonthermal energy-producing system, photovoltaic systems require no water for cooling.

The principal disadvantages of this concept relate to the high cost of photovoltaics (which can be reduced through more research and development), land requirements for photovoltaic energy-producing facilities that are somewhat greater than conventional fossil-generating plants, and the fact that the power output may not be available on demand (unless integrated with storage capabilities).

Many different types of semiconductor materials have been found to exhibit the photovoltaic effect. The most prominent material in commercial use today is crystalline silicon; its manufacture is based primarily on the same technology used to produce expensive, high-grade silicon material for computer chips. Other semiconductor materials, especially thin films, promise lower materials and manufacturing costs, although thin-film technology is much less developed than crystalline silicon technology.

Polycrystalline silicon cells are made from a less pure, and thus less costly, silicon material which is more readily adaptable to automated production techniques. Silicon material can also be formed in sheets or ribbons that, likewise, are more amenable to manufacturing automation. Thin-film materials offer the ultimate in low-materials requirements and low-cost manufacturing techniques. These processes involve the deposition of photovoltaic materials on low-cost substrates (such as glass, metal, or plastic) and are amenable to large-area (square meters) automated production. Finally, the use of concentrators, (i.e., lenses that focus sunlight on high-efficiency cells) also provides a potentially low-cost photovoltaic development pathway.

Several candidate thin-film technologies are currently being explored both by industry and government researchers. These materials include amorphous silicon (a-Si), copper indium diselenide ($CuInSe_2$ or CIS) and cadmium telluride (CdTe). To increase solar conversion efficiencies, photovoltaic materials can also be combined or stacked, a process that results in so-called multijunction cells.

Solar cells are interconnected and encapsulated into modules. A representative module incorporating today's crystalline silicon technology may be 0.372 m^2 (1 by 4 feet), producing 50 to 55 watts of power under peak solar conditions (typically 1000 W/m^2, 25°C cell temperature). Average power output will be somewhat lower because of daily and seasonal fluctuations in both the availability of sunlight and in the performance of the photovoltaic module. Numerous modules are then combined into large photovoltaic arrays. In the course of a year in an average U.S. location, a panel producing 55 watts of power under peak solar conditions would produce about 120 kWh of electricity.

Arrays can be used in either flat-plate or concentrating configurations. In concentrating systems, the solar radiation can be focused up to 1,000 times (1,000 suns) on the solar cell. The benefits of concentrators are that the required number of solar cells can be reduced, thus potentially allowing a high-cost, high-efficiency solar cell to be used economically with lower cost concentrating structures. Potential drawbacks include the need for 2-axis tracking devices to maintain optimum solar focus and the fact that application of the configuration is limited to regions such as the U.S. Southwest, which has minimal cloud cover.

Photovoltaic systems produce direct current (DC) power rather than the alternating current (AC) that most electrical equipment uses. Thus, power conditioning equipment (inverters) must by employed to convert the power from DC to AC. Also, for smaller, stand-alone (nongrid-connected) systems, some type of energy storage mechanism (typically batteries) may be required to ensure on-demand power delivery. For residential and other grid-connected systems, the utility grid can generally supply back-up power needs.

Finally, bulk power production from photovoltaics may be possible for penetrations of up to 10% to 20% of a utility's total system capacity without need for dedicated storage facilities. Such penetrations are possible because photovoltaic output has been shown to provide a good match to utility peak power loads in several high solar resource regions. In addition, many utilities already possess capacity cycling capabilities (such as pumped storage hydropower) that can provide for the intermittent photovoltaics output. With storage, photovoltaic penetration would be limited only by economic considerations since the solar resource is large enough to provide much more energy than is currently used.

Current Deployment Status

As of 1988, some 200 grid-connected photovoltaic systems were operating in the United States, primarily in California, but in other regions as well. These systems represent about 11.6 MW, ranging in size from 150 watts to 6.5 MW. Twice as much capacity exists in tens of thousands of stand-alone, nongrid-connected applications, such as remote housing, military communications, navigational systems, and cathodic protection systems. Although photovoltaics is still a fledgling industry, worldwide production more than doubled between 1985 and 1990 to an estimated level of 46.5 MW.

Key Issues

Areas requiring continued federal involvement or research and development investment include the following:

- improving the solar energy conversion efficiencies of candidate photovoltaic materials
- developing low-cost photovoltaic manufacturing techniques
- conducting fundamental materials research
- conducting research on new cell materials and devices
- reducing costs for balance of system equipment
- improving costs, system reliability, and performance
- building utility/user confidence in photovoltaic systems
- conducting research and development in photovoltaics/storage and other hybrid system configurations
- validating photovoltaic systems for meeting utility requirements
- validating the performance of megawatt-scale photovoltaic systems in a utility grid system
- transferring technology and information to industry.

4.1.7 Biofuels

Biofuels are liquid and gaseous fuels produced from biomass materials. The biomass used can range from woody and agricultural materials and municipal solid waste to microalgae and oilseed crops. End-use products can be in the form of alcohol fuels and hydrocarbons (gasoline/diesel) for transportation or methane for thermal applications or as a substitute for natural gas.

The principal advantages of this energy technology are that the resource used is renewable and widely available, even in arid regions; biofuels have few toxic effects on land, air, or water; waste materials can be converted into useful products; the end-product fuel can be easily integrated into existing fuel distribution networks and end-use systems; and biofuels production systems are modular, offering localized economic benefits and requiring little modification of existing infrastructures. Alcohol fuels are clean-burning and reduce the level of carbon monoxide and ozone produced in emissions from transportation vehicles. In addition, these alcohols can be converted to ethyl tertiary butyl ether (ETBE) and methyl tertiary butyl ether (MTBE), two high-octane blending stocks, totally compatible with the present vehicular mix. Combustion of biomass-derived fuels emits no net carbon dioxide to the atmosphere. Disadvantages include the lower energy density of biomass resources, which effectively limits the economically transportable range of the raw materials, and the potential for competition among traditional resource users.

Types of Biofuels

The major types of biofuels of concern here are ethanol, methanol, synthetic hydrocarbon fuels, and biomass-derived methane.

Ethanol. Ethanol can be produced from sugar, starch, or cellulosic feedstocks (wood, energy crops, and municipal and other wastes). Ethanol can be blended with gasoline or, with engine and system adjustments, used interchangeably with conventional gasoline. At present, the primary pathway in the United States for converting biomass to alcohol fuels is the fermentation of corn to ethanol. The largest potential, however, exists with the use of more abundant cellulosic biomass materials, which can reduce feedstock costs by 50% or more, compared with corn.

In the biochemical conversion of cellulosic materials into ethanol, the biomass is separated into cellulose, hemicellulose, and lignin in a pretreatment step. The cellulose can, with some difficulty, be hydrolyzed to sugars, primarily glucose, which are then easily fermented to produce ethanol. The hemicellulose portion can be more readily converted to sugars, primarily xylose, but the xylose is more difficult to ferment to ethanol. Finally, the lignin, although it cannot be fermented, can be thermochemically converted to a high-octane liquid fuel or can be used directly as a combustion fuel to provide process energy.

Acid hydrolysis, which can be used to convert the cellulose fraction to glucose, is a well-understood process. However, process yields to date have been disappointing. The major research and development requirement is to improve process configurations to increase sugar yields, reduce sugar degradation, and improve acid recovery.

Enzymatic hydrolysis is highly selective and does not degrade product sugars. Its promise is the achievement of high yields under mild conditions. Enzymes are also biodegradable and environmentally benign. Over the years, several enzymatically catalyzed processes have been studied at the laboratory scale. The most promising process is simultaneous saccharification and fermentation, which combine hydrolysis and ethanol production in a single step.

Enzymatic hydrolysis will benefit from current advances in biotechnology. Development of better enzyme preparation and process designs will increase the yield and concentration of ethanol. Pretreatments of cellulose feedstock must be improved so that a higher fraction of the sugars can be released more rapidly. Finally, the process of xylose utilization must also be improved. Research will focus on genetically modifying bacteria to produce the key enzyme for xylose fermentation more rapidly and on integrating the enzymatic and fermentation steps into a single continuous process.

Current research is providing an understanding of the effects of various pretreatment and extraction techniques on the structure and potential uses of the lignin fraction. To successfully convert the lignin portion of feedstock to fuels, better catalysts must be developed to increase the yield of the desired liquids and decrease undesirable byproducts. At the same time, low lignin feedstocks are being developed that promise to reduce the overall cost of ethanol production. Lignin may then be better utilized in process heat applications.

Methanol. Methanol from biomass is made by first gasifying the feedstock to form a syngas. Syngas is a mixture of carbon monoxide, hydrogen, carbon dioxide, higher hydrocarbons, and tar. The syngas is then cleaned and conditioned before being converted over commercial catalysts to form methanol. Research and development to date has developed several medium-Btu gasifiers capable of producing a syngas.

Several issues relating to producing methanol from biomass remain. The issues of reliability and scalability of the gasifiers for producing the raw syngas and the cleaning and conditioning of the raw syngas from the biomass gasifier all have yet to be addressed. Techniques exist to remove particulates, manage tar formation, compress the syngas, adjust the carbon-monoxide-to-hydrogen ratio, and remove acid gas. However, research is necessary to adapt these techniques to syngas from biomass and to define system parameters. This research would initially be conducted in the laboratory with subsequent confirmation at a larger scale. After a clean syngas is produced, it is passed directly into a catalytic reactor to produce methanol. Little additional research is required on methanol catalysts.

Synthetic Hydrocarbon Fuels (Gasoline, Diesel, Jet Fuel). The basic approach used in biomass-to-hydrocarbon conversion is to pyrolyze biomass to form an intermediate biocrude product that is then catalytically converted to gasoline. Past research and development efforts have demonstrated that intermediate biocrude products can be made rapidly with high yields in special reactors. This fast pyrolysis process has been demonstrated with three different reactor designs.

There are two potential routes for upgrading the biocrude product: 1) hydrogenation at high pressures, and 2) zeolite cracking at low pressures. The hydrogenation process reacts hydrogen catalytically with the biocrude oil to produce hydrocarbons (mostly 77-octane gasoline), carbon dioxide, and water. In the zeolite cracking process, the biocrude oil vapors pass directly from the pyrolysis step to the zeolite upgrading step without being cooled or condensed. These vapors are catalytically cracked and reformed to hydrocarbons with the oxygen removed as water, carbon monoxide, and carbon dioxide.

Major issues to be resolved in converting biomass to gasoline include scaling up the biocrude production processes and increasing gasoline yield and quality. In addition, the upgrading processes must be integrated with the necessary gaseous recovery and recycle steps and these integrated process units must, in turn, be scaled up.

Certain aquatic and terrestrial plants produce oils that can be extracted and upgraded to produce diesel fuel. The primary processing requirement is to isolate the hydrocarbon portion of the carbon chain that closely matches diesel fuel and to modify its combustion characteristics by chemical processing.

Biomass-Derived Methane. Biogas, a mixture of methane and carbon dioxide, is produced from the biological, anaerobic digestion of biomass materials, a natural process in which complex organic compounds are decomposed by microorganisms. The methane and carbon dioxide are easily separated using conventional technology. Methane is naturally generated in landfills by the anaerobic digestion of municipal solid waste. Many facilities exist today in the United States for tapping the landfill gas resource. The anaerobic digestion of municipal solid waste can also be performed in dedicated facilities. Although no such facilities currently exist in the United States, it is estimated that this process can be competitive today at municipal solid waste tipping fees above $50 per ton.

Biofuels Summary. Based on the large and diverse biomass resource base, the energy potential of biofuels is enormous, perhaps enough to supply all transportation fuel requirements. Furthermore, the development of specific dedicated energy crops could significantly increase this already substantial potential. However, in order to economically tap this large potential, which consists primarily of cellulosic materials, much process research remains to be done.

Current Deployment Status

Ethanol and biogas are being produced today in commercial quantities. In 1988, about 850 million gallons (0.07 quads) of ethanol were produced domestically, primarily from corn, for blending into gasoline. Eight percent of all gasoline produced in the United States today is ethanol blended. At a 10% blend, ethanol thus represents 0.8% of the motor vehicle fuel market. Because the production of ethanol is heavily subsidized, the current market penetration of ethanol-blended gasoline is probably higher than would be the case without the subsidies. Biogas systems, including those using landfill, sewage, and farm-generated gases, have been installed in many locations and provide an estimated 0.013 quads of energy supply in total.

Key Issues

Areas requiring continued federal involvement or research and development investment include the following:

- laboratory and bench-scale research on enzymatic hydrolysis and xylose utilization
- operation of integrated process and engineering scale unit for converting lignocellulosic biomass to ethanol
- development of biomass-to-methanol technology including improvement of gas cleaning/conditioning systems, resolution of scalability/reliability issues, and integration of biomass production/conversion systems
- development of biomass-to-hydrocarbon technology including testing the fast pyrolysis process, developing improved conversion catalysts, and improving the yield and quality of the hydrocarbon product
- genetic engineering work in support of improved oil yields from microalgae and oilseeds and the development of improved species for dedicated energy crop production
- research to improve production of dedicated biomass feedstocks for energy production
- advance technology for harvesting, recovery, and separation of biomass as an energy feedstock
- work in support of municipal solid waste conversion and to foster industry adoption of technology to convert municipal solid waste to biogas.

4.1.8 Solar Heat

Solar heat technology uses radiant energy from sunlight to produce thermal energy that is used in direct heating applications. These applications can range from relatively low-temperature domestic pool and water heating, space heating, and desiccant cooling applications to high-temperature industrial applications that might use highly concentrated solar flux and high temperatures to destroy toxic wastes.

The principal advantages of solar heating systems pertain to their use of a secure, domestic energy resource, their relatively low environmental impact, and their relative modularity and short construction lead times. However, high-intensity solar radiation with minimal cloud cover is required for the use of concentrator systems, a constraint that may limit many such applications to the southwestern region of the United States.

A typical active solar heating system will employ two or more of the following components: 1) the collectors, which will be either flat-plate or concentrating depending on temperature requirements; 2) a receiver, for concentrating thermal applications, which converts the energy to heat in a working fluid; 3) piping to transport the heated fluid; and 4) a conversion device, which converts the heat to useful energy. High flux solar reactors directly convert solar energy into concentrated photon energy.

Flat-plate thermal collectors are simple solar-energy-absorbing devices, either in sheets or boxes, through which a heating fluid, generally water, is circulated and then piped off for use elsewhere. This type of collector is characteristic of water heating for swimming pools or water/space heating for households and commercial establishments. The collected heat is then stored in a tank or other device until needed. Domestic solar heating systems generally supply 30% to 70% of the average heating load and, thus, are supplemented with conventionally fueled backup systems.

Some active solar heating systems installed in the late 1970s and early 1980s suffered from hastily developed designs, unreliable controllers and sensors, and poor installation. Since that time, system reliability has improved steadily. Further improvements could be realized through additional research and development in the area of hardware design and system controls, including lower cost collectors, freeze protection, sensor reliability, tank stratification, and low-flow sizing.

Similar progress has been made in developing building designs and materials that provide direct control over solar gains through building apertures that supply direct heating and lighting benefits without adding to the building cooling load.

Active domestic solar heating systems experienced rapid penetration in the late 1970s and early 1980s because of rising energy prices and government tax credits. With lower energy prices and the expiration of solar tax credits, the rate of installations has declined dramatically. Still, in selected markets, solar water heating systems remain economical on a life-cycle cost basis. However, current technologies have yet to achieve more widespread competitiveness or approach their technical potential in terms of efficiencies or energy contributions. Analyses have indicated that innovative concepts incorporating new materials and system designs could yield competitive solar technologies that, when incorporated with passive solar techniques, meet up to 80% of a building's heating and cooling requirements in many regions of the United States.

The combination of solar cooling with solar heating can provide year-round use of collected solar heat and thereby significantly increase the cost-effectiveness and energy contribution of solar installations. Currently, solar desiccant and solar-driven absorption systems are the active cooling technology options that appear to have the greatest potential.

Solar desiccant systems use a desiccant or drying agent to adsorb water vapor in recirculated or ventilation air to reduce humidity levels. The warm dry air is subsequently cooled evaporatively to the required temperature. The solar heat from the collectors is used to dry or regenerate the desiccant so it can regain its moisture-trapping or sorption capacity.

A solar absorption system uses the thermal energy from the solar collector to separate a binary mixture of an absorbent and a refrigerant fluid. The refrigerant is condensed, throttled, and evaporated to yield a cooling effect, after which it is reabsorbed to continue the cycle.

Prototypical solar cooling systems have demonstrated the ability to meet 40% or more of a building's cooling requirements. However, their performance-to-cost ratio must be increased by a factor of 3 before these systems can be economically competitive with conventional electrically driven air conditioning systems in most applications. Achieving competitiveness will require improvements in system performance, including reductions in auxiliary energy requirements and in system costs.

Solar systems can also be employed for industrial process heating. These systems generally use parabolic trough concentrators (see Section 4.1.5) producing heat as high as 750°F, a temperature that encompasses the range of many industrial process heat applications.

The future penetration rate of solar industrial process heating systems is hard to predict. Although the technology base for solar process heat applications is largely developed and the ability to integrate solar augmentation into existing process heat plants has been demonstrated, these systems are not economically competitive with today's lower fuels prices.

High concentration solar systems can use a focused beam of concentrated solar energy and the resulting high temperatures for such high-value applications as the destruction of hazardous chemicals, the production of fuels and chemicals, and the development of special materials properties. For instance, a solar detoxification reactor, placed at the focus of a solar beam, was able to produce dioxin destruction efficiencies of greater than 99.9999%, a level that would meet or exceed current EPA requirements. This high destruction efficiency is the result of two complementary effects: 1) the photolytic effect from the ultraviolet and visible portions of the solar spectrum and 2) the thermal effect from the infrared portion of the spectrum. Tests indicate that the combination of these effects leads to a more complete destruction of dioxin at lower temperatures than can be obtained through conventional incineration processes. Thus, the potential exists to displace conventional energy sources in toxic waste incineration, while at the same time introducing a more efficient incineration process.

Additional advantages of solar-based waste destruction include reduction of incomplete combustion products; the ability to incinerate in a nonoxidizing environment under better control of thermal input conditions; and the potential for onsite destruction, which could eliminate the need to accumulate and transport hazardous wastes to disposal sites. These applications of high solar-flux technology have only recently received serious attention. Even without high temperatures, concentrated solar flux has the ability to detoxify hazardous chemicals in water, a process resulting in complete decomposition of some classes of chemicals. This approach uses the high-energy photons in the ultraviolet portion of the solar spectrum.

Current Deployment Status

More than one million active solar heating systems have been installed in the United States, primarily for low-temperature residential applications. Another 250,000 homes and buildings are estimated to incorporate passive solar designs and materials. Combined, these installations provide an estimated 0.05 quads of primary energy displacement annually. Few solar industrial process heating systems have been installed to date. Finally, direct conversion, high solar-flux systems applications are now under development and, thus, are not yet commercialized.

Key Issues

Areas requiring continued federal involvement or research and development investment include the following:

- generic, standardized systems work focused on identifying system design, test, and operating procedures to achieve high-performance, high-reliability systems
- systems effectiveness work to identify reliability issues and validate reliability trends of systems in the field

- analysis, advanced materials development, performance measurements, and design tool development aimed at developing and implementing building aperture thermal control technologies for integrated heating, cooling, and lighting loads

- work on advanced systems and concepts including solar desiccant and absorption cooling systems

- demonstration of the long-term reliability of solar industrial process heating systems

- research on materials, processes, and components related to the generation of concentrated solar energy for the destruction of hazardous wastes

- research to apply the unique attributes of concentrated solar thermal flux to fuel and chemical production and materials processing.

4.2 POTENTIAL FOR REDUCING EMISSIONS FROM GREENHOUSE GASES

Most renewable energy technologies in operation produce no greenhouse gas emissions and, thus, are capable of displacing fossil fuel combustion emissions on a Btu-for-Btu or kWh-for-kWh basis. These renewable energy technologies include hydropower, wind, photovoltaics, and the solar thermal applications. In addition, solar desiccant cooling systems can displace the use of chlorofluorocarbons in cooling applications in buildings. The moisture adsorption performed by the desiccant system reduces the effective cooling load, thus allowing a downsizing of the refrigerant cycle where chlorofluorocarbons are currently used. Solar thermal/fossil fuel hybrid systems would emit greenhouse gases in direct proportion to the amount of fossil fuel used. However, these emissions would still be only some fraction of those from a dedicated fossil-burning plant.

Carbon dioxide is a common constituent of geothermal fluids. If the energy utilization process allows the fluids to depressurize, most of the carbon dioxide will be released to the atmosphere. The amount of carbon dioxide in geothermal fluids varies greatly from site to site and from well to well within a given field. Typical values range from 100 ppm to 8,000 ppm in liquid brine, and about 500 ppm to 40,000 ppm in dry or flashed steam. Steam electric geothermal power plants (dry steam or flash steam) depressurize the fluids and, thus, emit some carbon dioxide. Binary-cycle power plants keep the geothermal fluid pressurized sufficiently so that no carbon dioxide or other gases are released to the atmosphere.

Measurements from five dry steam plants at The Geysers in California indicate carbon dioxide emissions ranging from 40 to 76 lbs/MWh or only 2% to 4% of those from a typical western coal plant. Measurements from two commercial double-flash plants in the Imperial Valley of California indicate emissions of from 2 to 125 lbs/MWh or 0.1% to 6% of those from a typical western coal plant. Thus, geothermal development (based on either dry steam or flash-steam technology), on average, could displace more that 90% of the carbon dioxide emissions from equivalent coal-generating capacity. At most locations, the geothermal-related carbon dioxide could be contained and reinjected at modest additional expense. Development based on the binary- cycle technology could displace 100% of equivalent fossil-fuel-related carbon dioxide emissions at no additional cost.

The combustion of biomass produces about 90% as much carbon dioxide per Btu as coal combustion. To the extent that all living matter eventually decays to carbon dioxide and methane, the use of biomass for energy not only produces emissions that would occur naturally, but it also displaces carbon dioxide and methane that would be released by the combustion of fossil fuels. Dedicated biomass combustion systems might also result in an overall reduction of methane and nitrous oxide emissions that would occur naturally from decay or uncontrolled fire situations.

The use of biomass-derived alcohol fuels can also potentially reduce greenhouse-gas precursors. For example, methanol blends (in the form of MTBE) of 11% have been observed to reduce carbon monoxide and NO_x emissions from current gasoline-based automobile fleet averages. Ethanol blends of 10%, as commercially practiced today, also reduce both carbon monoxide and NO_x emissions.

All plants have the ability to absorb and, thus, reduce atmospheric levels of carbon dioxide. When a tree is used for energy, the carbon dioxide stored in the tree is released into the atmosphere, temporarily increasing carbon dioxide levels. However, a new tree planted to replace the one used will absorb carbon dioxide in amounts roughly equal to the carbon dioxide emitted from the original tree. As a result, biomass energy systems could be developed in which the net change in carbon dioxide levels over time is zero as long as trees used for energy are continuously replaced.

When conventionally grown biomass is replaced by fast-growing species in dedicated energy farms, additional carbon is captured from the atmosphere. Fast-growing species have crop rotations of 6 to 8 years and more than ten times the productivity of natural species. When fast-growing trees are harvested, up to 33% of the carbon remains in the living root mass as long as the root mass remains unexposed.

4.3 BARRIERS TO INCREASED USE OF RENEWABLE ENERGY TECHNOLOGIES

The barriers to increased use of renewable energy technologies as strategies for reducing greenhouse gases emissions fall into four general categories: 1) technical, 2) institutional, 3) market, and 4) public acceptance. A discussion of these factors is presented below.

4.3.1 Technical Barriers

Renewable energy technologies are in various stages of development. Many renewable energy technologies, such as hydropower, biomass combustion, and specific geothermal and solar heating technologies, are already well-established technologically and have successfully penetrated energy markets. Others, such as wind, photovoltaics, and solar thermal electric have attained a small degree of market penetration, but have yet to prove long-term economic application. Finally, some renewable energy technologies, such as biofuels production from cellulose and those needed to access unconventional geothermal resources, are still under development. In most cases, a greater and sustained research, development, and demonstration effort is required both to prove new concepts and to improve upon the performance, efficiencies, and reliability of existing concepts in order to bring competitive technologies to the marketplace. A more intensive research, development, and demonstration effort would accelerate the timing of cost competitiveness, and thus deployment, for all renewable energy technologies. As a result, these technologies could make a greater near-term contribution to reducing energy-related greenhouse gas emissions.

One potential technical limitation on some electricity-generating renewable energy technologies, such as wind, solar thermal electric, and photovoltaics, is the ability of a utility grid to accept large penetrations of intermittent generation. At greater penetrations, a greater system response capability must be developed to regulate generation fluctuations much the same as utilities now respond to load fluctuations. Those grids with a large preexisting base of such plants may be able to incorporate a large proportion of intermittent supply. For instance, the Pacific Northwest, with ample hydropower capacity, could conceivably incorporate a large fraction of intermittent technologies. Otherwise, additional costs may eventually be incurred in coupling these intermittent technologies to storage or dispatchable technologies either at the plant site or on a system-wide basis.

This is an important technical issue for achieving the longer-term potential of intermittent renewable energy technologies, and one that has yet to be resolved.

4.3.2 Institutional Barriers

Important institutional barriers keep renewable energy from realizing its full market potential. For instance, hydropower is a mature technology that thus far has captured only one-half of its estimated resource potential. The primary institutional barriers to increased hydropower development are its environmental impacts and a complex licensing process.

The Electric Consumers Protection Act (ECPA) of 1986 requires FERC to give equal consideration to nondevelopmental values, such as the environment, safety, and efficiency, when evaluating both new developments and relicensing existing hydropower facilities. The licensing process now requires the examination of dissolved oxygen, instream flow, and other cumulative impacts of hydropower development. New dam safety criteria require that existing dam structures be upgraded as part of any refurbishment or development. While these institutional concerns may be well-founded, the combined impact of the new requirements, without the concurrent development of valid and standard methodologies for assessing and mitigating these impacts, will be to slow hydropower development.

Increased use of the municipal solid waste resource is also constrained by institutional factors. Communities must be willing to make financial and organizational commitments to resource recovery plants; to incorporating and coordinating refuse collection, processing, disposal; and to the marketing of process products, including recyclables and energy.

Environmental issues can be an important stimulus for deployment of many renewable energy technologies. Although the use of renewable energy is generally viewed as being less environmentally harmful than the use of conventional energy supply, concerns still arise regarding impacts on land and water use and other environmental issues. On the other hand, until awareness of the total fuel-cycle costs of conventional energy supply is improved and these costs are internalized in energy supply decision making, the relatively smaller impacts of renewable energy will not be fully valued.

This last point speaks to the entire regulatory process as a potential obstacle to increased development of renewable energy technologies; to the extent that they perceive renewable energy technologies to be immature or exotic technologies that are costly and unreliable, public regulators may not adequately incorporate renewables into the decision-making process. Building greater awareness of the value of renewable energy technologies as energy options is necessary at all levels of decision making.

Finally, infrastructural issues will also play an important role in realizing the large potential of several renewable energy technologies. For example, longer-term penetration of alcohol fuels in transportation, above the 10% ethanol blends used at present, will require the production of vehicles that are fuel flexible and/or compatible with alcohol fuel. The market penetration of cost-effective solar heating and cooling technologies will depend largely on the willingness of the construction industry to incorporate these technologies into new buildings.

4.3.3 Market Barriers

The primary market barrier to greater development of renewable energy technologies pertains to the greater perceived risk of these technologies. As risk increases, so do required rates of return. To the extent that these technologies are reliably demonstrated, this barrier can be reduced.

Another aspect of this investment risk deals with the higher front-end costs of many renewable energy technologies. Because these technologies tend to be capital-intensive, investors must trade off the higher initial investment against longer-term savings in operation costs. In the electric utility sector, the prospect of prudency reviews of utility investments adds to the risk element in large capital outlays. With most fossil-fuel plant investments, the investor trades off lower capital costs against the risk of future fuel price escalation. In both cases, there is uncertainty that must be balanced in the decision-making process.

Finally, the matching of renewable energy supplies with markets presents a potential barrier to deployment. Given the remoteness of many renewable energy resources, important limitations may be imposed by the need and additional costs involved with transporting or transmitting the energy to the large load centers.

4.3.4 Public Acceptance Barriers

Public acceptance of energy-producing facilities of any type is a limiting factor on potential deployment. Public opposition is greatest to those energy projects that directly impact human values. Some renewable energy examples include hydropower development that threatens wilderness and recreational values and resource recovery plants that by necessity must be located in proximity to the populace. Aesthetics may be an important consideration for wind and some solar applications where large expanses of turbines and collectors are required to capture the diffuse resource. Public acceptance will also be critical to the success of alcohol fuels in penetrating the transportation fuels market.

4.4 OTHER IMPACTS FROM USE OF RENEWABLE ENERGY TECHNOLOGIES

Aside from the mitigation of greenhouse gases, important benefits accrue to the use of renewable energy sources. Environmentally, renewable energy sources are relatively benign on a total fuel-cycle basis when compared with conventional energy production and use.

The primary environmental impact of renewable energy sources is on land use. For instance, large areas of land will be required for dedicated biomass energy crops. However, both short rotation wood and perennial energy crops require less intensive management (fertilizer, herbicide, and insecticide applications) than do normal agricultural crops. Energy crops also stabilize eroded lands. In addition, the low sulfur and nitrogen contents of these feedstocks, along with their ability to recycle carbon dioxide, make them preferable to the use of coal or crude oil.

Large areas of land will also be required for greater deployment of wind and solar electric technologies. However, land used for wind farms can still be used for agriculture or grazing land. And very substantial areas of unused land, particularly in the Southwest, are available for the deployment of solar electric systems. In the case of buildings, solar energy technologies can be integrated directly into construction and, thus, have no land use impact. Finally, because the modularity of many solar technologies offers enormous flexibility in siting, many adverse impacts can be mitigated.

Although new hydropower facilities can have important environmental impacts on land use, systems are being increasingly deployed in a run-of-river mode, which provides an alternative to impoundments.

Renewable energy technologies are generally cleaner than conventional fuels in end-use applications. For instance, because of their high oxygen content, biomass-derived alcohol fuels and blends are clean-burning fuels, reducing carbon monoxide and NO_x emissions from vehicles. The higher octane of alcohol fuels also provides for better engine performance. Also, the use of biomass waste materials as process feedstocks can reduce waste disposal requirements.

Solar buildings technologies provide energy with no emissions, thus avoiding the deleterious localized impacts of fuel combustion. Because they are nonpolluting and modular, solar electric technologies such as photovoltaics can be deployed closer to or even within population centers, displacing locally polluting fossil plants and increasing the efficiency of electricity transmission and distribution.

Energy security benefits accrue to the use of domestic renewable energy sources. Oil imports can be directly displaced by alternate transportation fuels derived from biomass feedstocks. And the diversity in energy sources offered by renewable energy technologies broadens the national energy portfolio and reduces societal risk imposed by reliance on conventional energy sources.

Finally, national and local economic benefits derive from the development and use of renewable energy resources and technologies. On the national scale, reductions in oil imports yield an improved balance of payments and a stronger and less vulnerable domestic economy. A technological lead in the development of renewable energy technologies also results in important advantages for U.S. industrial competitiveness and, thus, in export markets. At the local level, deployment of renewable energy technologies can stimulate economic development, reduce the outflow of locally generated capital to pay for energy imports, and yield greater control over local and regional energy developments.

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5.0 ENERGY STORAGE, TRANSMISSION, AND DISTRIBUTION TECHNOLOGY

Energy storage technologies can play a key role in many applications because of their ability to decouple energy supply from energy demand. For example, large secondary (electrically rechargeable) batteries make electric utility system load-leveling possible. Without energy storage, load following is either impractical (for nuclear power plants) or impossible (for stand-alone wind or solar power generation). Energy storage systems enable greater efficiency and flexibility in electric utility systems. They can 1) improve efficiency by allowing full-load operation during low-load conditions, 2) improve the economics of intermittent renewable energy technologies, and 3) provide peak power at competitive cost without requiring new generating capacity. If energy storage systems based on renewable energy resources or other nonfossil resources are used instead of gas turbines to meet peak demands, the net result is a decrease in greenhouse gas emissions.

Storage is also beneficial for customer-side-of-the-meter (CSOM) applications when the customer's load profile contains intermittent peaks. The battery system is installed in the customer's facility and is controlled by the customer. It is charged during the customer's off-peak periods and discharged during the customer's peak demand periods. The purpose of the system is to reduce the customer's monthly electrical demand charge by reducing the maximum power load the utility supplies during the customer's peak demand periods.

Energy storage has many potential applications because of the various energy sources and energy end uses that exist. Energy storage technologies can be categorized into five major groups: electrochemical, thermal, mechanical, chemical, and magnetic. Energy storage systems are attractive because they are compatible with a wide range of energy conversion processes.

Storage systems do not directly emit greenhouse gases to the atmosphere, although they can be part of energy conversion processes that do have such releases. Fortunately, storage technologies also offer advantages for many advanced energy conversion and energy-use systems that have low or no emissions, particularly renewable resources. In general, the potential to reduce emissions by decreasing peak-load fossil fuel combustion (via gas turbines) results when storage technologies (using renewable resources or other nonfossil energy resources) reduce the need for additional energy conversion to meet peak-load demands.

Energy transmission and distribution technologies range from electrical grids that transmit electricity from electric power plants to various end users; to pipelines that transport liquid and gaseous fuels from wellfields or process facilities to end users; to trains that haul coal and other solid fuels from mines, forests, or fields to end users. Some of these transmission and distribution technologies emit negligible amounts of greenhouse gas, while others do not. In all cases, increasing the efficiency of energy transmission and distribution will lead to reduced emissions from lower energy generation or production requirements.

This chapter is divided into two main sections. In Section 5.1, the five basic categories of energy storage technologies are discussed. In Section 5.2, the energy transmission and distribution technologies are discussed. For each technology, the discussion includes a description of the technology, probable applications, performance and cost characteristics, typical greenhouse gas emissions, and potential reductions in those emissions.

5.1 ENERGY STORAGE TECHNOLOGIES

This section describes the five basic categories of energy storage technologies: electrochemical, thermal, mechanical, chemical, and magnetic.

5.1.1 Electrochemical Energy Storage

Since their discovery a century ago, batteries have been used to store electrical energy and deliver it on demand. Today, all our automobiles use a lead-acid battery to provide electrical power to the vehicle. Various types of batteries are also used in applications ranging from toys to lap-top computers. These energy storage devices are also used in many defense applications.

Batteries are efficient devices for storing electrical energy. Judiciously used, these storage devices can have major impacts on the nation's energy policies by providing realistic options for fuel flexibility and by helping to mitigate many of our air-quality problems. Commercially available batteries do not have the required performance and cost characteristics for applications in the utility and transportation markets. Consequently, an aggressive worldwide effort is under way to develop advanced batteries for these applications. DOE is a key player in this overall effort. This section discusses the status of the technology, the potential applications, the performance and life-cycle costs, and the potential impact of this technology in improving air quality and reducing greenhouse gas emissions.

Description of Electrochemical Energy Storage

During the charging process in a battery, electrical energy promotes an electrochemical reaction that produces two chemicals, one at the anode and one at the cathode. The electrical energy is stored in the form of these chemicals. When electric power is required, the battery is discharged and the reverse electrochemical reaction occurs; namely, the two chemicals revert to their earlier state and release the stored energy directly as electricity. The energy storage efficiency of an electrically rechargeable battery is generally high, ranging from 65% to 85%, depending on the type of battery.

Many different types of batteries are being developed for a wide variety of applications. In a recent DOE-sponsored study, battery developers proposed some 40 electrochemical couples (combinations) as potential battery systems for electric vehicle applications alone. Some of these advanced batteries are approaching commercial-scale demonstration; whereas, others are still in the laboratory research phase.

Well-developed advanced batteries that are being considered for large-scale utility and transportation applications are classified into two major groups: 1) batteries that operate at or around ambient temperature, and 2) batteries that operate at elevated temperatures of 200°C (390°F) or higher.

Ambient-Temperature Batteries. The ambient-temperature batteries commonly use aqueous electrolytes. Many of these batteries are currently in commercial use. Development efforts are directed toward meeting the stringent performance and cost requirements of the utility and transportation markets. Some of the promising systems are described below.

Lead-Acid Battery. The lead-acid battery is a mature technology that is widely used commercially. Since its discovery a century ago, it has been continuously improved. Recently, the improvements have focused on meeting the requirements of the utility and transportation markets. The lead-acid battery is probably the battery nearest to commercialization for these markets. The energy-efficiency of this battery is high, typically about 85%.

The lead-acid battery has been extensively tested as the power source in electric vehicles. It can deliver 40 Wh/kg of battery weight (called specific energy) and a peak power of 80 W/kg. This translates into a 60-mile range with acceleration from 0 to 30 mph in 30 seconds for a typical delivery van application. Recently, through a combination of innovative vehicle design and improved lead-acid batteries, General Motors produced a prototype electric vehicle (named Impact) that has a 100-mile range and can accelerate from 0 to 60 mph in less than 10 seconds. Fleet vans powered by lead-acid batteries are expected to be commercially available in the United States within the next few years.

Lead-acid batteries are also being demonstrated as an electric utility load-leveling technology at the

Chino facility of Southern California Edison. Their 10-MW, 40-MWh unit is one of the world's largest battery storage demonstration units. The unit has been in operation for about 3 years and has performed extremely well. The Chino battery is a low-maintenance vented design, to which water must be added regularly. The capital and operation and maintenance (O&M) costs for lead-acid battery storage are still too high for regular utility applications; however, the valuable operating experience obtained in this demonstration is allowing developers to pursue improvements to reduce both capital and O&M costs. To date, five large, lead-acid battery demonstration projects are ongoing worldwide, and commercial lead-acid battery installations in the utility sector are very likely to be a reality in the near future.

Nickel/Iron Battery. The nickel/iron battery is a commercially available, reliable battery with higher specific energy and power than the lead-acid battery. However, because of the inherent inefficiencies in electrochemical energy conversion, the nickel/iron battery's energy efficiency is only 60%. Therefore, it is not suitable for utility load-leveling applications but may be an attractive candidate for electric vehicle markets. Nickel/iron batteries designed for electric vehicle applications have demonstrated 55 Wh/kg and peak power of 120 W/kg, which translates to a range of approximately 100 miles for an electric van. DOE is supporting the development of this battery for transportation applications. The effort is focused on reducing the inherently high cost of the battery without sacrificing its ruggedness and performance.

Nickel/Zinc Battery. The nickel/zinc battery has demonstrated a specific energy of 80 Wh/kg and a specific power of 200 W/kg, with an energy efficiency of approximately 70%. These attractive characteristics prompted General Motors to seriously consider this battery for passenger electric vehicle applications. Unfortunately, it also has a short cycle life of only about 200 cycles primarily because the zinc electrode experiences rapid deformation during a series of charge-discharge cycles. Sustained research has not been able to overcome this technical hurdle.

The recent advances using zinc-calcium electrodes and modified electrolytes offer promise for longer lifetimes for this battery system. However, the advanced technologies have not yet been demonstrated in modules or full-size batteries. If the cycle life can be extended to over 500 cycles, this battery will again emerge as an attractive candidate for electric vehicle applications.

Metal/Air Batteries. Iron/air, zinc/air, and aluminum/air batteries have been considered for electric vehicle applications because of their high energy density. The energy efficiency has been low (approximately 60% for zinc/air and iron/air) primarily because of the pronounced irreversibility of the air electrode. The aluminum/air battery is a primary battery that is recharged by adding fresh aluminum anodes. Its energy efficiency is only 30%, reflecting the very poor efficiency of the electrolytic aluminum production process.

The development efforts for these technologies are in a relatively early stage and are focusing on innovative cell design and on improving the performance of the air electrode. The iron/air battery is the most developed within this group, and fabrication and testing of modules are just beginning. Another 5 to 10 years of aggressive research and development is required before any of these systems will be ready for prototype testing.

Flow Batteries. Each of these batteries has a circulating aqueous electrolyte. Although electrolyte circulation is necessary to separate the products of the charging reaction and to improve the battery's performance, it does increase the complexity of the system. The primary advantage of these batteries is their low cost, even though their energy efficiency is lower than other battery systems (approximately 65% to 75%).

The two most well-known flow batteries are the zinc/chlorine and the zinc/bromine systems. The chlorine and bromine produced during the charging of these batteries are stored separately by complexing with an organic solvent.

The best performance so far has been obtained by Japanese developers. Furukawa Battery Company has tested a 60-kW, 480-kWh zinc/chlorine battery with 78% energy efficiency early in life. Similarly, Meidensha has demonstrated a 50-kW, 400-kWh zinc/bromine battery with 75% energy efficiency. Neither of these batteries is ready for large-scale demonstration. Both systems still require frequent maintenance because of their complexity and the detrimental effects of trace contaminants present in the electrolytes. In addition, the electrode warpage problem in the zinc/bromine battery tends to shorten its life to less than 200 cycles.

Once these technical problems are overcome, these two batteries could become low-cost options for utility and transportation markets. The complex nature of these batteries will, however, be a problem for transportation applications, where packaging the battery in limited space is a primary issue. In addition, storing significant amounts of hazardous chemicals such as chlorine or bromine onboard a vehicle is not an attractive feature. These batteries may be attractive options in the utility load-leveling market, where the battery's size and use of hazardous chemicals are not critical.

High-Temperature Batteries. High-temperature batteries operate from 250°C to 450°C (480°F to 840°F). As a result, thermal management of these batteries is an important consideration. The higher operating temperatures, however, allow these systems to demonstrate better energy and power characteristics compared with the ambient-temperature batteries. The high-temperature batteries are classified into two groups: 1) solid electrolyte batteries and 2) molten electrolyte batteries.

Solid Electrolyte Batteries. The solid electrolyte of choice is beta-alumina, which demonstrates acceptable conductivity at elevated operating temperatures. The two batteries that fall into this category are sodium/sulfur and sodium/metal chloride.

The concept of the sodium/sulfur battery originated at Ford Motor Company about 20 years ago. Since then, its development has received extensive worldwide government and corporate support. Currently, an estimated $140 million annually is being spent to transfer this battery from the research and development stage to the pre-commercial pilot-plant production stage. European, U.S., and Japanese developers are actively pursuing the development of this battery, which is targeted for both electric vehicle and utility applications.

A 50-kWh sodium/sulfur battery for electric vehicle applications demonstrates specific energy of 100 Wh/kg and specific power of 130 W/kg, which translates into a 130-mile range under an urban drive-cycle regime. Several of these batteries have been installed and operated in actual vehicles. The battery system's performance has met expectations. A 50-kW, 400-kWh sodium/sulfur battery for utility load-leveling has been operated, demonstrating 85% energy efficiency. The areas of concern with the sodium/sulfur battery are as follows:

1. The beta-alumina electrolyte is fragile; it can crack under thermal and vibrational shock.

2. The lack of overcharge and overdischarge protection makes the interconnection strategy of cells and modules difficult.

3. The accidental combination of the sodium and sulfur in a cell with cracked electrolyte can cause runaway thermal reactions.

4. The battery may not have an adequate lifetime.

Research to address these concerns is in progress, and the prognosis of this battery being successfully used for utility load-leveling and transportation applications is good.

The sodium/metal chloride battery is a close analog of the sodium/sulfur battery. The only difference is that the sulfur electrode of the sodium/sulfur battery is replaced by molten iron or nickel chloride in the sodium/metal chloride system. It is a relatively new system that has been under development for approximately 7 years. The attractive features of this battery (as compared with the sodium/sulfur battery) are 1) lower operating temperature [(290°C) (550°F)], 2) limited overcharge and overdischarge toleration, 3) higher cell voltage, and 4) better safety characteristics.

This battery is being developed under the leadership of a South African conglomerate (Anglo-American Company), which has elected not to divulge much of their test data. The limited data available in the public domain indicate that this battery is at a much earlier state of development than the sodium/sulfur battery. The energy and power characteristics are about 20% lower than the sodium/sulfur battery, but the enhanced safety features and potentially lower cost make this battery a very viable competitor to the sodium/sulfur system. The developers have fabricated and tested 25-kWh battery modules for electric vehicle applications.

Molten Electrolyte Batteries. The lithium/iron monosulfide battery has received the most attention in this battery class. It operates at 450°C (840°F) and employs a LiCl-KCl electrolyte. Lithium and iron monosulfide are the two electrodes. This battery is targeted for electric vehicle applications. Batteries have been constructed that deliver 100 Wh/kg and more than 100 W/kg. The cycle life is over 1000 cycles, which meets the goals of most electric vehicle applications.

The lithium/iron disulfide battery is a variation of the monosulfide version. The recent use of dense FeS_2 and a modified electrolyte of LiCl-LiBr-KBr has greatly improved the capacity retention in this battery. It has a lower operating temperature of 400°C (750°F) and an excellent cycle life of over 1000 cycles. Although it is in an earlier stage of development than its monosulfide counterpart, it promises to ultimately deliver better overall performance.

The corrosive environments in these batteries require the use of molybdenum current collectors, which contribute substantially to the battery's cost. Research efforts are directed towards finding a lower-cost substitute for molybdenum.

Applications for Energy Storage Technologies

The two major applications of battery energy storage are as follows:

1. **Electric Vehicles.** Advanced batteries exhibiting high specific energy and power, durability, and low cost can provide electric vehicles with the range, acceleration, and competitive life-cycle cost necessary to be commercially acceptable. An international effort to promote electric vehicles has resulted in tremendous progress in battery technology. Electric vans are now in the proof-of-concept stage in the United States, with market entry expected in the next few years.

2. **Utility Energy Storage.** Battery energy storage for load-leveling is a very attractive option for utilities. The ongoing lead-acid battery load-leveling demonstration project at Southern California Edison is a testimony to utility interest in this technology. In addition to providing greater fuel flexibility and environmental benefits, batteries also provide utilities additional benefits by their ability to respond quickly to rapid load changes. Utility planning is facilitated by the short lead time, ease of siting, and modular construction of battery systems.

If batteries are to be acceptable for these applications, they must meet stringent performance and cost goals. They must offer high specific energy and power, long lifetime, and low life-cycle cost. Table 5.1 lists the criteria that are considered essential for the commercial viability of battery technology (McLarnon and Cairns 1989). Currently, no battery systems can satisfy all of these criteria. The two major thrusts of the ongoing research and development efforts are to improve performance and lower costs. Dramatic progress made in the last decade raises the realistic hope that some of the battery systems under development will meet the stringent requirements and will be commercialized in the next 5 years.

Table 5.1. Requirements for Energy Storage Batteries

Requirement	Electric Vehicles	Load Leveling
Specific energy (Wh/kg)	>70	--
Energy density (Wh/l)	>140	>13
Energy/area (kWh/m^2)	--	>80
Specific power (W/kg)	>130	--
Energy-efficiency (%)	>60	>70
Cycle life	>800	>2000
Calendar life (years)	>5	>10
Cost ($/kWh)	<100	<100

Source: McLarnon and Cairns 1989.

Performance and Cost of Energy Storage Technologies

Table 5.2 summarizes the current performance of some of the advanced batteries (DeLuchi et al. 1989). When the current battery performance characteristics are compared with the requirements listed in Table 5.1, many of the advanced battery systems appear to be close to meeting the performance targets. This is a remarkable improvement compared with a decade ago and indicates the early demonstration and commercialization of these technologies. Figure 5.1 shows the levelized cost of battery energy storage in utility load-leveling applications (Humphreys and Brown 1990). For comparison, the cost of advanced gas turbines calculated on the same basis is 13 cents/kWh. Some of the advanced batteries, such as sodium/sulfur and zinc/bromine, are approaching the point where they may be economically competitive with gas turbines for meeting peak electricity demands. If other benefits such as reduced emissions, ease of siting, and modular construction are considered, batteries appear to be a viable alternative to gas turbines.

Figures 5.2 and 5.3 similarly consider the levelized cost of battery-powered vans and cars (Humphreys and Brown 1990). The battery-powered van is close to being economically competitive with its internal combustion engine counterpart, and such vans for fleet applications are expected to be on the market within a few years. The case for the general-purpose passenger vehicle is more difficult. Both the initial and the life-cycle costs are high compared with their internal combustion engine counterparts, especially at current gasoline prices.

Greenhouse Gas Emissions from Energy Storage Technologies

Unlike internal combustion engines, battery-powered vehicles will not produce any harmful emissions, including greenhouse gases. However, producing the additional electricity required for electric vehicles will involve greenhouse gas emissions if that electricity is produced by burning fossil fuels. Thus, the electricity generation mix will play an important role in the net impact that electric vehicles will have on greenhouse gas emissions. The potential impacts of electric vehicles on emissions are shown in Figure 5.4 (Landgrebe et al. 1990). The three scenarios for fuel mix for utility power generation considered in this analysis are as follows:

1. *Probable*: coal 55%, gas + oil 14%, renewable + nuclear 31%

2. *Progressive*: coal 20%, gas + oil 34%, nuclear + renewable 46%

3. *Ideal*: nuclear + renewable 64%, gas + oil 36%.

The impact on carbon dioxide emissions in each of the three scenarios is very significant, ranging from a 65% to 90% reduction. In the "probable" scenario, however, sulfur dioxide emissions increase substantially, reflecting the increased use of coal to produce the additional electricity.

Similarly, the impact of battery storage on emissions in the utility sector is shown in Figure 5.5 (Landgrebe et al. 1990). The impact also depends critically on the utilities' baseload generation mix, ranging from a 7% reduction in carbon dioxide emissions for the probable scenario to a 100% reduction under the ideal scenario. It is important to note that each scenario considered involves significant reductions of all the harmful emissions. The scenarios

Table 5.2. Characteristics of Electric Vehicle Storage Batteries

Battery References	Volumetric Energy Density (Wh/l)	Mass Energy Density (Wh/kg)	Peak Power (w/kg-% DOD)	Energy Efficiency (%)	Life Cycles to 80% DOD	Projected OEM Cost (1985/kWh)	Type of Estimate
Pb/acid							
USDOE (1988)	(a)	22	80-50%	(a)	500	124	JCI current gell cell module performance
Hamilton (1988a)	(a)	35	(a)	70	800	95	Current battery performance
USDOE (1987b)	75-94	30-38	79-50%	75	375	58	DOE battery goals (50-mi range)
JPL (1987)	80	40	150-80%	(a)	400	50	JPL sealed Pb/acid cell goals
Ni/Fe							
USDOE (1988)	(a)	53	110-50%	(a)	500	(a)	EPI current module performance
Hamilton (1988a)	(a)	53	(a)	60	1,100	150	EPI current battery performance
USDOE (1987b)	77-97	45-56	79-50%	70	1,125	125	DOE battery goals (75-mi range)
Zn/Br							
USDOE (1988)	(a)	55	86-50%	(a)	>35	(a)	JCI current battery performance
USDOE (1987b)	76-96	60-75		65	600	75	DOE battery goals (100-mi range)
EVD (1987); SNL (1988)	60	56	150-?	>70	(a)	(a)	SNL battery goals
Zagrodnik and Eskra (1988)	(a)	70-80	(a)	(a)	1,000	55	JCI battery projections and goals
Li-me/Fe-S							
Barlow and Chilenskas (1987)	(a)	60-120	97-50%	85-97	125	(a)	Current ANL/Gould module performance
USDOE (1987b)	87-109	80-100	106-50%	75	600	91	DOE battery goals (100-mi range)
Beck et al. (1988)	150	100	150-?	(a)	1,200	80-100	Canadian battery goals
Kaun et al. (1987)	(a)	200	200-80%	(a)	1,000	(a)	ANL cell goals
Na/S							
Hamilton (1988a)	(a)	90	(a)	70	1,000	118	CSPL current battery performance
Fischer and Shiota (1988)	97	86	127-80%	(a)	250	(a)	ABB-B11 current battery performance
USDOE (1987b)	87-109	80-100	106-50%	75	600	91	DOE battery goals (100-mi range)
Fischer and Shiota (1988)	145	108	200-80%	(a)	600	(a)	ABB projected battery performance
Angelis (1987); Haase (1987)	129	120	188-	(a)	1,000	50	1990 ABB/BMW goals (120-mi range)
EVD (1987); SNL (1988)	150	125	150-	>70	(a)	(a)	SNL CSPL battery goals
Mulcahey et al. (1987)	(a)	143	140-50%	(a)	>2,300	(a)	CSPL current cell performance

Table 5.2. (contd)

Battery References	Volumetric Energy Density (Wh/l)	Mass Energy Density (Wh/kg)	Peak Power (w/kg- % DOD)	Energy Efficiency (%)	Life Cycles to 80% DOD	Projected OEM Cost (1985/ kWh)	Type of Estimate
Metal/air							
USDOE (1988)	(a)	70	50-50%	(a)	>120	(a)	Current Fe/air cell performance
USDOE (1987b)	87-109	80-100	106-50%	75	600	91	DOE Fe/air goals (100-mi range)
Ross (1987)	53	106	200	60-70	650	80	LBL projections for Zn/air battery
LLL (1988); Sen et al. (1988)	167	320	140-?	(a)	(a)	See text	LLL projections for Al/air battery

ABB = Asea Brown Boveri; ANL = Argonne National Lab; CSPL = Chloride Silent Power Limited; DOD = depth of discharge; EPI = Eagle-Picher Industries; EVD (1987) = Electric Vehicle Developments; JCI = Johnson Controls Inc., LBL = Lawrence Berkeley Lab; LL = Lawrence Livermore Lab.; OEM = original equipment manufacturer; SNL = Sandia National Lab; ">" means "at least" and refers to ongoing work; "?" means information not supplied in reference.

(a) Not available. Wh or kwh, in Wh/l, Wh/kg, and $/kWh, generally refers to maximum deliverable energy (e.g., 2-hour discharge to 100% DOD).

(b) OEM cost and battery life estimates are projections. Specific energy is nominal Wh/kg delivered at 3-hour constant discharge.

(c) The DOE has established battery goals based on the mission requirements of an efficient, lightweight van using the Eaton DSEP system. The maximum power of the battery was limited to that required to accelerate the DSEP vehicle to 50 mph in 20 seconds, and the required range was 50, 75, or 100 miles, depending on the battery technology. The battery weight includes battery trays, thermal enclosure, and auxiliaries. Battery energy is maximum net energy delivered over the Federal Urban Driving Schedule (FUDS). The low end of volume or mass energy density shown is the goal for late in life; the high end is for early in life over modified FUDS. The $/kWh cost goal is the cost to an OEM and is based on 10,000 units/year (battery charger not included). Cost goals for the battery were set such that the electric vehicle would achieve "economic parity" with other modes of transportation in 1995.

(d) 12-hour constant discharge to maximum capacity.

(e) Murphy and Diegle (1988). Wh/kg includes cell-to-battery scale-up losses. Efficiency includes energy used by auxiliaries.

(f) Low figure is for SAE D cycle; high figure is constant low-power output.

(g) 85% efficient at constant discharge without regenerative braking; 97% over SAE D cycle with regenerative braking.

(h) Early cell failure due to defective welds.

(i) 4-hour discharge rate.

(j) Life-cycle estimate from Altmejd and Dzieciuch (1988), who also show 175 W/kg for peak specific power.

(k) They state at least 100,000 km: 160 km/cycle assumed here.

(l) Battery cost estimated to be 3,000 DM at "an industrial scale," which is $1,630 or $50/kWh, a remarkably low cost.

(m) The figures shown are cell performances adjusted to account for the 50% additional weight, in insulation and auxiliaries, that a battery would have. Specific energy is at 30 W/kg discharge rate.

(n) Power is invariant with DOD in Zn/air batteries. It was projected to range from 183 W/kg at the beginning of battery life to 216 W/kg at the end.

Source: DeLuchi et al. 1989.

assume that clean coal technology will be in use and that the fuel mixes in the three scenarios are

1. *Probable*: integrated gasification combined cycle (IGCC) 64%, nuclear + renewable 36%

2. *Progressive*: nuclear + renewable 70%, IGCC coal 30%

3. *Ideal*: nuclear + renewable 100%.

5.1.2 Thermal Energy Storage

Thermal energy storage (TES) is unique among storage options in that it is designed to store lower-quality (low-temperature) energy. The other storage options discussed in this document store high-quality energy that can readily be converted to work (e.g., electrochemical and mechanical storage). Many applications require the storage of lower-quality

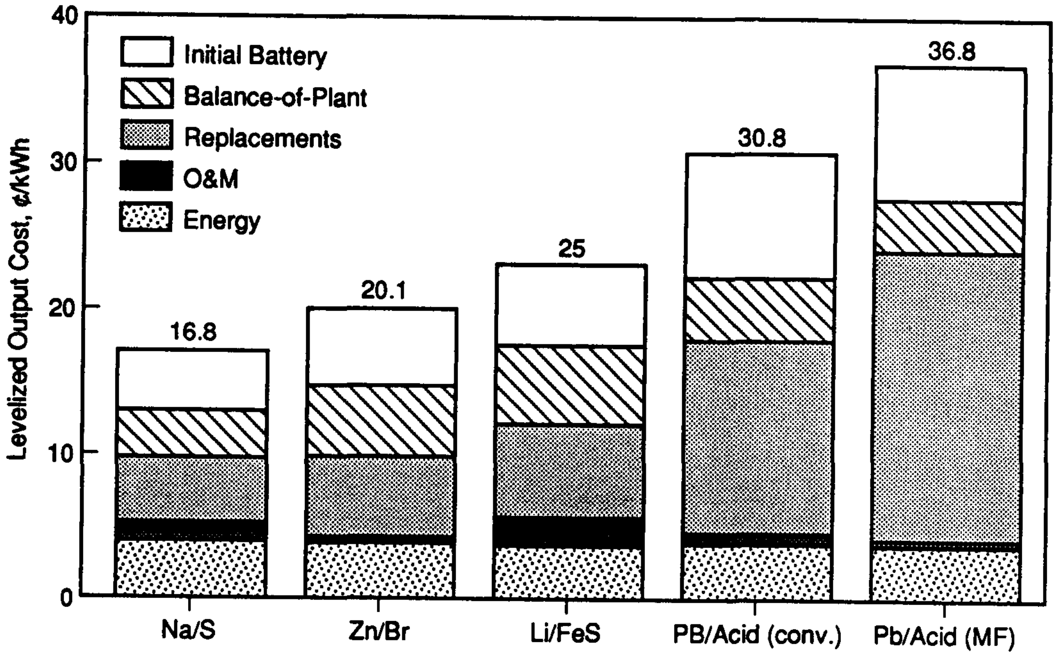

Figure 5.1. Component Contributors to the Levelized Output Cost of Load-Leveling Systems

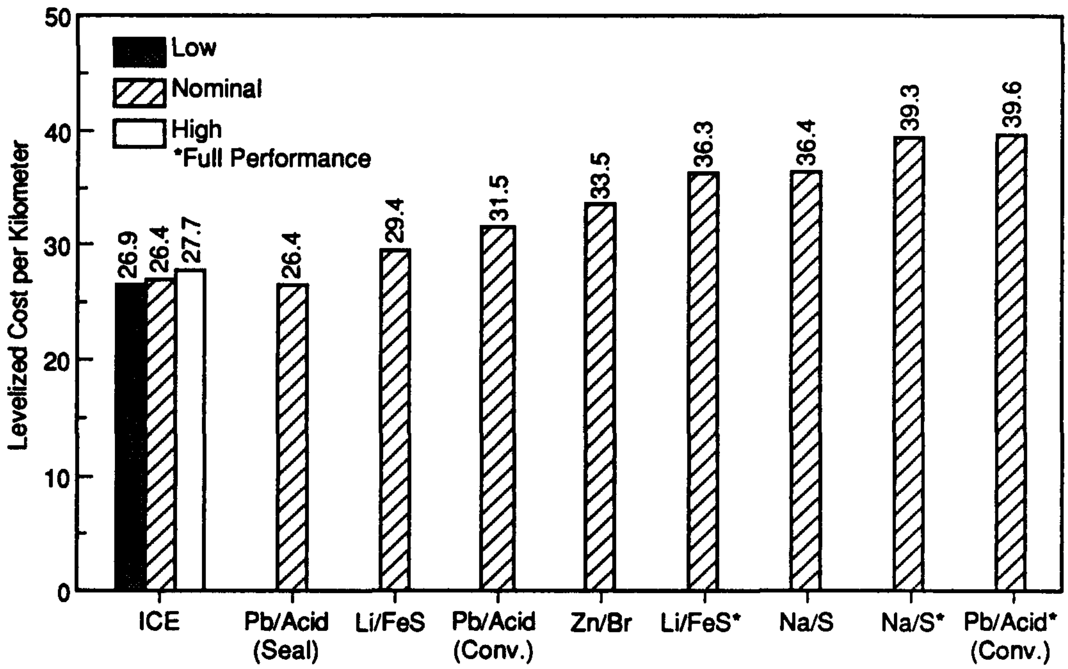

Figure 5.2. Levelized Cost per Kilometer-Traveled for Electric Vans

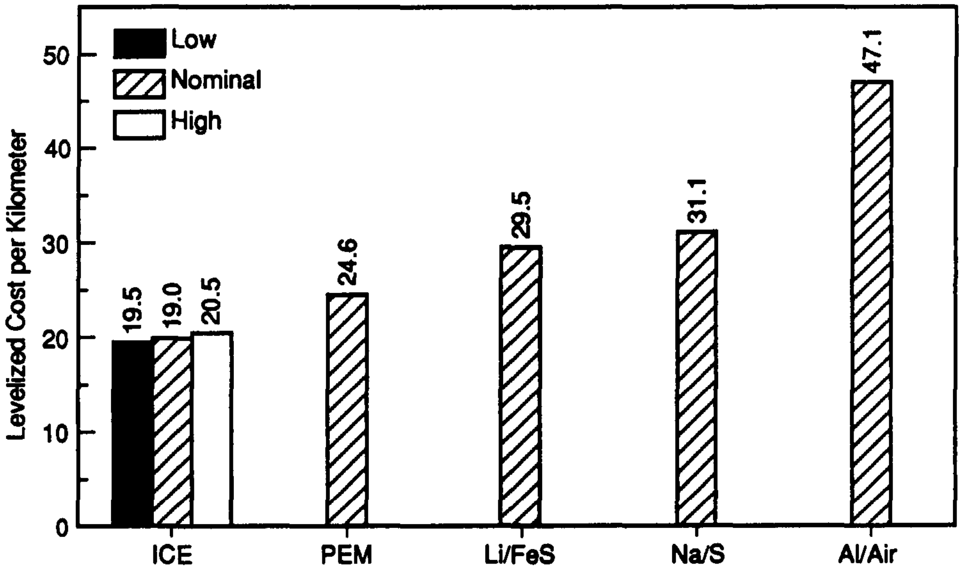

Figure 5.3. Levelized Cost per Kilometer-Traveled for Electric Cars

thermal energy. In these cases, thermal energy storage is the only economically viable storage option.

Thermal energy storage technologies can be divided into diurnal TES systems, which are charged and discharged daily, and seasonal thermal energy storage (STES), where charging, storage, and discharging take place over periods of many months. The following subsections discuss 1) the technology status, 2) the potential applications, 3) the performance and life-cycle costs, and 4) the potential impact of these technologies in improving air quality and reducing greenhouse gas emissions.

Diurnal Thermal Energy Storage

Diurnal TES includes a range of thermal energy storage technologies that are typically charged and discharged at least once every 24 hours. Diurnal TES can be applied to the residential, commercial, and industrial sectors and can either store thermal energy (heat storage) or provide a low-temperature reservoir for cooling (chill storage).

Description of Diurnal Thermal Energy Storage. Diurnal TES can be divided by temperature range into three classifications: chill storage (-40°C to 0°C); medium-temperature heat storage (20°C to 38°C); and high-temperature heat storage (50° to 100°C). Low-temperature chill storage systems provide electric load management in food processing and storage industries.

Thermal energy storage technologies considered for chill storage include latent heat storage in carbon dioxide at the triple point (-57°C) and ammonia storage in complex compounds (-7°C to -48°C). In the ammonia TES system, thermal storage is achieved through the adsorption and desorption of ammonia vapor in a solid salt, and the thermal energy is extracted by heat exchangers embedded in the salt. Low-temperature chill TES systems are in the research and prototype stage of development (Fulkerson et al. 1990).

Chill storage for commercial building space conditioning is widely used for electrical load management.

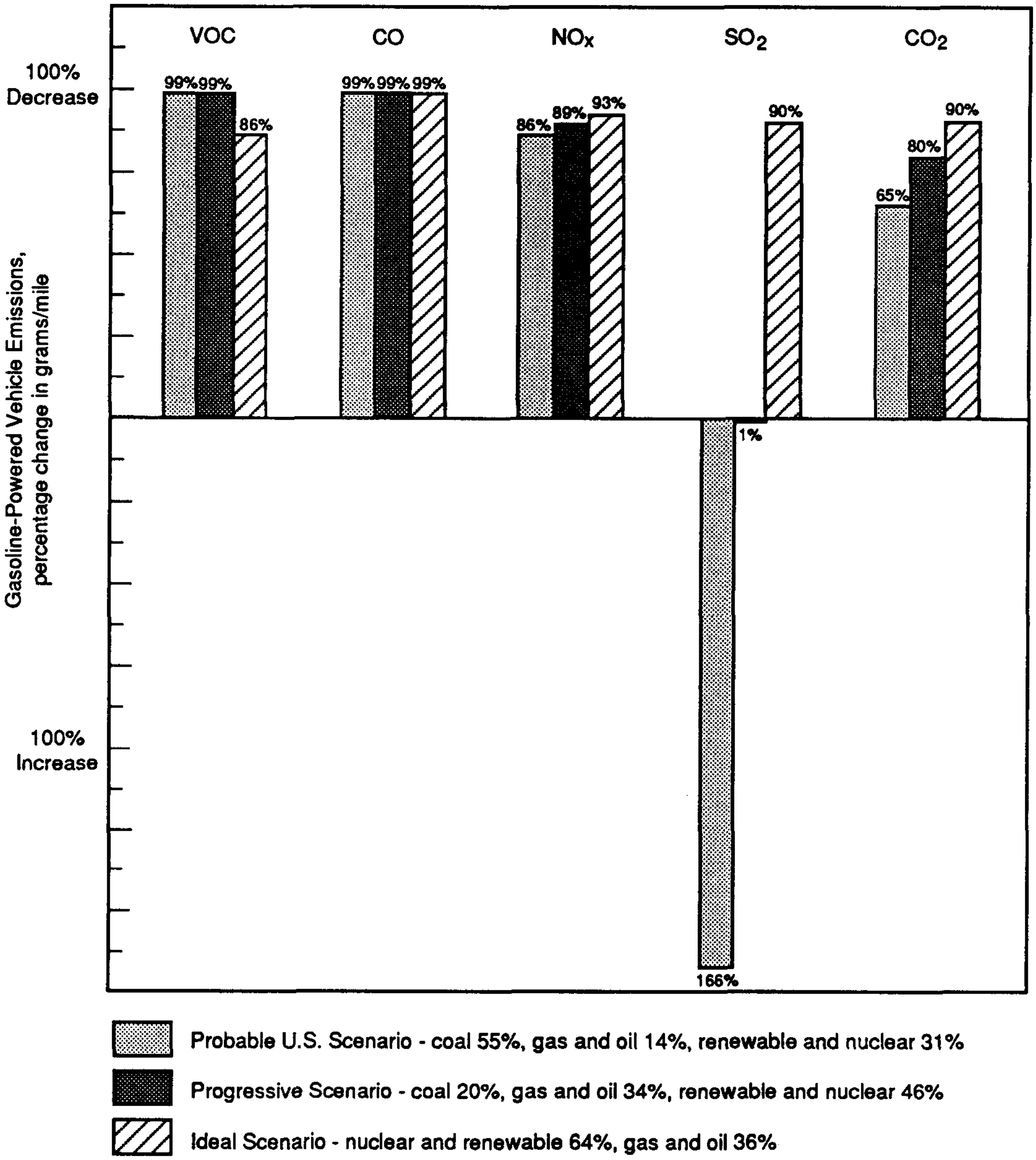

Figure 5.4. Potential Impacts of Electric Vehicles on Emissions

These systems typically store chill as sensible heat in water or as latent heat in ice. While research on improved ice storage systems is in progress, chill storage for commercial buildings can be considered a mature technology with follow-on generations being developed.

Medium-temperature heat storage systems are defined as systems that operate in the temperature range suited for passive solar applications and for room temperature control. Sensible heat storage in water or masonry has been considered for many years, but economic and architectural problems have

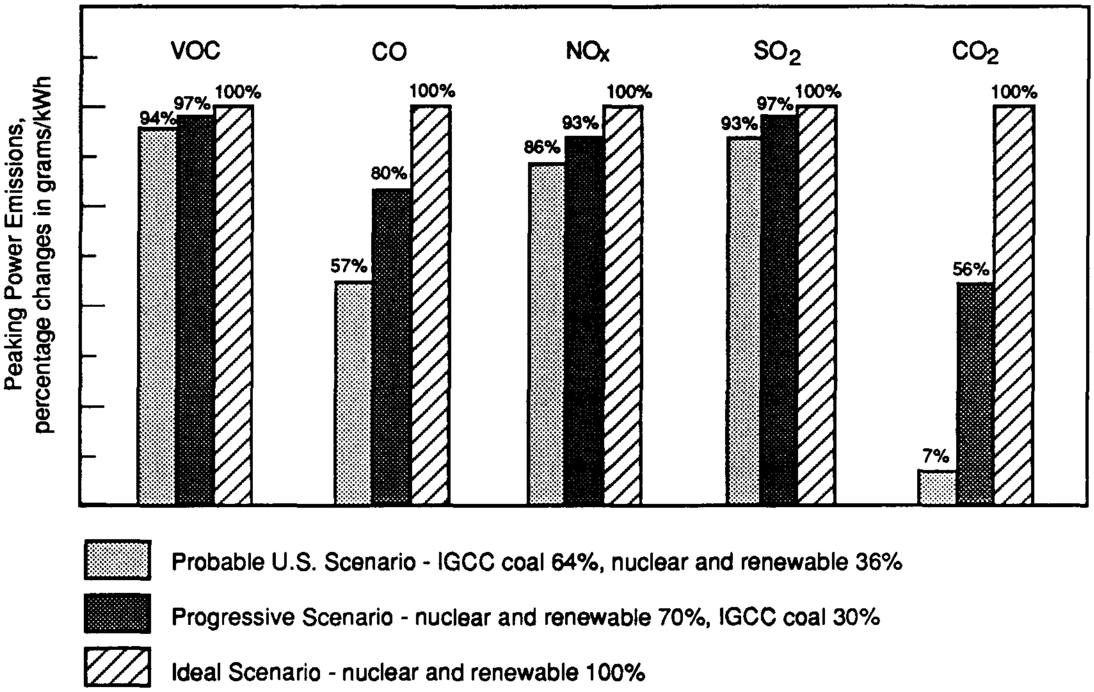

Figure 5.5. Impact of Battery Storage on Emissions in the Utility Sector

limited its application. An alternative approach is to develop building materials that contain phase-change materials (PCM); that is, materials that absorb heat while changing from a solid to a liquid phase and release heat during the opposite reaction. Recent research has developed a method of imbibing straight-chain hydrocarbons in common gypsum wallboard. The hydrocarbon will freeze or melt at 27°C, resulting in a material with large thermal storage capacity that is easily installed by conventional building trades. Building materials imbibed with phase-change materials are in the research and prototype stage of development (Fulkerson et al. 1990).

High-temperature heat storage can be used for industrial energy conservation or for power generation applications. While sensible heat storage in refractory material is widely used in industry, the large size and cost of the systems have limited their applications. The composite phase-change material (CPCM) is an alternative to sensible heat storage in refractory material. The CPCM concept involves incorporating salts with high latent heats of fusion within the porous structure of a ceramic material. The salts are retained within the ceramic structure even when they are in the liquid phase.

The advantage of CPCM over a strictly sensible heat storage medium includes a higher energy storage density, which reduces the physical size of the TES containment, and substantial energy availability at a constant temperature. Entrapment of the phase-change medium within the ceramic material makes the composite more amenable to direct contact heat exchange with working fluids and eliminates the need for a separate heat transfer surface (Olszewski 1987). The CPCM concept is in the research and prototype phase of development.

Most utility application studies for thermal energy storage have focused on sensible heat storage in liquids such as heat transfer oils and molten nitrate salt. The systems consist of 1) a charging heat exchanger where the liquid is heated, 2) a storage tank where the heated liquid is stored, and 3) a discharging heat exchanger where the stored thermal energy is extracted and supplied to the load. In some cases, the charging heat exchanger can use direct contact heat exchange. Studies have investigated application of utility TES with pulverized coal-fired technology, integrated gasification combined-cycle power generation technology, and solar thermal power (Drost et al. 1989, 1990). Both molten salt and oil TES systems have been extensively investigated for applications with solar thermal power technology, and large-scale field tests have been successfully completed.

Applications for Diurnal Thermal Energy Storage. Heat and chill diurnal thermal energy storage can be applied to all sectors of the American economy. Sensible heat storage in crushed rock or refractory brick is widely used in Europe for electric load-leveling in residences. Similar systems are now commercially available in the United States. This application is attractive for winter peaking utilities where diurnal heat storage can reduce the need for additional generating capacity.

Residential chill storage is being tested for electric cooling load-leveling. Systems typically use chilled water or ice storage to allow air conditioners to run at off-peak periods and store chill until air conditioning is required. While residential chill storage is technically feasible, the economics and the difficulty in predicting the behavior of occupants have discouraged utilities from promoting the technology.

An alternative approach to using thermal energy storage in the residential sector is to use building material, such as wallboard, that is impregnated with a phase-change material. The increased thermal storage capacity of the phase-change material increases the potential for thermal energy storage in the mass of the building. This is particularly important for solar residences, where an economic system requires a means of storing solar energy during the day for use at night. Building materials impregnated with phase-change material are being developed but have not been field tested or commercialized.

In the commercial sector, diurnal chill storage is used extensively to reduce peak electric loads. During off-peak periods, electricity runs the chillers, producing chill that is stored by the diurnal chill TES until the next peak-demand periods, when the chill TES system is used to reduce the demand for air conditioning. Diurnal chill TES is a mature technology with established equipment suppliers.

Industrial processes in which large quantities of heat are rejected are potential applications for thermal energy storage. Application studies have indicated that this technology may be attractive in the food processing, iron and steel, and ceramics industries. These are energy-intensive industries in which energy consumption accounts for a large portion of the production costs. Industrial TES options include commercially available sensible heat storage using refractory material and advanced composite CPCM.

Thermal energy storage can be applied to power generation applications, where it allows base-load power generation technologies to meet peak loads and intermediate loads. A base-load heat source, such as a continuously operated pulverized coal-fired power plant, can be used to charge the TES system. During peak-demand periods, the TES system is used as a heat source for a conventional Rankine steam cycle. Thermal energy storage is usually required for the economic operation of solar thermal power plants to allow the plant to operate when solar energy is not available. Similarly, thermal energy storage can be used in cogeneration power plants, allowing the plants to meet varying and noncoincident electric and thermal loads. Most studies of utility TES applications have focused on using sensible heat storage in molten nitrate salt.

Performance of Diurnal Thermal Energy Storage. Chill storage for commercial buildings has been successfully commercialized both using chilled water and ice storage. Residential chill storage based on ice storage has been field tested, but the high energy consumption associated with ice production made the concept unattractive. New residential chill storage systems are being developed.

Building material imbibed with PCM can be integrated into passive solar buildings to reduce the amount of supplemental building heating required to maintain the air temperature within the desired range (65°F to 80°F). Simulation results show that a floor constructed of PCM-imbibed building material would save 61,500 Btu per day for a typical residence. The annual savings was 145 times greater then the peak-day savings (Tomlinson 1985).

Laboratory-scale tests have confirmed the technical feasibility of the composite phase-change material. Over 6,000 hours of testing through 200 thermal cycles have shown that weight loss is under 2%. Calculations predict that a large TES system using CPCM for waste heat recovery in the brick industry will have a thermal efficiency >90% (Institute of Gas Technology 1982).

Utility TES systems are projected to be extremely efficient. Because of the very large size of a utility TES storage system (500-5,000 MWhe), the thermal losses from the system are very low. Projected efficiency is typically higher then 99% (Drost et al. 1989).

Cost of Diurnal Thermal Energy Storage. Commercial chill storage systems have proved to be economically attractive when utilities offer cost incentives from $250 to $750 per displaced kW. In the residential sector, the allowable incremental cost of a chill TES system has been estimated to be between $1,000 and $2,800. The allowable incremental cost is strongly influenced by local electricity rates and meteorology (Brown and Spanner 1988). Estimates for the incremental cost of residential chill storage range between $2,000 and $5,000.

Preliminary cost analyses of PCM-imbibed wallboard suggest that the concept can be competitive with conventional sources of space heating with a PCM cost of $0.65 to $0.75/lb. The estimated cost of phase-change material in bulk quantities is between $0.15 and $0.30/lb, suggesting that this concept can be cost-effective in solar space heating applications.

The projected costs of CPCM storage were developed by Olszewski (1987) for a high-temperature system operating between 900°F and 1,800°F and a lower-temperature system operating between 450°F and 900°F. Based on projected material costs of $0.19 to $0.30/lb and a bed packing factor of 60% to 75%, the total installed cost (including storage media, containment, charging and discharging equipment, installation, and indirect and contingency charges) for the high-temperature CPCM system ranged from $4,820 to $6,179/MMBtu of storage capacity. Conventional sensible heat storage was estimated to cost from $6,380 to $10,450/MMBtu (Olszewski 1987).

Recent engineering design studies for solar thermal applications project the cost of a utility TES system at approximately $11/kWh. At this capital cost, utility TES with either pulverized coal-firing technology or with an integrated combined-cycle power plant will reduce the cost of coal-fired peak and intermediate electric power by 5% to 20% compared with other coal-fired alternatives that provide the same service (Drost et al. 1989).

Greenhouse Gas Emissions from Diurnal Thermal Energy Storage. None of the diurnal storage technologies emit greenhouse gases. The significant question is related to the source of the energy used to charge the storage system and the source of the energy being displaced by the diurnal storage device.

Both diurnal heat and chill storage for residential and commercial space conditioning deliver less energy to the load than is used to charge the systems. Greenhouse gas emissions will increase if the charging energy is generated by combustion of fossil fuels. Diurnal heat and chill storage for residential and commercial space conditioning will reduce greenhouse gas emissions if the storage devices are charged by technologies that do not produce greenhouse gases (such as nuclear and solar energy) to meet peak cooling loads and consequently will displace fossil-fired peak power generation. When used to level cooling loads, diurnal chill storage allows a smaller-capacity chiller to be used than would be required by a conventional system, thus reducing the inventory of chlorofluorocarbons in the heating, ventilating, and air conditioning (HVAC) system.

Building materials impregnated with PCM do not emit greenhouse gases and typically do not use fossil fuels for storage charging. Such building materials can reduce greenhouse gas emissions by efficiently storing solar energy collected in passive solar buildings for later use in space conditioning. The combination of passive solar heating and PCM-impregnated building materials can displace fossil-fuel use for space heating, decreasing greenhouse gas emissions. In addition, PCM-impregnated building materials increase a building's thermal mass. In many cases, increased thermal mass will reduce a building's space heating energy requirements. This drop will reduce greenhouse gas emissions associated with space heating and may allow the installation of smaller-capacity HVAC equipment with a smaller inventory of chlorofluorocarbons.

Industrial applications of diurnal TES typically involve using waste heat to charge storage. The stored thermal energy is later used to meet some other energy load in the facility. In this case, neither the storage device nor the generation of charging energy causes an increase in greenhouse gas emissions. The use of diurnal TES for industrial applications typically will reduce greenhouse gas emissions by allowing the use of waste heat to displace fossil fuel consumption in industrial processes. Additionally, thermal energy storage can allow components to operate at full capacity, improving part-load performance and energy efficiency.

Utility TES does not emit greenhouse gases, and studies have shown that a utility plant with thermal energy storage will have a heat rate that is equal to or less than a conventional cycling coal-fired power plant (Drost et al. 1989, 1990). This suggests that the use of utility TES will not increase greenhouse gas emissions when compared with coal-fired alternatives for producing intermediate-load power. Utility TES can reduce greenhouse gas emissions by allowing nuclear and solar thermal power to be substituted for fossil fuel-fired peak and intermediate power generation. When applied to cogeneration applications, utility TES can allow the cogenerating facility to fully use the thermal output of the plant. In many cases, the demands for electric and thermal energy do not coincide. If both the thermal and electric output of the cogeneration facility are to be fully used, a TES system will have to be used to decouple the generation of thermal and electric energy. As a result, the cogeneration facility will have the flexibility to meet varying loads that are not coincident.

Seasonal Thermal Energy Storage

Seasonal thermal energy storage is intended to decouple the generation of thermal energy (chill) from its use on a seasonal basis.

Description of Seasonal Thermal Energy Storage. This technology can be used for the seasonal storage of thermal energy for heating (heat STES) or for the maintenance of a low-temperature reservoir for cooling (chill STES). In both cases, the system will consist of five components: a source of heat (chill), the charging subsystem, the storage subsystem, the discharging subsystem, and the load. When thermal energy (or chill) is available, the charging subsystem collects and transfers thermal energy (or chill) to the storage subsystem, where the thermal energy (or chill) is stored in the storage medium. When the load requires thermal energy (or chill), the discharge subsystem extracts thermal energy (or chill) from storage and delivers it to the load.

Aquifer thermal energy storage (ATES) is an example of an STES option. During cold winter months, aquifer water is removed from a suitable aquifer and cooled in a cooling tower or heat exchanger. The cold water is returned to the aquifer, where it is stored until the following summer. The cold aquifer water is then removed from the aquifer and used for space conditioning or process cooling. In the process, the aquifer water will be heated. The warm water is returned to the aquifer, where it is stored until the next winter, when the process is repeated. A similar system can be used to store thermal energy for heating applications. Aquifer thermal energy storage systems can store thermal energy at temperatures in excess of 100°C and chilled water at temperatures as low as 0°C.

While ATES is currently considered to be the most attractive STES option, a wide range of alternative STES concepts is being developed for applications where ATES is not feasible. Options include storing water in rock caverns, in naturally occurring lakes, in rock and clay, in ice, and in stratified salt ponds. The ATES technology is in the development stage, with major field tests in Minnesota and Mississippi. Other STES concepts are currently under development in Europe.

Applications for Seasonal Thermal Energy Storage. Seasonal thermal energy storage has been considered for applications where a source of thermal energy (chill) and its use do not coincide on a seasonal basis. To be successful, the STES technology needs a low-cost source of thermal energy (chill) and an application that can use relatively low-temperature thermal energy (or chill).

The largest application for seasonal thermal energy storage is space conditioning in the residential, commercial, and industrial sectors. When space heating is required, industrial waste heat, heat from a municipal waste-fired incinerator, or solar energy can be used during summer months to charge the STES system. During the heating season, the stored thermal energy is extracted and used for space conditioning in residences and commercial buildings. Similarly, cold winter air can be used to cool water that is stored in a chill STES system. During the subsequent air conditioning season, the cold can be extracted to provide cooling.

One special application is the use of solar energy to charge STES systems. In northern climates, the short winter days and extensive cloud cover prevent solar thermal space heating. STES allows solar energy to be collected during the summer and used during the following winter. This concept has been extensively investigated in Europe, and a demonstration is being planned in New England.

Heat and chill STES systems are also being applied to process cooling and heating in the industrial sector. Studies have shown that tempering of large industrial spaces, such as auto assembly plants, is a particularly attractive application for early commercialization of chill STES.

The potential impact of STES is large. Anderson and Weijo (1988) estimated that STES has the potential to economically displace 2 to 4 quad of primary energy consumption in the residential, commercial, and industrial sectors. Actual market penetration will be somewhat less than the potential penetration.

Performance of Seasonal Thermal Energy Storage. The performance of ATES systems has been determined by modeling and field testing. Field test results are available from the University of Minnesota for high-temperature ATES (100°C) and from the University of Alabama for ATES chill storage.

The most important performance figure-of-merit for STES is the round-trip efficiency, which is defined as the annual total energy supplied to the load divided by the annual total energy taken from the source. The measured round-trip efficiency for the University of Minnesota high-temperature ATES field test is 65% to 70% (Stirling and Hoyer 1989). Initial measurements of the University of Alabama chill storage field test showed a round-trip efficiency of approximately 38%. Strong regional flows in the local aquifer resulted in a low recovery efficiency, but modifications to the aquifer charging procedures have resulted in measured efficiency increases 70% to 76% (Midkiff et al. 1989).

The field tests have also demonstrated the feasibility of economical water treatment and have shown that ATES does not result in significant environmental impacts. Recent studies on the behavior of pathological micro-organisms have shown that ATES does not have a significant impact on the native microorganisms.

Cost of Seasonal Thermal Energy Storage. The costs of most STES technologies are site-specific, depending on the characteristics of the local aquifers or the mechanical properties of the local rock formations. This discussion will focus on ATES costs because they have been estimated in more detail than costs for other STES technologies.

Table 5.3 presents the current, projected, and required costs for heat and chill ATES. The costs are

Table 5.3. Current, Projected, and Required Costs for Aquifer Thermal Energy Storage ($/MMBtu)

ATES Technology	Current Costs	Projected Costs	Required Costs
Chill	6-25	4-25	7-9
Heat	4-61	4-61	5-22

presented as levelized energy costs in $/MMBtu of energy delivered from the ATES system. "Current costs" represent the costs of a system built using current practice. "Projected costs" include the impacts of cost reductions projected to occur in the future. For ATES, most cost reductions are associated with well-understood design improvements such as replacing steel pipe with plastic pipe and using plate-and-frame heat exchangers instead of shell-and-tube heat exchangers. "Required costs" are the costs that the systems must achieve to be competitive with conventional vapor compression cycle chillers or conventional fossil-fuel-fired heaters.

The large cost variations of the ATES systems are the result of different assumptions for aquifer characteristics. A low cost represents an aquifer with attractive characteristics; high cost represents an aquifer with unattractive characteristics. As Table 5.3 shows, ATES can be competitive for both heating and air conditioning if a suitable aquifer is available.

Greenhouse Gas Emissions from Seasonal Thermal Energy Storage. Applying STES will result in a small increase in greenhouse gas emissions. The increase is associated with producing electricity to run pumps and fans. Producing thermal energy (or chill) can result in greenhouse gas emissions, but economical heat STES applications require that the STES system be charged by waste heat from an industrial process or municipal waste incinerator. In these cases, greenhouse gas emissions will occur whether or not the system uses the waste heat, and the emissions cannot be charged to the STES system. Using cold winter air for charging chill STES will not result in greenhouse gas emissions. While a small overall increase in greenhouse gas emissions is associated with STES, the reduction in emissions associated with the end-use applications is orders of magnitude greater.

Wide application of seasonal thermal energy storage will displace fossil fuel use and will significantly reduce greenhouse gas emissions. Heat STES will displace combustion of fossil fuels for space heating and low-temperature process heat applications, while chill STES will displace electricity (and fossil fuels used to generate the electricity) used to drive chillers. In addition, chill STES will displace vapor compression chillers, reducing chlorofluorocarbon emissions.

Anderson and Weijo (1988) have shown that seasonal thermal energy storage can displace 2 to 4 quad of primary energy consumption, representing the output of 140 to 280 500-MWe power plants. If coal were used to supply this energy, 100 to 200 million tons of coal would be burned annually, producing 370 to 740 million tons of carbon dioxide.

5.1.3 Mechanical Energy Storage

This section describes two types of mechanical energy storage systems: pumped storage (including compressed air energy storage and pumped hydroelectric) and flywheels.

Compressed Air Energy Storage

In the following sections, compressed air energy storage (CAES) technology is described, and its applications, performance, cost, and potential greenhouse gas emissions are discussed.

Description of Compressed Air Energy Storage. A CAES plant combines slightly modified gas turbine plant machinery with an underground air cavern to provide several hours of electric generation storage capacity. Off-peak electricity runs a motor (also used in reverse as a generator on discharge), which drives a series of intercooled compressors to pressurize air for storage in an underground cavern. The compressed air is later released, mixed with natural gas or distillate oil, and combusted to produce power. The hot gases pass first through the turbine and then through a recuperator which preheats the incoming compressed air.

Three geologic formations are suitable for the cavern: salt, rock, and aquifer. Salt caverns are created by solution mining salt domes. Conventional mining techniques are used to create caverns from rock formations. Aquifer formations require no mining; several shafts are drilled into the top of a permeable dome-shaped rock (aquifer) formation that has a nonpermeable rock cap. Compressed air displaces water in the formation as it is stored, and the reverse occurs when the air is withdrawn. A similar effect is accomplished with rock caverns by hydraulically coupling an aboveground reservoir with the cavern to apply a compensating pressure. The result is more uniform air pressure during storage discharging. A compensating water pressure line is not used with a salt formation. Potable water would further dissolve the cavern, while saturated salt water presents environmental concerns. The variable capacity of the aquifer "cavern" allows greater system operating flexibility, which could be a significant advantage over the other cavern media.

A commercial-size (290 MW) CAES plant has been operating in Huntorf, West Germany, since 1978. Other demonstration-size (35 to 100 MW) units are currently operating or under construction in Japan, Israel, and Italy. U.S. experience has been limited. Soyland Electric Cooperative ordered a unit in the early 1980s but later canceled the order. Alabama Electric Cooperative began operating a 110-MW, 26-hour plant in May. No other CAES plants are currently operating or being constructed in the United States. Several different equipment manufacturers could supply the necessary hardware, and considerable experience in storing natural gas in underground formations exists. Nevertheless, implementation of CAES technology has been slow.

Several advanced CAES designs could significantly reduce or eliminate the need for firing fossil fuel with compressed air. Heat of compression energy removed by the intercoolers in the conventional CAES plant could also be stored and recovered. These systems would be more expensive than the conventional CAES system described above and have not been demonstrated, but could still be developed. The Electric Power Research Institute (EPRI) continues to conduct analytical studies of advanced CAES concepts.

Applications for Compressed Air Energy Storage. About three-fourths of the United States lies on top of one or more of the three geologic formations that are potentially suitable for compressed air energy storage. Appropriate rock formations are the most common, followed by aquifers and salt domes.

The principal application of compressed air energy storage is for utility-scale load-leveling. Low-cost, off-peak energy is stored for use during higher-valued, on-peak periods. However, like other electric utility storage technologies, CAES provides many other system operating benefits such as minimizing nighttime turndown on baseload plants, providing spinning reserve or backup capacity, and regulating system or supply/load balancing capability.

Compressed air energy storage can be viewed as having characteristics similar to intermediate-duty generation facilities, such as relatively inexpensive capital costs at moderate capacity (100 MW) and a flexible range of operating hours, but the low marginal cost of adding storage hours in salt and aquifer formations makes it similar to a baseload plant. Site applicability for compressed air energy storage is generally better than pumped hydroelectric, but not as good as batteries.

Performance of Compressed Air Energy Storage. In a conventional gas turbine plant, about two-thirds of the shaft energy produced is used to drive the air compressors and only one-third is converted to electricity in the generator. In a CAES plant, all of the shaft energy produced on discharge is applied to generating electricity. Thus, the fossil energy heat rate of the CAES plant is about one-third that for a gas turbine. Of course, this does not consider the energy form consumed in producing the off-peak electricity used to charge storage. According to EPRI (1989), a conventional CAES plant requires 0.76 kWh and

4,040 Btu (annual average) input per 1.0 kWh output. An advanced CAES plant that stores and recovers the heat of compression would require about 1.5 kWh input per 1.0 kWh output, with no fossil input.

Cost of Compressed Air Energy Storage. Because of the differences in the difficulty of creating the cavern, costs vary depending on the geologic formation. Aquifer formations are the least expensive because the "cavern" exists naturally. Salt formations are slightly more expensive, while mining of rock formations incurs significant additional costs. As with all storage systems, costs depend on both the plant's MW and MWh rating. Charging and discharging equipment costs relate to the power (MW) rating, while containment and media costs relate to the capacity (MWh) rating. Storage plant costs must be based on the same number of daily operating hours to be comparable.

EPRI (1989) has estimated initial capital (overnight construction) cost and annual O&M costs for each of the three geologic formations. The cost estimates were based on the actual contracted cost for the CAES plant being built for Alabama Electric Cooperative and on EPRI preliminary cost studies. Cost data for 110-MW/1100-MWh plants are shown in Table 5.4. EPRI considers the estimates to be accurate within $\pm$10% for the salt and aquifer formations and $\pm$20% for the rock formation.

Greenhouse Gas Emissions from Compressed Air Energy Storage. A conventional CAES plant burns either natural gas or distillate fuel oil during discharge. Thus, greenhouse gas emissions include carbon dioxide, NO_x, and SO_x (fuel oil only).[a] According to EPRI (1989), NO_x emissions can be expected to range from 15 to 150 ppm, depending on the fuel type and whether water injection is used. SO_x emissions depend directly on the quality of the fuel. Although about one-third less fossil fuel is consumed in a conventional CAES plant than a conventional combustion gas turbine, this figure does not include any fossil fuel that may have been consumed in generating the off-peak electricity used to charge the storage system. In general, if a fossil-fired plant is the source of charging electricity, then greenhouse gas emissions will be increased by the use of compressed air energy storage or any other storage device because of the inherent inefficiencies of storage.

This increase in greenhouse gas emissions would be at least partially offset, however, by the increased fuel efficiency of operating fossil-fired plants closer to full-load conditions. Total greenhouse gas emissions would be reduced if the CAES plant supplied peaking power rather than a gas turbine and the CAES plant was charged with electricity from a nonfossil energy source.

Table 5.4. CAES Power Plant Costs

Geologic Formation	Overnight Construction Costs, Dec. 1988$/kW		Operation and Maintenance Costs, Jan. 1989 mills/kWh	
	Power	Storage	Fixed	Variable
Rock	390	124	2.3	1.9
Salt	390	10	1.2	0.9
Aquifer	390	2	1.2	0.9

Source: EPRI 1989.

Pumped Hydroelectric

In the following sections, the pumped hydroelectric technology is described, and its applications, performance, cost, and potential greenhouse gas emissions are discussed.

Description of Pumped Hydroelectric. Pumped hydroelectric plants operate by pumping water to an upper reservoir during the charging mode. The stored potential energy is later discharged by releasing the water to flow back to a lower reservoir through a turbine. In addition to the upper and lower reservoirs, key elements of a pumped hydroelectric plant are a reversible turbine/pump, reversible pump/motor, and the penstock connecting the upper reservoir with the turbine/pump.

(a) As noted above, some advanced CAES plant designs consume no fossil fuels on discharge and would have no direct greenhouse gas emissions.

The technology has two basic versions, conventional and underground. Both the upper and lower reservoirs are located at ground level in a conventional pumped hydroelectric (CPH) plant. As the name suggests, the lower reservoir for an underground pumped hydroelectric (UPH) plant is located below the surface of the local terrain. An air shaft connecting the surface with the lower reservoir of a UPH plant maintains near atmospheric pressure over the lower reservoir.

Pumped hydroelectric plants must be relatively large to capture necessary economies of scale, especially UPH plants. Economically attractive sizes are about 1000 MW and 2000 MW for CPH and UPH, respectively, with 10 hours of storage. Conventional pumped hydroelectric plants are a mature commercial technology. Approximately 40 CPH units currently operate in the United States, with a total generating capacity of about 18,000 MW or about 25% of the U.S. hydroelectric capacity. However, no UPH plants are currently in operation or under construction.

Applications for Pumped Hydroelectric. As with CAES, the principal application of pumped hydroelectric is for utility-scale load-leveling. Low-cost, off-peak energy is stored for use during higher-valued, peak-demand periods. However, like other electric utility storage technologies, pumped hydroelectric systems provide many other system operating benefits, such as minimizing nighttime turndown on baseload plants, providing spinning reserve or backup capacity, and regulating system or supply/load balancing capability. Pumped hydroelectric has characteristics similar to baseload generation facilities, such as relatively large unit sizes with high capital costs and better economic feasibility at high system capacity factors (more storage hours).

Site applicability is the biggest concern for pumped hydroelectric plants, especially CPH plants. Conventional pumped hydroelectric plants require local terrain with a minimum of several hundred feet elevation difference within a short horizontal distance. Underground pumped hydroelectric plants bypass this requirement, but both types of pumped hydroelectric plants may face difficulties in siting the aboveground reservoir(s). Siting is definitely of greater concern for pumped hydro than for compressed air or battery energy storage systems.

Performance of Pumped Hydroelectric. The average annual efficiency of either type of pumped hydroelectric plant is expected to be about 70% to 75% (EPRI 1989; Loyd 1988; Rashkin 1988). About 1.35 kWh is consumed during charging per kWh generated on discharge. Pumped hydroelectric plants can reach 50% of rated output power in about 1 minute.

Cost of Pumped Hydroelectric. Underground pumped hydroelectric costs are higher than those for conventional pumped hydroelectric because of the costs of developing the underground reservoir and connecting water and air conduits. As with all storage systems, costs depend on both the MW and MWh rating of the plant. Charging and discharging equipment costs relate to the power (MW) rating, while containment and media costs relate to the capacity (MWh) rating. Storage plant costs must be based on the same number of daily operating hours in order to be comparable.

EPRI (1989) has estimated initial capital (overnight construction) costs and annual O&M costs for CPH and UPH plants. The cost estimates were based on actual costs for CPH plants and EPRI preliminary cost studies of UPH plants. Conventional pumped hydroelectric costs are based on three 350-MW units with 10 hours of storage; the UPH plant is assumed to have three 667-MW units with 10 hours of storage. Reference plant cost estimates are shown in Table 5.5. EPRI considers the estimates to be accurate only within ±40%. The high degree of uncertainty is directly attributable to differences in site-specific terrain.

Greenhouse Gas Emissions

A pumped hydroelectric plant is essentially emissions-free when viewed by itself. However, this perspective does not include any fossil fuel that may have been consumed in generating the off-peak electricity used to charge the storage system. In general,

Table 5.5. Pumped Hydroelectric Power Plant Costs

Plant Type	Overnight Construction Costs, Dec. 1988$/kW		Operation and Maintenance Costs, Jan. 1989 mills/kWh	
	Power	Storage	Fixed	Variable
Conventional	700	117	3.8	3.8
Underground	700	419	5.0	5.0

Source: EPRI 1989.

if a fossil-fired plant is the source of charging electricity, then greenhouse gas emissions will be increased by using pumped hydroelectric or any other storage device because of the inherent inefficiencies of storage. This increase in greenhouse gas emissions would be at least partially offset, however, by the increased fuel efficiency from operating fossil-fired plants closer to full-load conditions. Total greenhouse gas emissions would be reduced if the pumped hydroelectric plant rather than a gas turbine supplied peaking power and if the pumped hydroelectric plant was charged with electricity from a nonfossil energy source.

Flywheels

Kinetic energy stored in rotational motion can be easily converted to and from other types of mechanical or electrical energy. Thus, flywheels have been in use since ancient times and have more recently become common in machinery. Primarily, they are used to mechanically correct the timing mismatch that commonly occurs in most energy-delivery systems. This correction allows the energy sources to meet energy demands more effectively. Some flywheel applications include punch presses, piston engines, spinning wheels, and grain milling machines.

Flywheel energy storage technologies offer several particularly attractive characteristics for energy conservation. One is the ability to accept and deliver energy at high rates. In contrast to electromechanical energy storage methods, flywheel energy storage capacity is independent of delivery rate. Compared with other mechanical energy storage devices such as hydraulic accumulators, flywheels are more volume-efficient and lighter (i.e., store more kJ/kg).[a]

Applications for Flywheels. The components of a flywheel energy storage system include rotor, bearings, the flywheel assembly housing (also called containment), and power transmission:

- **Rotor.** The amount of energy stored in a body rotating about a fixed axis is proportional to its moment of inertia and the square of its angular velocity. In practice, the maximum possible energy storage for a flywheel is obtained from the relation (Jensen and Sorensen 1984):

  $$W/M = (\sigma/\rho)K_m$$

  where W is energy, M is the flywheel mass, ρ the density, K_m is a shape factor that is dependent only on flywheel geometry, and σ is the maximum allowable (design) stress. Thus, flywheel rotor development has emphasized finding and testing materials that are stronger and less dense, particularly for aerospace applications, where weight and volume concerns are critically important.

  Advances in composite graphite fiber technology have enabled experimental flywheel rims to attain storage densities as high as 878 kJ/kg compared with 20 to 40 kJ/kg for steel flywheels (Olszewski

(a) Phone conversation with Mitch Olszewski of Oak Ridge National Laboratory, June 26, 1990.

1988). With these high-strength densities, practical operational storage densities of 200 kJ/kg can be achieved. These lower levels account for cyclic fatigue constraints on the materials.

- **Bearings.** An essential problem with flywheel technology is control of frictional losses in bearings, especially in applications requiring slower energy discharge rates. Mechanical bearings are generally avoided because of high losses. Instead, magnetic suspension systems using both permanent and electromagnets are preferred and are feasible for flywheels of up to about 200 tons. For stationary applications that may have even larger flywheels, the recourse is to mount them horizontally, with rollers along the rim or magnetic suspension used for support (Jensen and Sorensen 1984).

- **Power Transmission.** The input and output of power from the flywheel is application-specific and can be electrical-to-mechanical or mechanical-to-mechanical. Electrical-to-mechanical power transmission is achieved using a motor-generator inserted between the magnetic bearing suspension and the flywheel rotor. If the motor is placed inside the containment vacuum (when used), a brushless type is preferred (Jensen and Sorensen 1984). Mechanical-to-mechanical power transmission assemblies are typical of envisioned vehicle applications of flywheel technologies, where the flywheel integrates mechanically with an engine/transmission system.

- **Containment.** Containment requirements of flywheels are dictated by the importance of windage losses on the specific application being considered. Windage losses have been found to increase with increasing energy density and decrease with mass density (Fulkerson et al. 1990). Thus, high-energy-density and low-mass-density composite flywheels have much larger windage losses than steel flywheels. Along with bearing frictional losses, windage losses also become more important for applications in which energy recovery periods are prolonged. Windage losses are controlled by operating the flywheel in evacuated containment.

Applications. Applications currently being considered for flywheel energy storage technology are primarily in the aerospace industry, but several potential land-based applications also have been identified. Perhaps the most seriously considered land-based application of flywheel energy storage is for urban transportation applications, where many starts and stops typically occur. The braking energy losses are stored in the flywheel in this application, rather than dissipated as heat.

A stationary flywheel application is envisioned as a wayside energy storage system for recuperating potential energy from electric trains. As in automotive applications, braking energy losses are stored in the flywheel rather than dissipated as heat. The stored energy is delivered back to the train as electricity to boost its acceleration when traveling uphill or when starting up from a dead stop. Studies of these applications found that large steel flywheels might be cost-effective on heavily trafficked rail lines (Lawson et al. 1981) and that little or no additional development is required for such systems because they can be engineered with available technology.

Another application for flywheels is electric utility load-leveling. By operating on a 24-hour cycle, baseload power could be stored during periods of low demand for use during peak-demand periods (Eisenhaure et al. 1981). This discharge rate is much slower than transportation applications and thus requires much more attention to windage and bearing losses.

Flywheels can also be used to complement other energy storage devices, such as batteries in electric vehicles, for a more effective and economical system. In such an electric-flywheel hybrid vehicle, a flywheel would be used to 1) extend the battery life by reducing peak demands, 2) improve acceleration by complementing the total power, and 3) increase the range by allowing the battery to operate in a more favorable load regime.

Performance of Flywheels. A combined engineered system that uses 1) the flywheel to obtain power through this regeneration braking concept, 2) a continuously variable transmission, and 3) a controller capable of controlling these components while retaining conventional acceleration control could increase fuel efficiencies in taxicabs by as much as 150% to 170% (Kubo and Forrest 1981). A numerical optimization study using an urban bus duty cycle predicted savings as high as 148% if all components of the flywheel system could be optimized (Flanagan 1982). However, about half of the theoretical fuel savings obtained from such a system would come from the continuously variable transmission alone because it facilitates use of a small, efficient internal combustion engine with constant (steady-state) power output.

In contrast to these urban driving benefits, highway driving applications of the flywheel system result in losses that are predicted to be greater than the potential braking energy recovery. Thus, flywheels may be less applicable for highway driving (Kubo and Forrest 1981).

The mass/energy storage requirements for flywheels in urban transportation applications are small, and steel rather than composite rotors provide adequate energy densities (Beachley and Frank 1981). Also, because energy recovery periods are quite short, friction and windage losses are less critical than in other applications, making bearing and containment design less critical.

Estimates of range increases in electric-flywheel hybrid vehicles are as high as 40%.[(a)] Such a hybrid system would likely have a favorable impact on the use of electric vehicles.

Cost of Flywheels. On a 20- to 30-year lifetime basis, a flywheel system for electric utility load-leveling applications would have to have a capital cost for storage capacity of $100 to $150/kWh to be competitive with other storage technologies. This cost goal theoretically can be achieved by current steel flywheels. Composite rotors will require substantial cost reductions or further improvements in material energy densities in order to meet the goal. No cost information is available for transportation applications of flywheels.

Greenhouse Gas Emissions from Flywheels. Unfortunately, although the component designs of flywheel energy storage systems have progressed quite far, very little work has been completed on physically integrating the components into actual systems. This lack of either laboratory or field-test data makes it very difficult to assess the impact that integration of flywheel technology would have on fossil fuel consumption and, hence, on greenhouse gas emissions.

One assessment looked at the potential energy savings from using flywheel technology in the New York City taxicab fleet (Krupka and Jackson 1981). Assuming a 50% gain in fuel economy in a 12,000-car fleet traveling 50,000 to 80,000 miles per year, savings were estimated to be about 25 million gallons of gasoline per year. The results of that study suggest that applying flywheel energy storage to urban taxi and bus fleets nationally could substantially affect both energy conservation and greenhouse gas emissions.

Assuming that fossil-fired power plants supply the electricity for electric-flywheel hybrid vehicles, flywheels could reduce greenhouse gas emissions at the source compared with nonhybrid electric vehicles because fuel efficiency is dramatically increased by adding flywheels. If source electricity is supplied by nonfossil power plants, emissions reductions attributable to flywheels will likely be even larger, equal to the total displaced emissions provided by the net increase in using electric vehicles that the performance benefits of this hybridization would cause. Given the current mix of fuels used to generate electricity, carbon dioxide displacement assuming a 20% battery-powered domestic vehicle fleet in the year 2010 is estimated to be approximately 1×10^8 tons annually (Landgrebe and McLarnon 1989). If using flywheels to enhance the range and acceleration of electric

(a) Phone converation with Mitch Olszewski of Oak Ridge National Laboratory, June 26, 1990.

vehicles increases their use to 25% of the domestic fleet, another 25 million tons of carbon dioxide production would be displaced.

Similar benefits could be obtained by using wayside flywheel systems for electric trains. Finally, fossil-fired power plant greenhouse gas emissions could be reduced if flywheel systems were used for electric utility load-leveling rather than gas turbines, assuming renewable energy resources or other nonfossil resources are used to charge the flywheel systems.

5.1.4 Chemical Energy Storage

This section discusses two types of chemical energy storage: hydrogen and reversible chemical reactions.

Hydrogen

Hydrogen has long been recognized as an efficient energy carrier. Analyses of scenarios with hydrogen as the only liquid energy carrier in an industrial economy show that hydrogen can be an adequate replacement for conventional fuels such as petroleum and natural gas. In the 1960s and even in the early 1970s, the "hydrogen economy" concept was seriously considered, with nuclear power plants as a source of inexpensive electricity to produce hydrogen. As the cost of nuclear power escalated and fears of an impending energy crisis subsided, so did our interest in the hydrogen economy. The costs of adapting to a hydrogen economy and the sustained commitment of resources required to develop and implement the technology were considered to be prohibitive, and federal support was drastically reduced.

The emerging concerns about global warming and the realization of the harmful effects of increasing greenhouse gas emissions are again encouraging consideration of hydrogen as a clean energy carrier. Under appropriate circumstances, its use could provide the nation with an alternate form of fuel and, depending on the production method, reduce greenhouse gas emissions. This section summarizes the current status and future prospects of hydrogen technology, potential applications, performance and cost characteristics, impacts on greenhouse gas emissions, and key issues that must be addressed for this technology to enter the marketplace.

Description of Hydrogen. Hydrogen is an exceptionally clean energy carrier. When hydrogen is burned, there are no emissions of carbon monoxide, carbon dioxide, or SO_x, and reduced emissions of NO_x.

Hydrogen does not occur naturally in abundant quantities. It is obtained either from fossil-fuel sources such as natural gas or from the electrolysis of water. If it is produced from methane, it has no greenhouse gas emissions benefit. Nonetheless, if the end use is in urban centers, hydrogen still makes a significant contribution to mitigating air-quality problems at the possible expense of the area where the primary source energy was consumed.

The real advantage of hydrogen in terms of both greenhouse gas emissions and urban air quality is realized if the hydrogen is produced via the electrolysis of water, with the electricity being generated by nonfossil fuels such as nuclear energy or solar photovoltaics. To realize the environmental benefits of hydrogen, it has to be produced, stored, and distributed competitively with similar energy carriers. Unfortunately, it cannot at present, especially compared with fossil fuels like oil and natural gas.

The following sections summarize the current status and future prospects of hydrogen production, storage, and distribution technologies.

Production of Hydrogen. As mentioned earlier, if the hydrogen is produced from natural gas or from electricity produced at a fossil-fired power plant, greenhouse gas emissions are not reduced. Because of production inefficiencies, they would actually be increased. Consequently, technologies related to these options for producing hydrogen are not discussed further. Hydrogen produced by the electrolysis of water, using electricity from photovoltaic arrays, solar thermal electric conversion, wind, or nuclear power plants, or through the direct photoelectrolysis of water will have the maximum positive impact on greenhouse gas emissions and are discussed below.

Water Electrolysis. At present, only about 1% of the worldwide production of hydrogen is via water electrolysis. The remainder is produced by steam/methane reforming of natural gas. This fact clearly indicates the cost differential between the two processes. Electrolysis is economical only in locations with an abundant supply of very inexpensive electric power. At typical electricity prices, the cost of the produced hydrogen is several times higher than prevailing prices of competing fuels. Developing cost-effective water electrolyzers is a major goal if an environmentally benign hydrogen economy is to become a reality.

Photoelectrolysis of Water. The photoelectrolysis of water produces hydrogen directly from solar energy in an electrochemical cell using photoactive semiconductor electrodes as anodes and cathodes. The maximum theoretical energy conversion efficiency in such systems is expected to be 35% to 40%. Laboratory results to date have accomplished conversion efficiencies from 5% to 10%. Some preliminary estimates indicate that efficiencies from 15% to 20% are required for the system to be economically competitive.

The technology is still in its infancy. Not only are improvements in conversion efficiency needed, but other major technical hurdles have to be overcome. One such hurdle is the photoinduced corrosion of the semiconductor electrodes. The electrodes that are least susceptible to corrosion also have high band gaps and absorb in the ultraviolet region of the solar spectrum. Thus, they use only a small portion of the available solar energy. Many innovative approaches are being investigated to stabilize low band-gap semiconductors (which absorb most of the solar spectrum, but also have a greater propensity to corrode) for use in this application. These approaches include chemically modifying the semiconductor surface and depositing islands of precious metal catalysts. Success is essential if this technology is to be commercially viable.

Research on the photoelectrolysis of water is still in a very early stage and is primarily focused on identifying promising semiconductor electrodes and on understanding how the system operates. Very little development activity is in progress. For example, no long-term testing has been done on any of the promising systems. Thus, even if the technical hurdles are overcome, this technology option will require at least a decade before it reaches the demonstration phase. However, this approach is probably the most exciting in terms of low-cost hydrogen production using a renewable energy resource.

Storage of Hydrogen. Hydrogen can be stored as a compressed gas, a cryogenic liquid, or a solid hydride. The last option would appear to be ideal; however, although hydrides can store a large amount of hydrogen on a volume basis, they can only store about 1% hydrogen on a mass basis. This obviously leads to extreme weight penalties and increases the cost for hydrogen storage, particularly for transportation applications.

Cryogenic hydrogen storage and distribution also are technically feasible but extremely expensive because of the high cost of cooling the hydrogen enough to keep it in a liquid state. Storage of hydrogen as a compressed gas is probably the least-cost option. Large-scale storage of hydrogen gas is feasible in depleted gas and oil fields. Fields that are considered to be tight for natural gas are expected to be suitable for hydrogen storage. Underground storage of hydrogen at 700 psia will, however, only hold about one-quarter of the Btu-capacity of an equivalent volume of natural gas. As a result, the cost of hydrogen storage is at least 2 to 3 times that of natural gas for every million Btu stored.

Transmission and Distribution of Hydrogen. Hydrogen can be transported through pipelines either as a compressed gas or as a liquid. However, transmission of liquid hydrogen is expected to be very expensive because of the need for significant refrigeration and pipe insulation and, thus, is not expected to be a practical option.

Transmitting hydrogen as a compressed gas is more practical, with an estimated cost of $0.034 to $0.048/million Btu per 100 miles at 750 psia. These costs are approximately 2 to 3 times higher than the cost of natural gas for equivalent energy throughput.

Commercial experience with hydrogen transmission through pipelines is limited. In the United States, experience is limited to a 50-mile network in the Houston area. A 130-mile network has also been in operation in the Ruhr area of Germany since 1940. These networks do not have any online compressor stations and are constructed from seamless steel pipe.

A common assumption made by proponents of a hydrogen economy is that the existing natural gas pipelines can be used for transporting hydrogen. These pipes may well be corroded by hydrogen through a phenomenon known as hydrogen embrittlement. The extensive experience at the National Aeronautics and Space Administration in handling hydrogen and the experience of the local hydrogen pipelines in operation today indicates that mild-steel pipes may not be adversely affected. Further materials science research is needed to resolve this issue.

Applications for Hydrogen. In principle, hydrogen can replace petroleum and natural gas in all their current end uses. Its most important potential impact would occur if it replaces gasoline as our primary transportation fuel. In this application, hydrogen could potentially 1) reduce dependence on imported oil, 2) profoundly improve urban air quality, and 3) eliminate greenhouse gas emissions from the transportation sector, but only if it is produced from domestic renewable or nuclear energy sources. Conventional spark-ignited internal combustion engines have operated with hydrogen fuel in many prototype vehicles. Stratified-charge engines are also fully capable of operating with hydrogen fuel. In addition, hydrogen greatly facilitates the use of alkaline fuel cell technology as a propulsion system for vehicles. Because fuel cells are approximately twice as efficient as the best internal combustion engines, this technology can dramatically improve vehicle on-board fuel efficiency.

The storage of hydrogen in vehicles is a problem. The two common options are storage as compressed gas or as metal hydrides. Both options involve significant weight and volume penalties. Research is needed to develop compact and lightweight hydrogen storage systems for vehicles.

In addition to transportation applications, hydrogen as an energy carrier also has the following applications:

1. residential and commercial space heating and/or small cogeneration systems using fuel cells to supply both electricity and heat for residential and commercial buildings

2. industrial heat and power using conventional cogeneration techniques or fuel cell technologies.

The use of hydrogen in these applications requires that it be safe. Everyone remembers the Hindenburg disaster; thus, the widespread use of hydrogen in consumer applications is of some concern. However, certain physical properties of hydrogen (e.g., limits of flammability in air, minimum energy for ignition, buoyant velocity in air, leak rate, and toxicity) compare very favorably with gasoline and natural gas. Hydrogen-rich "town gas" (50% hydrogen) was extensively used for residential heating in the United States until the 1950s. It is still commonly used in many parts of the world.

Performance and Cost of Hydrogen. The production of hydrogen commercially via water electrolysis consumes 4.5 kWh per cubic meter of hydrogen. Advances in electrolyzer technology are expected to reduce this energy consumption to approximately 3.0 kWh per cubic meter of hydrogen. As photoelectrolysis technology matures, further significant reductions in energy consumption are possible for hydrogen production. It is too early to speculate on the magnitude of those reductions. Thus, at present, the major cost component of hydrogen production is the electricity cost.

An optimistic estimate projects the delivered cost of hydrogen produced with electricity from photovoltaic arrays to be $13 to $18 per gigajoule (GJ) for transportation and residential use (Ogden and Williams 1989). This analysis assumes that photovoltaic modules will be 12% to 18% efficient and that their costs will come down to $0.2 to $0.4 per peak watt. Even under these optimistic assumptions, the price of gasoline must rise to more than $2.50 per gallon for hydrogen to be competitive. However, these costs are in the same general range as the cost of many other synthetic fuels being considered for transportation applications. The likely cost of hydrogen will probably be from $25 to $30 per GJ, making it competitive only at much higher gasoline prices. The only realistic scenario that will encourage hydrogen use in transportation is an international consensus to aggressively pursue policies to reduce greenhouse gas emissions.

Greenhouse Gas Emissions from Hydrogen. The shift from gasoline (or any other carbon-based fuel) to hydrogen in the transportation sector will eliminate all on-board emissions of carbon monoxide, carbon dioxide, particulates, and volatile organic compounds. If the hydrogen is used in conjunction with internal combustion engines, then NO_x will still be produced; however, the amount could be 20% lower than with gasoline-powered vehicles. In addition, if the hydrogen is used in conjunction with a fuel cell, emissions of NO_x at the vehicle point of use will also be eliminated. The overall impact on greenhouse gas emissions by a complete switch to hydrogen in transportation could be favorable, depending primarily on the method by which the hydrogen is produced.

The present domestic fleet (including trucks) is about 180 million vehicles, annually consuming approximately 2900 million barrels of oil equivalent (MBOE). It is expected to grow to 300 million vehicles by the year 2010. Oil consumption, however, is not expected to increase because the increased number of vehicles will be offset by the improved energy efficiency of the newer vehicles. If only 20% of the vehicles are switched to hydrogen, 580 MBOE will be displaced, and carbon dioxide emissions will be reduced by 200 million tons. The corresponding worldwide reduction of carbon dioxide will be 550 million tons. These reductions are very significant. In addition, there will be parallel major reductions in SO_x and NO_x emissions. However, these emissions would be offset by emissions, if any, that occur during the hydrogen production stage.

As hydrogen is introduced for residential and commercial buildings and for industrial cogeneration, the effect on carbon dioxide emissions will also be directly proportional to the displacement of fossil fuels used for those purposes. The impact, however, will not be of the same magnitude as described for the transportation case.

Reversible Chemical Reactions

Reversible chemical reactions provide one approach to storing and transporting thermal energy. Some reversible chemical reaction concepts were originally considered in connection with using waste heat from nuclear power plants, but they can also readily use heat from solar thermal systems. Research on this energy storage technology has been limited, particularly in the United States. The limited research reflects the fact that public support for nuclear energy has waned in the United States and that solar photovoltaic technologies to produce electricity and solar thermal systems with hot water storage for heating residential and commercial buildings are judged to be more attractive. Reversible chemical reaction storage technology is not at the point where reliable cost projections can be made; and because it will be applicable to relatively small niche markets, its impacts on greenhouse gas emissions are expected to be marginal. It is not clear whether this technology will ever be commercialized, when its potential benefits are compared with alternative storage technologies.

Description of Reversible Chemical Reactions. The process of burning fossil fuels is a chemical reaction where the chemical energy of the fuel is released in the form of heat and other products. If the reversible chemical reactions are promoted by catalysts and the original reactants are regenerated from the products, releasing the stored energy in the process, a closed-loop energy storage system is formed. This is precisely what the reversible chemical reaction energy storage concept attempts to accomplish.

The interest in reversible chemical reaction storage technology emanates from the pioneering work of German investigators on the steam/methane reforming reaction:

$$Q + CH_4 + H_2O = CO + 3H_2 \quad (5.1)$$

This reaction was studied as a method of transmitting high-temperature heat from nuclear reactors over long distances. The process consists of the steam reforming reaction (5.1) at the nuclear power generation site, transport of the reformed gas containing carbon monoxide and hydrogen through natural gas pipelines, and the subsequent methanation at the customer's site. The methanation reaction [reverse of reaction (5.1)] releases heat that can be used to produce electricity or provide district heating. The methane produced must be transported back to the original site so that it can be reused in the steam reforming reaction. Both reactions require specific catalysts in addition to thermal energy, thus the reverse reaction is prevented from occurring until it is needed.

A very similar process has been considered by General Electric in their HYCO process, which uses the reaction:

$$CH_4 + CO_2 = 2CO + 2H_2 \quad (5.2)$$

Many other schemes have been considered, such as 1) splitting ammonia into nitrogen and hydrogen, 2) adsorbing ammonia onto salt compounds, 3) reducing sulfur trioxide to sulfur dioxide and oxygen, and 4) adsorbing gases onto materials such as silica gel, charcoal, zeolites, and salts.

A problem shared by all of these approaches is the small enthalpy of reaction (or adsorption) that results in systems where large quantities of materials must be handled for each unit of energy storage. This accounts for the low energy density and high cost of these systems. There are other chemical reactions involving high specific heats; however, the complicated separation processes required create severe problems in implementing the technology.

Another approach to energy storage using reversible chemical reactions is the chemical heat pump. Two experimental demonstration systems are in use in Sweden, where the heat pump is charged by the reaction:

$$Na_2S + 5H_2O = Na_2S.5H_2O + 312\ \text{kJ/mole} \quad (5.3)$$

One is a demonstration of a 7000-kWh system for a residential building, the other is a 30,000-kWh system for a commercial building. Although the systems operate reliably, they do not appear to be cost-effective compared with other storage options.

Applications of Reversible Chemical Reactions. Thermal energy storage through reversible chemical reactions can have applications in district heating and space heating for residential and commercial buildings. The closed-loop systems were originally considered for district heating using the waste heat from nuclear power plants, but they can also be used with solar thermal energy. The chemical heat pumps are mostly targeted toward the heating needs of residential and commercial buildings.

In each of these applications, the reversible chemical reactions are competing with other storage technologies such as batteries and passive solar systems. Performance, reliability, and cost will determine the extent to which reversible chemical reaction storage systems will be commercially acceptable.

Performance and Cost of Reversible Chemical Reactions. The typical enthalpy of reaction for a reversible chemical reaction is approximately 200 to 300 kJ/mole of reactants. This low enthalpy change requires a very large volume of chemicals to be processed to store an adequate amount of energy. The resulting energy density can be as low as 10 kJ/kg, increasing the size and cost of the system. In some specialized cases, in conjunction with the ready availability of high-grade waste heat from nuclear plants, these technologies may be competitive. However, in most common applications, other storage technologies are clearly more cost-effective.

When used in conjunction with solar energy, the low conversion efficiency of the reversible chemical reaction energy storage scheme causes additional problems. For example, a combined solar thermal and chemical heat pump system offers no economic advantage over solar thermal systems with hot water storage. Conversion efficiencies of the reversible chemical reaction storage processes must be increased to 30% to 40% before they can be cost-effective. Some analyses show that, considering the energy in the solar spectrum, achieving more than 20% may be very difficult. Current conversion efficiencies are only 5% to 10%.

The two Swedish chemical heat pump demonstrations proved that these prototypes will not be cost-effective for residential or commercial buildings. The same study projects that with automated production techniques, the cost can be reduced to \$0.04 to \$0.05/kWh for a 15-m^3 storage system for a detached house. The cost of this unit is equally divided between the solar collectors and the chemical heat pump.

Greenhouse Gas Emissions from Reversible Chemical Reactions. The low energy density of reversible chemical reaction storage technology makes it unlikely that this technology will be commercially viable for many applications. District heating within an industrial energy park may be its only realistic application. Consequently, it will probably not have any significant impact on greenhouse gas emissions in the foreseeable future. The most optimistic projection is that if nuclear power becomes the dominant contributor to the energy generation mix in the United States, reversible chemical reaction storage technology may be viable for less than 1% of the district heating market. Even under this optimistic scenario, the potential impact of reversible chemical reaction storage technology on greenhouse gas emissions would be very small.

In addition, many of the reversible chemical reaction concepts use greenhouse gases in the energy storage process. Leakage of these gases and/or the greenhouse gas emissions that might occur during the synthesis of the reversible chemical reaction reactants would increase greenhouse gas emissions. Thus, it appears that the overall impact of this technology on greenhouse gas emissions would be marginal at best.

5.1.5 Magnetic Energy Storage

This section discusses superconducting magnetic energy storage (SMES). It includes a description of the technology and its applications, performance and cost characteristics, greenhouse gas emissions characteristics, and potential greenhouse gas emissions reductions that might occur if SMES technology were introduced into electric utility operations. The discussion is largely based on a preliminary scoping analysis done by the Pacific Northwest Laboratory to illustrate examples of the benefits that utilities might derive from SMES (DeSteese and Dagle 1990).

Overall, the benefits and economics of superconducting magnetic energy storage suggest that it might be the first superconducting technology to penetrate the utility component market. The earliest applications of this technology would contain superconductors operating at liquid helium temperatures. Eventually, high-temperature superconductors (HTS) operating at liquid nitrogen temperatures or above, may be developed. If HTS technology is adaptable to SMES systems, their economics could improve significantly.

Description of Superconducting Magnetic Energy Storage. In this decade and into the next century, U.S. utilities will face the need for increased power loadings and interconnections and for the integration of new energy resources into their systems. Electric utility systems will be forced to operate nearer to their limits and with lower reserve margins. These developments will cause new stability, reliability, and peak load management problems that could be addressed, in part, by adding dynamic energy storage to the systems. If SMES technology continues to advance, it could become a major energy storage option and provide many other potential benefits in utility applications.

Superconducting magnetic energy storage provides the means for the direct storage of electrical energy without the need for mechanical or chemical energy conversion in the charging and discharging processes. The essence of the storage system is an electric current passing through a circular inductor made of superconducting material. Because superconductors incur no resistance losses, current will circulate forever in a superconducting wire in a huge coil (approximately a half-mile in diameter in a large system) held below the critical temperature.

The core of the SMES concept is a superconducting solenoid or toroid. The intense magnetic field created when high-amperage direct currents flow in this coil is the medium for storing magnetic energy. Energy is stored proportionally to the coil's inductance and the square of the current flowing at any instant. In published designs, the superconducting coil is contained in a liquid-helium cryostat and is charged from and discharged into the utility's AC-transmission system through a power conditioning system that includes solid-state, multiphase AC-DC converters.

Applications for Superconducting Magnetic Energy Storage. The storage efficiency, instantaneous dispatch capability, and multifunction uses of superconducting magnetic energy storage are unique attributes, giving it the potential for revolutionary applications in the electric utility industry. The results of a preliminary study by DeSteese and Dagle (1990) indicate several potential cost-effective SMES applications in credible system-specific scenarios. With relatively simple benefit and cost-estimating methods, several representative SMES applications were shown to have annual benefit/cost ratios that exceed unity. However, in the cases considered, it appeared that the value of SMES derived from a single design purpose rarely justifies the unit's cost. For this reason, the best applications for SMES, in all but the smallest unit sizes, may be in situations where benefits from multiple-function use are realized.

In addition to its value as an energy storage technology, SMES has other valuable attributes including higher cycle-efficiency and instantaneous charge, discharge, and dispatch capabilities that may make it more attractive than competing storage technologies for certain applications. The following are some specific beneficial applications of SMES (from Schoenung et al. 1989):

- load following - SMES units could be used to provide load-following capacity, allowing conventional generating plants to approach constant load operation. SMES could also be the controllable element in Automatic Generation Control systems.

- ramping - Conventional generators could operate with less cycling and at reduced ramping rates (MW/min) with SMES online.

- set points - SMES could facilitate the operation of conventional generation plants at optimum settings to maximize thermal efficiency and reduce cycling at times of minimum load.

- system stability - A demonstrated capability of SMES is its ability to damp low-frequency power oscillations (see discussion of Tacoma experiment under "Performance of Superconducting Magnetic Energy Storage"); SMES could also damp system oscillations that are due to transient disturbances.

- spinning reserve - SMES could provide some of the spinning reserve capacity of a system at higher levels of availability and lower cost than conventional generating units.

- volt ampere reactive (VAR) control - The power transfer and stability limits of transmission systems could be extended by using SMES to absorb and dispatch reactive power, as required.

- black start capability - SMES could provide power to start a large generating unit without power from the grid.

- peak load management and capacity value - SMES could be incorporated into a system as capacity to supply peak loads and as a component of a dispatchable peak load management portfolio of measures. Such a portfolio could be designed to substitute for construction of equivalent conventional generation and, in some cases, transmission capacity.

Opportunities appear to exist where SMES units at a single location could provide several of the above benefits either simultaneously or at the discretion of the dispatcher in real-time responses to system conditions. Many of these capabilities are unique to SMES and increase its utility application potential to a larger number of opportunities than might be achieved on the basis of its energy storage value alone.

Performance of Superconducting Magnetic Energy Storage. In 1983, a 30-MJ (8-kWh), 10-MW SMES unit began operation in the Tacoma substation of the Bonneville Power Administration (BPA) utility system to damp unstable oscillations. As energy was exchanged between the SMES system and the Pacific Intertie grid, the unit effectively damped the 0.35-Hz oscillations typically observed on the grid. The unit operated for over 1 million cycles during a 1-year period, at frequencies of 0.1-1.0 Hz. Although BPA had originally intended the unit for dynamic stability control of transmission lines, it was mainly used for dynamic response characterization studies of the BPA power grid.

The results of over 1,200 hours of operation showed that the SMES unit was a versatile and responsive device for power system testing and control. It provided an initial base of operating experience for estimating the cost- effectiveness and special requirements of superconducting power equipment (Rogers and Boenig 1984).

Even though the stored current in a SMES unit is DC and must be converted to AC before going out onto the grid, round-trip energy storage efficiencies of 90% to 95% are expected (Fitzgerald 1988). According to Loyd (1988), SMES technology should be approximately 95% efficient. About 3% of the input energy is lost in converting from AC to DC and back, and the other 2% is consumed by the refrigeration equipment.

One key benefit of a SMES unit is that it can respond to a load change in only 20 milliseconds (Boutacoff 1989), which is faster than any other energy storage system except batteries. This capability would enable SMES to damp out disturbances in the electrical grid that could cause large-scale power outages.

Cost of Superconducting Magnetic Energy Storage. EPRI has estimated the cost of a 1000-MW SMES plant, including engineering, land, materials, and allowance for interest and escalation during construction (Boutacoff 1989). The total cost of $975/kW was obtained by multiplying the energy-related costs ($275/kWh) by the hours of storage (3 hours), and adding the result to the power-related costs ($150/kW). As stated previously, these costs may be substantially reduced if high-temperature superconductors can be made into appropriate shapes that can withstand the high current fluxes required in a SMES unit. According to Loyd (1988), the SMES capital costs could be reduced by as much as 25%.

The literature emphasizes the attributes of SMES as a potential competitor to pumped hydroelectric, gas turbines, batteries, and CAES peaking systems. Typical comparisons between systems have been based on predominantly large systems in the storage capacity range of 1,000 to 10,000 MWh with power capabilities at the 1000-MW level. With fuel costs of $6/MMBtu and a 3-cent/kWh cost of charging electricity, SMES systems have a competitive application potential when used as a large storage system operating with a capacity factor between 0.05 and 0.25 (1 to 6 hours/day) (Luongo et al. 1987). This result was based on the value of energy storage only, without the benefits of the other numerous SMES functions that can enhance an electric power system.

Greenhouse Gas Emissions from Superconducting Magnetic Energy Storage. A SMES system, when viewed by itself, is essentially free of greenhouse gas emissions. However, this perspective does not include any fossil fuel that may have been consumed in generating the off-peak electricity used to charge the system. In general, if a fossil-fired plant is the source of charging electricity, then greenhouse gas emissions will be increased by 5% to 10% if a SMES system is used because of its 90% to 95% round-trip storage efficiency. This increase in greenhouse gas emissions would be partially offset, however, by the increased fuel efficiency of operating fossil-fired plants closer to full-load conditions. Total greenhouse gas emissions would be reduced if the SMES system were used to supply peaking power instead of a gas turbine and if the SMES system were charged with electricity from a nonfossil energy source.

Environmental acceptability of SMES technology has yet to be established. In particular, the impacts of intense long-term magnetic field exposure must be evaluated.

5.2 ENERGY TRANSMISSION AND DISTRIBUTION TECHNOLOGIES

This section deals with the impacts of the transmission and distribution of various fuels on the atmospheric levels of greenhouse gases. The problems created by transporting fuel to its point of use are likely to be more socioeconomic than ecological. A definite exception is the oceanic oil contamination from tankers. Noise and traffic from energy transportation systems such as large and frequent unit trains are likely to annoy people but have little direct effect on plants, animals, or the environment. However, ecological difficulties are possible both with diverting water at the source and disposing of the water at the terminus if coal-slurry pipelines are ever used on a very large scale.

In the following sections, solids, liquids, gases, and electricity are described, and their applications, performance, cost, and potential greenhouse gas emissions are discussed.

5.2.1 Solids

In this section, coal and biomass are discussed.

Coal

Of all the nonrenewable fuels, coal is the most abundantly available. In terms of total energy content, the United States has roughly six times as much coal as oil. The potentially recoverable reserves are roughly equivalent to 12 trillion barrels of oil, while the economically recoverable reserves are equivalent to about 3 trillion barrels. In 1982, U.S. coal energy production was 18.65 quad. To use coal as a "bridging fuel" from today's oil-based economy to a future economy based on renewable resources, the United States will have to use 50% more coal in the year 2000 than it does today. Thus, serious economic, social, and environmental issues may have to be resolved.

Description of Coal. Coal is mined in three ways:

1. Surface mining accounts for 60% of U.S. coal production. In the eastern United States, strip mining is the main type of surface mining. In the West, open-pit mines are more common. In the hilly regions, hillside contour mining is practiced.

2. Underground mining accounts for most of the remaining 40% of U.S. coal production. This method is used when the coal deposits are deep underground (up to 1000 meters) or when the deposits are located near or under heavily populated or heavily used areas. Underground mining is not as efficient as surface mining. Underground mining is economical only when the coal deposits are at least a few feet thick. Even then, only half the available coal can be extracted from an underground mine; the rest must be left to support the weight of the overburden.

3. Auger mining is relatively unimportant, but in special situations, it can be the best method of extracting coal.

Coal accounts for 21% of the primary energy use in the United States. Not all the coal produced in this country is consumed at home; 14.5% of U.S. coal exports go to Japan, the largest importer of coal in the world (Mills and Toke 1985). Within the United States, 84% of all coal consumed is used to generate electric power. To minimize coal transport, much western coal is burned in power plants located at the mine site ("mine-mouth" plants). The balance is used for industrial purposes, including iron and steel and chemical production.

Performance and Cost of Coal. Because coal is a heavy, solid fuel, transportation is a relatively expensive component of coal consumption. Unlike oil or natural gas, coal cannot simply be pumped to the point of use. This has made the coal industry vulnerable to breakdowns in transportation and railroad strikes, as well as to problems in coal production.

Rail transport is widely used to move coal from the mine to the end user. Large trucks and barges are also used; and more recently, waterway traffic ton-miles and the number of barges and towing vessels have been steadily increasing. Because few waterways are directly adjacent to coal mines, most waterway coal movements include a short truck or rail haul from the mine. Most utilities and industrial plants using waterborne coal are located on waterways, and the coal is unloaded directly at the destination. The average waterway is a circuitous route between origin and destination. Nevertheless, waterway rates, which have been less than half the corresponding rail rates, make water transport attractive for hauling coal despite longer distances and slower speeds. This advantage is subject to change with the implementation of user charges and increasing waterway traffic congestion.

Truck transportation is dominant in the short-haul segment of coal shipping and is the most flexible mode. However, it is not significant in the cross-country movement of coal.

A more efficient method of transporting coal is by slurry pipelines. The coal is mixed with water to make a slurry that can be pumped through a pipeline. However, slurry pipelines require large amounts of water to be transported along with coal. Much of the coal mined in the western portions of the country cannot benefit from this technology because of water supply shortages. It is difficult to generalize about the relative economics of coal slurry pipelines versus unit trains because the comparison depends heavily on route conditions such as the relative circuitry of each system and the terrain. However, several general statements can be made:

- The construction cost per mile for slurry pipelines exceeds that of a railroad track with equivalent capacity.

- Railroads have much higher variable costs than pipelines, and consequently, their rates are more susceptible to inflation.

- Pipelines are only economically competitive with railroads when the transport distance is relatively long (probably over 500 miles) and the throughput is large (probably over 10 million tons annually).

A second concern pertains to the possible future transport of coal slurries composed of coal and liquid fuel mixtures. Such transport may present potentially severe safety and environmental problems in the event the pipeline ruptures or slurry is spilled at terminal transfer points. Carriers besides water, such as alcohol or petroleum, have been considered. The liquid fuel carrier would be burned with the coal, and the slurry pipeline could operate without the disadvantage of consuming potentially scarce water resources. However, the potential environmental effects and safety concerns in liquid fuel/coal slurry pipelines appear to be more severe than those for a water/coal slurry.

A third concern is that a continuing increase in inland waterway congestion might reduce the future value of barge transportation as a competitive alternative for moving coal. Other than slowing traffic, congestion has the potential of increasing transportation cost and causing accidents (groundings, rammings, or collisions) and pollution. Waterway congestion will probably affect the national petroleum delivery system far more than the coal system because of the relative volumes involved.

Greenhouse Gas Emissions from Coal. The environmental consequences of burning coal will require the development of expensive and technically sophisticated pollution-control technologies. The air pollutants of concern for coal combustion are carbon monoxide, carbon dioxide, and hydrocarbons. However, the transportation and storage of coal have no direct environmental impact, except for the socioeconomic concerns that are discussed later. Two factors could cause the quantity of waste requiring disposal to approach one half ton for every ton of coal consumed: 1) large amounts of sludge are generated, combined with the ash collected, and 2) the sulfur content varies.

Large increases in coal consumption will accelerate the depletion of present disposal sites and force the expansion of waste disposal systems. This expansion will likely involve increased shipping distances and, thus, develop an increased dependence on adequate and compatible transportation facilities. Present transportation planning efforts do not appear to adequately address the long-term implications of greatly increased sludge production. Therefore, the biggest concern is the lack of preparation to transport large amounts of sludge and ash that may restrict the use of coal in future environmentally compatible generating stations and plants.

Biomass

The term "biomass" refers to a wide variety of energy resources based on converting plant material to usable forms of energy. Wood burning can be regarded as a form of biomass conversion, but the term is usually reserved for more complex processes such as the production of gas or alcohol fuels from plant materials. Agricultural wastes, animal wastes, garbage, and forestry by-products are all classified as biomass. Biomass can be used for energy needs through a variety of conversion processes, categorized under three general headings: 1) direct utilization, 2) thermochemical conversions, and 3) biochemical conversions.

Biomass production is not an especially efficient way to convert solar energy. Most plants store only about 1% or 2% of the sunlight that reaches their leaves; therefore, large-scale biomass projects would require large areas of land. Promoters of biomass conversion recommend using land that currently lies idle. This land could be used to produce rapidly growing energy crops such as sugarcane or hybrid trees. Up to an estimated 20 quad of energy per year could be obtained by using about 5% to 10% of the idle land in the United States. However, the costs and energy needs of irrigation, transportation, and processing of vegetable matter produced by such a scheme need to be considered.

Some environmentalists fear that widespread cultivation of biomass crops could take prime farmland out of production or impede wider cultivation of human foods. The other widespread impact of cutting down plants is the loss of the key mechanism for removing carbon dioxide from the environment. However, the ecological balance can be attained by planting more crops and trees where they once were. In many cases, the environmental effects of reducing municipal wastes and replacing fossil fuels by widespread biomass conversion are clearly beneficial.

5.2.2 Liquids

In this section, petroleum and other liquid fuels are discussed.

Petroleum

In the following sections, petroleum is described, and its applications, performance, cost, and potential greenhouse gas emissions are discussed.

Description of Petroleum. Petroleum is the largest single energy source for the Western world. As of July 1983, the United States used approximately 14.8 million barrels of petroleum per day (1 bbl = 42 U.S. gallons). This is approximately 30% of the world's total consumption of petroleum by a country with only 5% of the world's population (Mills and Toke 1985). Because total domestic oil production is only 8.67 million barrels per day, the United States imports roughly 6 million barrels per day, approximately 40% of its total petroleum consumption. This percentage has recently risen to more than 50%, even though projections were to reduce the import levels and the total consumption.

In the past, oil drilling was done on land near surface deposits or other known sources of petroleum. As land deposits became less abundant, oil drilling moved offshore. As the search for oil has moved to more remote regions, the cost and effort involved in drilling a well have increased. In 1980, the average depth of a U.S. oil well was 1425 meters (nearly nine-tenths of a mile) and the average cost was $130,000, measured in constant 1972 dollars.

Performance and Cost of Petroleum. Petroleum is distributed by primary and secondary systems (DeSteese and Dawson 1979). The system of pipelines, tankers, and barges that move crude oil from producing areas to refineries, and similar facilities that move petroleum products in bulk to marketing areas, make up the primary distribution system. Shipments from the bulk terminals by pipeline, truck, barge, and rail to consumers characterize the secondary distribution system. Approximately 24,000 bulk terminals handle the interchange of petroleum products among the transport modes.

Transport modes and storage facilities shown in Figure 5.6 are the basic elements involved in moving petroleum. When oil is to be transported across the ocean (e.g., from the Persian Gulf to the United States or Japan), it is carried in specialized oil tankers. However, ocean transport of oil can cause environmental problems. Some oil tankers are enormous and have significant problems in maneuvering. A loaded "supertanker" can take more than 2 miles to stop. If a tanker is damaged in an accident, the consequences can be very serious, as evidenced by the Exxon Valdez and the Megaborg incidents in different oceans.

Accidents are not the only source of oil contamination to the oceans. Some operators routinely flush out their empty tankers with seawater before picking up a new shipment of oil. This practice accounts for roughly 30% of the oil discharged to the environment.

New technologies are being developed to prevent oil spills at sea and to cope with them when they occur. Double-bottomed tankers, deep-water "superports," new detergents for cleaning up oil spills, oil-absorbent sponges, and even oil-eating bacteria have been developed in an attempt to cope with the environmental problems caused by ocean transportation of petroleum.

While tank trucks are used for distributing petroleum products to gas stations and residential users, pipelines and railroad tank cars are the preferred methods for long-distance land transport. Pipelines are expensive to build and maintain, and breaks along a pipeline can cause significant oil spills. Because of the great length of a pipeline, locating and repairing leaks can be quite expensive, often requiring repair crews to travel long distances over difficult terrain. However, pipelines are the most energy-efficient means of transporting petroleum overland.

Tank truck and railroad tank car are the most expensive modes of transportation (Figure 5.7 and Table 5.6). Although movement by tank truck and rail is expensive, these modes are relatively less susceptible to interference by outside forces. Barge traffic is vulnerable to disruption from natural occurrences such as severe weather or too much or too little water in the waterways. Fuel efficiency of the various transport modes varies significantly, with the large tankers being the most efficient means at 0.41×10^{-5} fuel Btu/Btu-mile.

Greenhouse Gas Emissions of Petroleum. The air pollutants of concern in transporting oil are hydrocarbons, carbon monoxide, and carbon dioxide, in addition to the ecological problems created by any oil spills from tankers or pipelines. The costs of preparedness, reaction time following an accident, and the actual cleanup are gradually rising to the point of maintaining shared resources among the governments, the oil companies, and the tanker operators. The only legitimate way of minimizing the risks involved is by being prepared and taking quick and efficient actions to control the damage caused by a leak or spill.

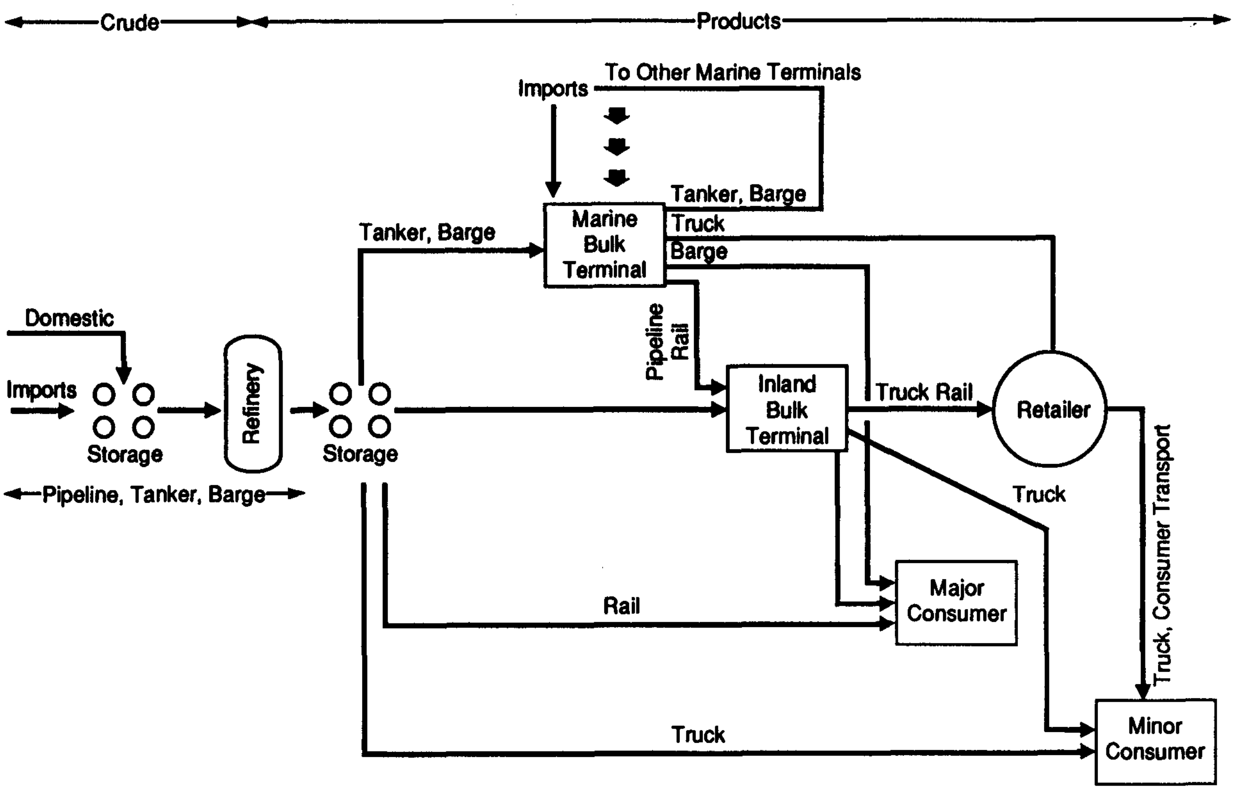

Figure 5.6. Elements of the Petroleum Transport and Distribution System

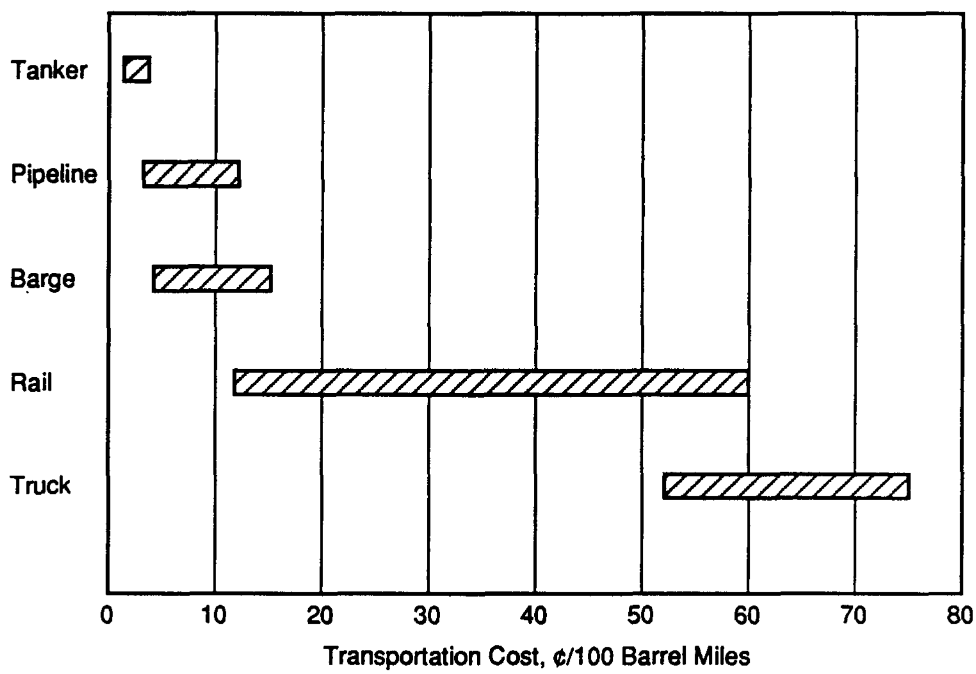

Figure 5.7. Range of Petroleum Transportation Costs

Table 5.6. Comparative Costs of Moving Petroleum

Transportation Mode	Mills per bbl Low	High
Tanker	0.13	0.35
Pipeline	0.20	1.00
Barge	0.23	1.50
Rail	1.05	5.00
Truck	4.70	6.50

Other Liquid Fuels

Other processed fuels such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG) can also be shipped in specially designed tankers. For LNG, the vessels contain large dewars that keep the liquid at or below the boiling point of natural gas: -160°C (-260°F).

An alternative to LNG is converting natural gas to methanol. Because natural gas consists primarily of methane, the technology is relatively straightforward. Methanol is a liquid at normal outdoor temperatures and therefore does not require refrigeration; and it can be burned directly in its liquid form.

In the United States, about 30% of the LPG consumed is refined from crude oil, while 70% is extracted from natural gas. Total production in 1975 was 430.5 million barrels, while imports totaled nearly 41 million barrels. LPG characteristically moves from the oil or gas well to the refinery or gas processing plant by pipeline. It may then continue by all of the transport modes to a distribution plant, an underground storage cavern, or a consumer. Though infrequent, the problems that exist with the tanker transport of LPG or LNG are similar to those with the transport of petroleum, in that spills and leaks can cause environmental damage.

5.2.3 Gases

In this section, natural gas is discussed.

Natural Gas

In the following sections, natural gas is described, and its applications, performance, cost, and potential greenhouse gas emissions are discussed.

Description of Natural Gas. Natural gas and crude oil (petroleum) are usually found in the same geographic areas. Natural gas is usually found to coexist with oil, although there are cases where an oil well contains no natural gas, and some natural gas wells produce no oil. The geological requirements for natural gas formation are the same as for oil and so are the prospecting, exploration, drilling, and production procedures. Natural gas also shares some of the advantages of petroleum, in that they are both easy to transport and control. Natural gas is somewhat easier to produce and distribute, and its clean-burning properties make it preferable to oil for many purposes.

The world's supplies of natural gas are being used up, although not quite as rapidly as the supply of petroleum. Some energy policy analysts believe that huge reserves of natural gas remain to be tapped, and that natural gas presents fewer supply problems than most other forms of energy. As of 1980, U.S. proven resources consisted of approximately 200 trillion cubic feet (tcf) of natural gas, with an energy content of approximately 200 quad. (Total U.S. energy consumption in 1987 was 76 quad.) Total recoverable reserves are closer to 1,000 quad. Ultimate recoverable reserves (assuming improved technology and favorable economic conditions) around the world are estimated at 13,000 tcf of natural gas and 2,100 tcf of liquid reserves, equivalent to 13,000 and 5,750 quad, respectively (WEC 1989).

Natural gas is generally found with oil in the pore spaces of oil-bearing sands or rock. The gas may be dissolved within the crude oil or may be entrapped separately in a geological structure known as a gas cap. About half the current supply of natural gas is produced from oil wells and must undergo field treatment to be separated from the oil (DeSteese and Geffen 1978). Most of this gas also contains substantial amounts of water vapor, which must be removed at dehydration plants because the water can react with the gas to form hydrate crystals, which may in turn accumulate and partially or completely block pipeline systems.

Performance and Cost of Natural Gas. Transportation can be a difficult and costly process because in its gaseous state, natural gas occupies an enormous volume compared with liquid and solid fuels. However, natural gas flows through pipelines readily, so most overland transportation of natural gas is carried out by pipelines. However, it can also be a dangerous arrangement. Explosions and fires can occur as a result of improper installation or operation of gas-fired appliances, breaks in gas lines (resulting in the leakage of methane gas to the atmosphere), or even sabotage.

A schematic diagram of the natural gas transportation system is shown in Figure 5.8. After separation and dehydration, the gas travels through field gathering lines to a natural gas processing plant, which is designed to recover certain gaseous and liquefiable hydrocarbons (natural gas liquids) from the gas stream. A typical plant removes 40% of the ethane (as a gas), 95% of the propane, and 100% of the butane and other heavier hydrocarbons.

Before the gas enters transmission lines, hydrogen sulfide and carbon dioxide must also be removed because these gases are extremely corrosive. Natural gas can also enter the transmission lines as gas imported from Canada and Mexico, gas from synthetic natural gas (SNG) and LNG plants, or from underground storage facilities. Distribution systems radiate from transmission line terminals to individual consumers.

The marginal cost of transmission and distribution of natural gas is expected to remain constant at about $0.52/mcf (thousand cubic feet), expressed in 1978 dollars (Nieves and Lemon 1979). Pipelines may not always be the most appropriate form of transporting natural gas; it may also be shipped in tankers after it has been liquefied into LNG or methanol, as discussed in the earlier section. However, LNG and SNG have higher accident risk and emission levels than conventional natural gas does. Thus, their increased use will lead to increasing nonmarket costs (those costs that are not borne by the producers and consumers) for natural gas. The effects of emissions from natural gas processes cannot be accurately quantified from currently available information. Research is needed on both models and data for emissions dispersion and damage functions.

Greenhouse Gas Emissions from Natural Gas. Greenhouse gas emissions from the transport of natural gas would occur if the pipeline fails or ruptures. The gas industry is heavily involved in improving materials and procedures to prevent pipeline damage. Pipeline materials, welding techniques, and cathodic protection against pipeline corrosion have received a great deal of attention. Much of the current effort focuses on materials suitable for use in arctic and undersea pipelines, which are subjected to stresses quite different from those affecting pipelines on land.

Public relations programs to make farmers and construction contractors aware of the danger of digging without checking with the gas company for pipeline locations are also a major part of industry safety programs. The gas industry is developing improved leak detection methods, such as acoustic detectors which "hear" leaks. Distribution companies add chemicals to natural gas to give it an odor, which would help detect gas leaks.

The transportation of natural gas does not have a significant effect on air or water quality because most of the U.S. pipelines are underground. However, the initial construction of a pipeline may have severe local impacts on the environment. The land must be cleared; the pipeline trench must be excavated, and, after the pipeline is laid, the fill dirt is spread and compacted. Major natural disasters may cause extensive damage to gas distribution systems, damage that

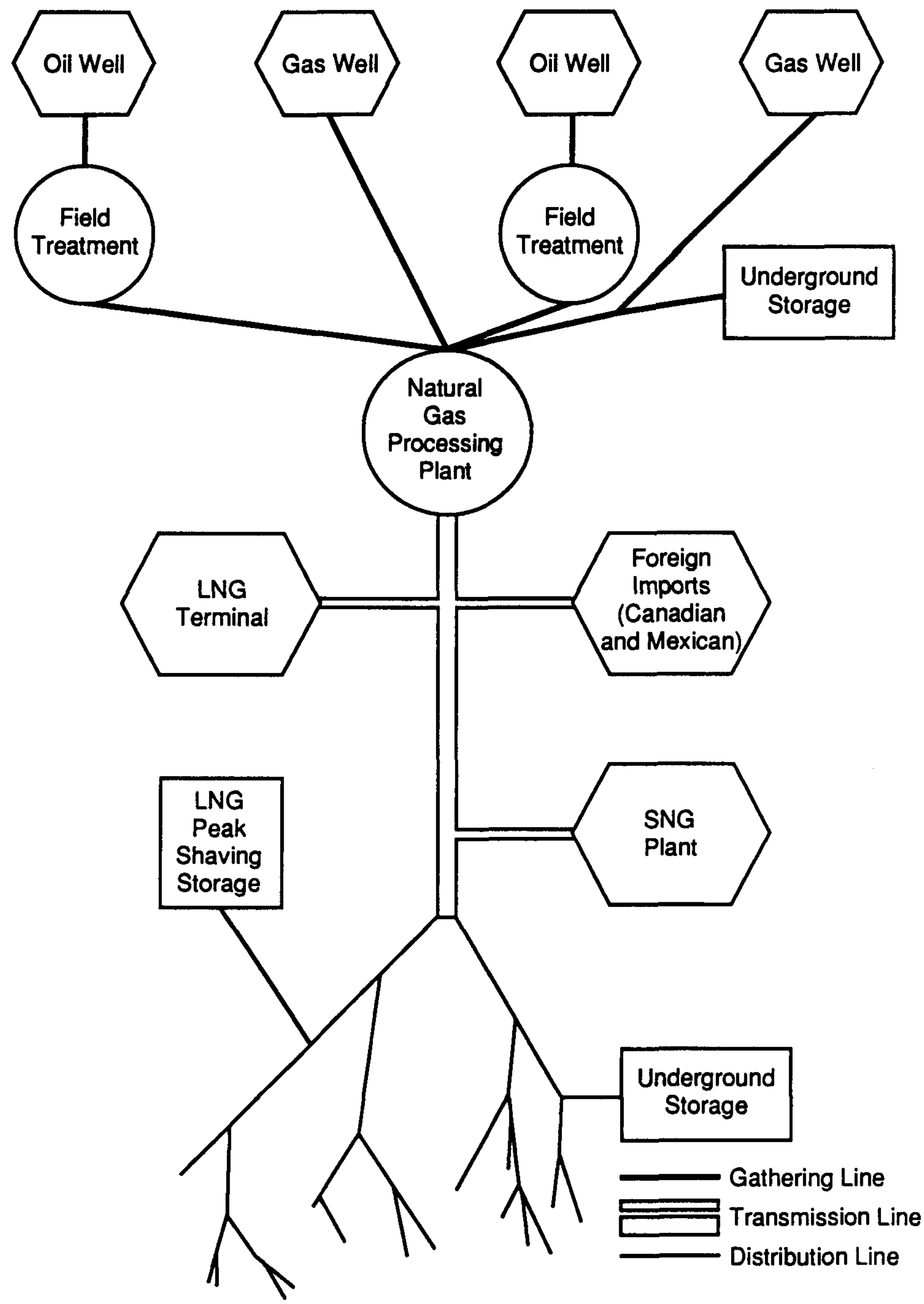

Figure 5.8. Natural Gas Transportation System

could result in fires and explosions in populated areas. The potential deterioration of aging distribution systems may cause safety hazards in the older and larger urban areas.

Substituting natural gas for coal/petroleum fossil fuels is one of the options to reduce carbon dioxide emissions. The specific carbon dioxide emissions from burning natural gas are lower, and the energy conversion efficiency in stationary applications (e.g., power plants, boilers) generally is higher than coal/petroleum fuels. However, concerns have been raised about emissions from increased natural gas use (e.g., pipeline leakage). Furthermore, the infrared absorption of one molecule of methane is 30 to 50 times as much as the infrared absorption of one carbon dioxide molecule. This has led to several suggestions that leakage of natural gas, even of small quantities, would offset the advantage of its lower carbon dioxide emissions. But the effective atmospheric lifetime of carbon dioxide is longer than that of methane. Moreover, the atmospheric lifetime of methane is, to some extent, determined by the magnitude of carbon monoxide emissions.

5.2.4 Electricity

In the following sections, electricity is described, and its applications, performance, cost, and potential greenhouse gas emissions are discussed.

Description of Electricity

Electricity is a vital commodity in modern societies and economies. In 1987, the United States consumed 76.01 quad of energy, and 36.3% (27.56 quad) of this consumption was electricity. The U.S. electric power system is the largest in the world, with a generating capacity larger than the sum of the next four largest power systems combined.

The transmission and distribution (T&D) network used to deliver electricity to consumers represents a major part of any electrical utility system. Transmission is the generic term used to describe high-voltage facilities (69 kV and above) that carry electricity from generating stations to major substations throughout the bulk electric system. At these major substations, the voltage is reduced and supplied to the distribution system (typically between 2.4 kV and 34.5 kV). Distribution transformers, which are located along distribution feeder lines, provide electric service at voltages between 120 and 600 volts to homes, commercial buildings, and industries. Figure 5.9 shows the elements of this system.

The major transmission components are the overhead and underground lines and substations. Within substations, the major components are typically circuit breakers, transformers, and related control gear. The amount of electrical power dissipated as heat during transmission is proportional to the square of the current flow. One method of reducing power losses in T&D systems is to operate them at as high a voltage as is economically practical. Hence, long-distance transmission lines operate at between 230 and 765 kV in the United States, and up to 1,000 kV elsewhere in the world (Callaway and DeSteese 1986).

Performance and Cost of Electricity

Power plants normally generate electricity from 2 to 25 kV. Step-up transformers connected between the generator and transmission line typically increase this voltage to a level appropriate for long-distance, bulk-power transmission. Substations located along the transmission route connect the line with other generators and primary and secondary transmission lines in the network. Distribution substations, containing step-down transformers, supply the distribution networks serving load centers. Feeder lines in the distribution system bring power to end-use customers.

Typical transmission and distribution losses, as a percentage of sales, are estimated to be about 8%. Feeders are responsible for a relatively large portion of transmission losses (32%) because of the relatively low voltage and correspondingly high current transmitted. The distribution transformers are next in contributing 28% of the overall losses.

Several approaches to improving T&D efficiency are established practices of the electric utility industry. However, most system improvements are made to increase system capacity and reliability. Efficiency gains alone are relatively infrequent motivations for system improvements. Reconductoring (i.e., rewiring with larger-size conductors), transformer replacement, voltage upgrading, and capacitance additions are the most frequently used options. High-efficiency distribution transformers now on the

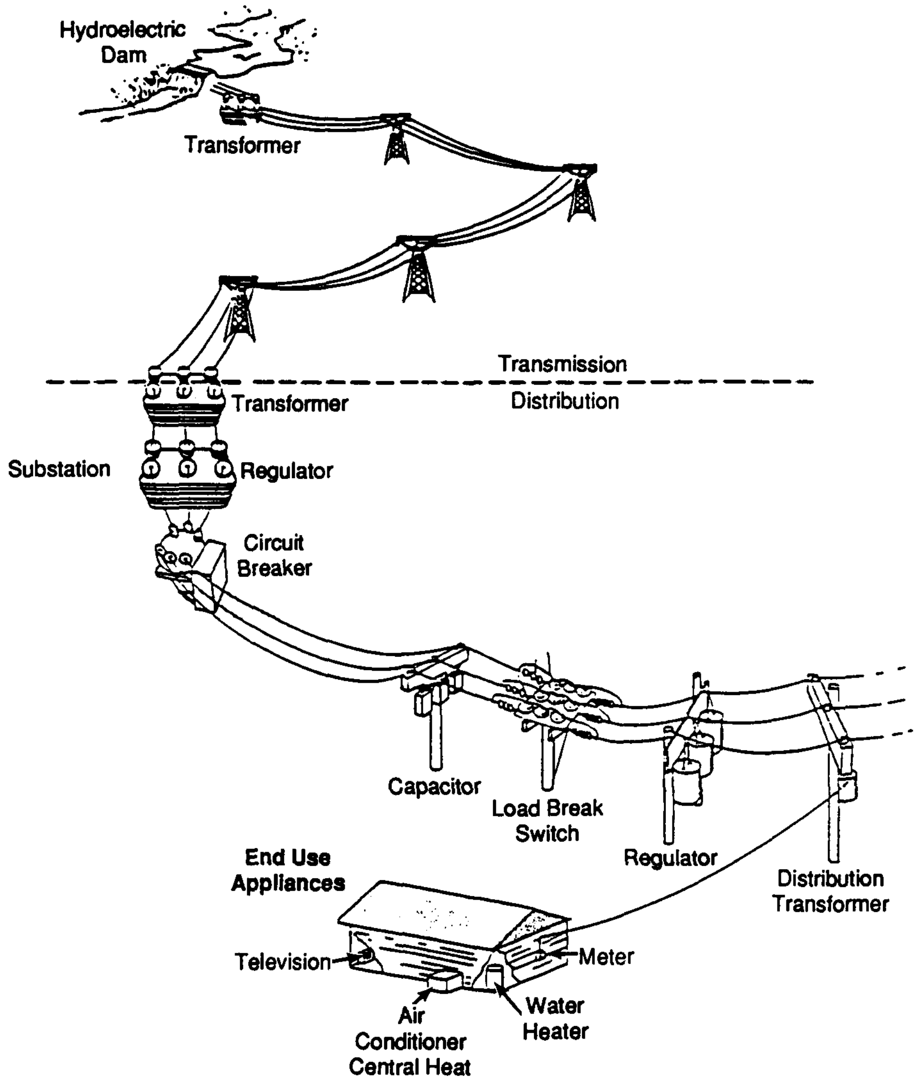

Figure 5.9. Transmission and Distribution of Electricity

market use an amorphous steel core to reduce core loss by 75% compared with that of a conventional transformer.

Potential future improvements may occur through development of high-temperature superconducting materials. While losses in transmission cables could be substantially reduced, the major benefits of superconductors may be their ability to increase the capacity of existing transmission corridors. This is expected to be an important value as it becomes more difficult to obtain new transmission rights-of-way, largely because of environmental restrictions.

Superconducting transmission cables offer several significant advantages over current systems, including the potential for reduced losses. At a given capacity, superconducting cables potentially could be designed to operate at lower voltages than those of conventional systems. Direct connection of lower-voltage superconducting cables with conventional generators may be a possible option that could eliminate the need for generation step-up transformers. Lower-voltage operation might be more reliable and allow the use of reduced clearances for terminal facilities. Therefore, when the costs/benefits of systems using superconducting cables are compared, the entire circuit, including all terminal equipment, must be considered.

If the enabling materials technology is developed, analyses done at the Pacific Northwest Laboratory show that high-temperature superconducting (HTS) power transformers could be made significantly more efficient, smaller, lighter, and less expensive (on a life-cycle cost basis) than conventional units of the same capacity. Depending on capacity and design efficiency, a three- to sixfold reduction in size and weight appears possible. These potential new attributes translate into several system benefits and operational advantages. The size and weight reduction potential of HTS transformers could result in lower transportation costs and easier logistics when new units are delivered or when failed units need replacement. Also, the HTS transformers could embody higher capacities than conventional units of a given size and weight, an attribute that offers a means of expanding the capacity of facilities that might otherwise be limited.

Superconductors may also allow an efficiency improvement in the generation of electricity. The efficiency of large conventional generators is typically 98.6%; whereas, efficiencies of superconducting generators have been estimated to be from 99.5% to 99.7%. Generator weight may be reduced by about 50%, with a corresponding reduction in volume. Superconducting generators could be designed to produce electricity directly at transmission voltages and thereby provide another way to eliminate the need for generation step-up transformers.

The exposure of the public to electric and magnetic fields has become a significant concern in T&D system siting. Visual "pollution" also limits public acceptability of transmission lines, particularly high-capacity lines. Difficulties in siting new transmission lines and the need for increased transmission capacity are creating additional pressures to increase the capacities of existing transmission corridors. Superconducting cables and other components may become the enabling technology that addresses this need.

Greenhouse Gas Emissions from Electricity

The transmission and distribution of electrical power makes essentially no contribution to greenhouse gas emissions. Corona, which exists in varying degrees on most high-voltage equipment, may result in noise, radio and television interference, and a small amount of ozone production. Any improvement in T&D efficiency would offer little net reduction in greenhouse gas from generating plants. In most cases, the energy saved by system improvements would be made available for sale to consumers.

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6.0 TRANSPORTATION TECHNOLOGY

This chapter discusses technology to reduce greenhouse gas emissions in the transportation sector. Except for carbon dioxide, sources of carbon in vehicle exhaust are minimal for circa 1990s vehicles in the United States. The less fuel consumed, the less carbon dioxide emitted. Accordingly, it has been asserted that the most important way of decreasing the emissions of carbon dioxide from automotive vehicles operated on gasoline is to improve their fuel economy (Amman 1989). From this perspective, research on the attainment of fuel economy is, in effect, research on the problem of reducing carbon dioxide and other greenhouse gas emissions.

An alternative approach is to switch fuels. DeLuchi (OTA 1991) has estimated that nuclear-electric, solar electric, and/or biomass-based alcohols could reduce net greenhouse gas emissions substantially. These reductions are accomplished either because there is no carbon in the fuel used (nuclear and solar) or because the carbon is recycled in the global system (biomass).

6.1 TECHNOLOGY OPTIONS TO ACHIEVE EMISSION REDUCTIONS

6.1.1 Gasoline Technologies Available to Reduce Carbon Dioxide in Light-Duty Vehicles

Large increases in the fuel economy of light-duty vehicles have been demonstrated for various "concept" four-passenger vehicles using current engine technology (Bleviss 1988; EEA).[(a)] A computer model constructed by Argonne National Laboratory (ANL), based on 1988 vehicles, was able to closely reproduce the miles per gallon (mpg) performance of these vehicles.

(a) Energy and Environmental Analysis. (EEA). 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.

However, while technical feasibility exists, economic feasibility is far less certain. For example, to achieve a doubling of fuel economy through advanced fuel economy concepts, consumers would probably have to shift to smaller, lighter vehicles with some possible sacrifice to performance--including acceleration and ride quality. Consumer resistance to these changes, together with the rebound effect of extra travel in response to lower per-mile driving costs, would delay and partially offset reductions in carbon dioxide emissions from light-duty vehicles.

The question of an optimal rate of mpg improvement that will not excessively disrupt the vehicle manufacturing industry is another key issue. Santini (1988, 1989) has presented a theory that argues that sharp, dramatic multiyear fuel efficiency and fuel type transitions in transportation can cause depressions through direct effects on vehicle sales and indirect effects on cost of travel. The same theory, however, argues that the transitions are ultimately necessary to maintain long-term economic growth (Santini 1988). Thus, the implications of the theory are that any transition should be made with as little disruption as possible.

Several currently available automotive technologies could improve the new car fleet economy if adopted universally. However, if these technologies are to result in greater mpg values for cars, they must be used for fuel economy rather than performance. Thus if engine and drivetrain systems were redesigned to hold horsepower per pound of vehicle weight constant, then technologies such as supercharging, turbocharging, 4 valves per cylinder, overhead camshafts, intercooling, multipoint fuel injection, four-speed lockup automatic transmissions, and continuously variable transmissions could all be used to improve fuel economy. However, Difiglio et al. (1990) have shown by engineering calculations and Santini and Vyas (1988) have determined by statistical testing that this is a costly proposition because new engine and transmission production lines would have to be set up to produce the smaller engines. The last time the industry dramatically reduced engine sizes to improve fuel economy, it went through a depression; and the economy suffered two closely spaced recessions, the second of which was the worst since the Great Depression. The current emphasis is on using these technologies to increase performance by modifying a proven engine coming off of an existing production line.

Section 6.2 contains several different sources of estimates of the mpg gains possible with most of these technologies. Section 6.2 also lists other technologies--many of which are not in production--compiled from Bleviss' book (1988), from an EEA report,[a] and from an SRI International report (1991).

6.1.2 Alternative Fuels Available to Reduce Carbon Dioxide

At present, essentially five major fuel alternatives are being considered for future use in the transportation sector: modified gasoline, diesel oil, alcohols (methanol and ethanol), natural gas, and electricity. Gasoline and diesel oil are derived from crude oil. Most analysts expect any large quantities of methanol to be produced from natural gas, although coal has been touted as a feedstock in the past. However, DeLuchi et al. (1987, 1989) have shown that methanol produced from coal would have a very detrimental effect on carbon dioxide emissions. If methanol is produced from natural gas and if all other technical factors are equal, DeLuchi et al. (1989) estimate that it can have a slight beneficial effect on greenhouse gas emissions. DeLuchi et al. (1989) also estimate that the use of natural gas in vehicles dedicated to the use of natural gas only and with reduced range and performance relative to average cars sold today could reduce carbon dioxide equivalent emissions by between 10% and 15% (see Figure 6.1). Unnasch et al. (1989) come to a similar conclusion with respect to vehicles dedicated to the use of natural gas. In more recent research, DeLuchi (OTA 1991) has estimated significant carbon dioxide reductions for alcohol fuels produced from woody biomass.

Electricity

The ideal transportation fuel, if greenhouse gas emissions are the only consideration, is electricity generated from nuclear power plants (Figure 6.1). However, like any of the other options, this one has a cost. In the case of electric vehicles (EV) the costs tend to be quite high. Asbury et al. (1984) estimated in 1984 that methanol from offshore natural gas (NG) suppliers was then economical (at 85¢ per gallon in 1984$), while finding that electric commuter vehicles could compete with gasoline engines if the price were $2.00 per gallon. However, even at that price, the electric vehicles could only compete with passenger cars for which a range of 50 to 90 miles would be acceptable to the consumer. They found that natural gas fleet vehicles could compete with gasoline vehicles if the vehicles used 1,000 gallons of fuel a year (20,000 miles per year at 20 mpg) and the natural gas cost 50¢ per gallon less than gasoline on a "gasoline-equivalent" basis. Thus, at 1984 prices, wholesale natural gas prices had to be less than half those of gasoline on a "gasoline-equivalent" basis. Through 1988, real gasoline prices had been at lower levels than those prevailing in 1984, giving methanol, natural gas, and electric vehicles a tougher target with which to compete.

Natural Gas

A detailed analysis of the potential of substituting natural-gas-based transportation fuels for crude-oil-based gasoline in light-duty vehicles has been completed (Santini et al. 1989). The numbers developed by Santini et al. (1989) imply that, aside from electric vehicles using nonfossil electric power or woody biomass-based fuels, fuel substitution in transportation cannot alone accomplish significant

(a) Energy and Environmental Analysis. (EEA). 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes.* Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.

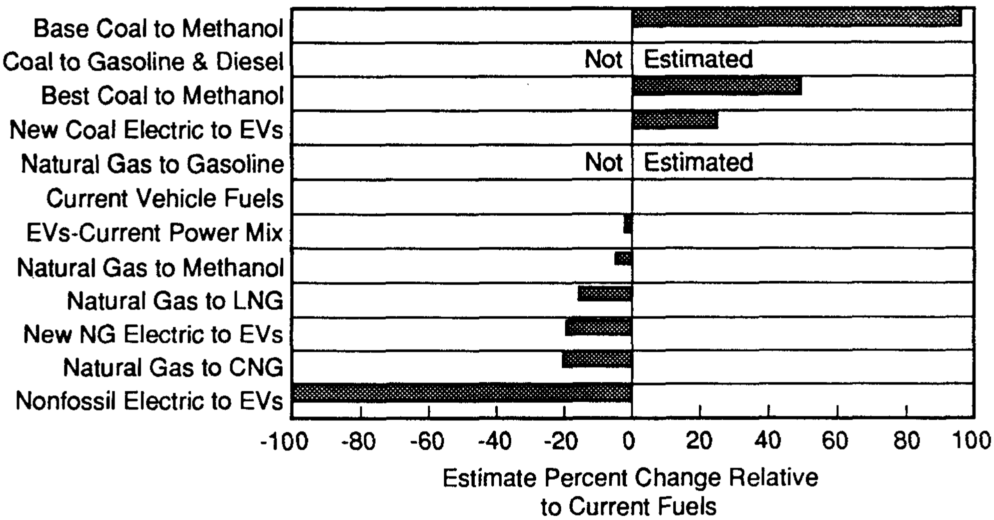

Figure 6.1. Selected Prior Estimates of the Percent Change in Vehicle Greenhouse Gas Emissions Resulting from Selection of Alternative Fuel-to-Vehicle Production/Use Pathways (DeLuchi et al. 1989)

reductions in greenhouse gas emissions from light-duty vehicles if consumers insist on owning vehicles with driving ranges typical of today's vehicles. Substitution of coal-based transportation fuels for oil-based fuels is not desirable because it would clearly increase greenhouse gas emissions (Figure 6.1). However, use of natural-gas-based transportation fuels does offer the opportunity for some improvement. It depends a great deal on the specifics of the fuel produced from natural gas and the way it is used in vehicles.

DeLuchi et al. (1989) and Unnasch et al. (1989) have shown that compressed-natural-gas (CNG) vehicles (using only natural gas and optimized specifically for natural gas) could achieve per vehicle reductions of approximately 20%, compared with vehicles using gasoline produced from crude oil. In order for this reduction to be achieved, however, vehicle consumers must be willing to purchase natural-gas-fueled vehicles with considerably less range and less acceleration than current light-duty vehicles. Even if consumers were willing to buy such vehicles, the achievement of a 20% per vehicle reduction would not be a large enough improvement to offset the increases in vehicle ownership and use that would accompany economic growth. If consumers were to insist on performance and range equivalent to current light-duty vehicles, then current fuel economy and performance test data indicate that use of either compressed-natural-gas or methanol vehicles (using methanol from natural gas), with the exception of dual-fuel gasoline/compressed-natural-gas vehicles, would result in only small changes in emissions (Figure 6.2). Use of compressed natural gas in a dual-fuel vehicle, however, would increase emissions by a few percent. Use of gasoline produced from natural gas instead of gasoline produced from crude oil was estimated to increase greenhouse gas emissions by 30% to 40%, depending on fuel production technology.

Modified Gasoline

An option not investigated by Santini et al. (1989) was that of partial substitution of natural-gas-based chemicals into gasoline, as is now being seriously considered by automakers and gasoline refiners. A "clean gasoline" for the 1990s has been proposed in a recent paper by Colluci (1989) and has been introduced by Atlantic Richfield in California. One of the key differences in the proposed

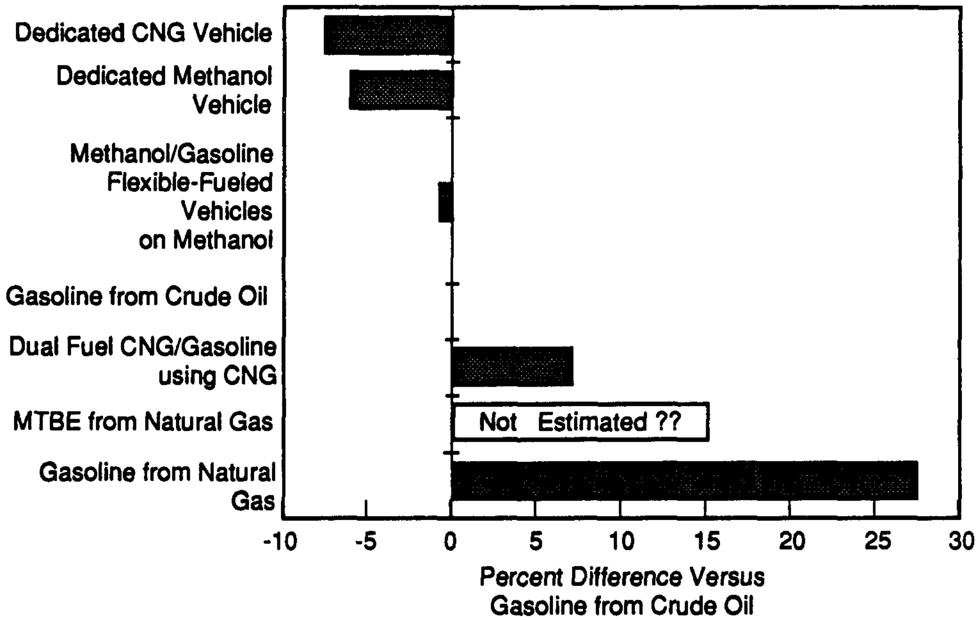

Figure 6.2. Estimated Differences of Greenhouse Gas Emissions for Natural-Gas-Based Transportation Fuels in Light-Duty Vehicles Versus Gasoline from Crude Oil (Performance Equivalent Vehicles Using Best Pathways from Santini et al. 1989)

"clean gasoline" and the current gasolines is the substitution of methyl tertiary butyl ether (MTBE) for some of the more volatile and carcinogenic constituents of gasoline. Such a substitution is already under way on a small scale, but would be substantially expanded if planned environmental experiments with "clean gasoline" demonstrate that the fuel can reduce ozone as well as, or better than, methanol or compressed natural gas in vehicles designed to use those fuels.

The environmental evaluation of the proposed clean gasoline should include an evaluation of its potential to cut emissions. The probable result of such an investigation can be logically deduced. MTBE is produced by further processing of methanol. Accordingly, more total energy will be used in the production of MTBE than in the production of methanol, so greenhouse gas emissions from fuel production will be greater. Converting methanol to MTBE and blending it into gasoline lowers the effective octane of the resulting MTBE/gasoline mix relative to the methanol feedstock. Accordingly, the efficiency of the vehicle optimized for the clean gasoline will be less than for methanol, causing more energy to be used as the vehicle moves. This also will increase greenhouse gas emissions.

While it is critical that specific values be estimated in future research, the physics of the substitution makes it certain that use of methanol-derived MTBE as a constituent of clean gasolines will lead to greater emissions per vehicle-mile than if the methanol (or the natural gas feedstock) were used directly in the vehicle. Thus, the speculative value presented in Figure 6.2 implies that use of MTBE in gasoline will increase emissions, but the magnitude of the effect remains to be determined. DeLuchi (1991) has recently presented an estimate that the effect is slight, on the order of a few percent.

Note that a relatively wide long-term swing in emissions is possible. If natural gas used to produce MTBE were instead used in a compressed-natural-gas vehicle with limited range and acceleration, as characterized by DeLuchi et al. (1989), then the compressed natural gas vehicle would cause 19% less greenhouse gas emissions per mile. Use of compressed natural gas or natural-gas-based methanol in "performance equivalent" vehicles dedicated to use of the single fuel could also offer moderate advantages compared with using MTBE blended into gasoline. In any of these cases, the emission advantage would also translate into an energy conservation advantage, allowing natural gas reservoirs to provide more miles of vehicular travel before exhaustion of the reservoir.

The relationships discussed above and presented in Figure 6.2 imply that great reductions effects cannot necessarily be obtained by substituting alternative natural-gas-based fossil fuels such as compressed natural gas or methanol for gasoline refined from crude oil. However, they also imply that turning natural gas into the wrong types of transportation fuel could, over the long run, cause increases in emissions. The "wrong" fuels, from the greenhouse gas emissions perspective, are MTBE from natural gas and especially gasoline from natural gas. The economic incentives to introduce a natural-gas-based transportation fuel or fuel extender at this time are substantial. The desirability of the added processing step and capital expenditure for the MTBE plant will be a function of whether methanol or MTBE is the natural-gas-based transportation fuel of choice. Thus, economic decisions about natural gas transportation fuel are being made now in anticipation of mid-1990s choices of transportation fuels. One of many questions to be asked now is how far governments and industry wish to continue down a natural-gas-to-MTBE path that they may later choose to reverse because of emission concerns.

In addition to the small greenhouse gas improvements possible if compressed natural gas or methanol is substituted for current gasolines, the near-term limits to a fuel substitution strategy involving methanol or compressed natural gas can be further delineated by using Santini's logistic curve equation fitted to the U.S. substitution of oil for coal in the powered ground transportation sector of the U.S. economy (Santini 1989). If natural-gas-based fuels were to substitute for oil-based transportation fuels at the same rate that oil substituted for coal, then to go from 0.5% of the powered ground transportation market to 5% would take about 15 years. To go from 5% of this market to 95% would take about 35 more years. Since 0.5% of the transportation fuel market is not yet held by natural gas, a complete replacement of oil-based transportation fuels by natural-gas-based fuels would be expected to take over 50 years, a time frame far longer than the "near term." Thus, even if the "best" natural-gas-for-crude-oil substitution were made, it would not reduce the emissions enough per vehicle to offset expected economic growth (expansion of population, vehicles, and vehicle use) in the next half century.

The primary point here is that the substitution of the best alternative natural-gas-based fossil fuels for gasoline would be a relatively costly and ineffective proposition as a means to reduce transportation-related greenhouse gas emissions to proposed target levels in the time period being considered.

Diesel Fuel

Another fuel substitution option is the diesel engine for the gasoline engine. An equivalent performance diesel engine can obtain about 30% better mpg fuel economy than a gasoline engine. However, because there are more Btu per gallon of diesel fuel, the energy efficiency advantage is significantly less than the mpg advantage. Unnasch et al. (1989) estimate that the energy advantage in the vehicle is about 15%. Further, since diesel fuel is carbon rich, there are more carbon dioxide emissions per Btu from diesel fuel, resulting in an estimate that diesels emit about 88% of the carbon dioxide per mile that gasoline vehicles do. After accounting for the effect of nitrous oxide and methane emissions, Unnasch et al. (1989) estimate that diesel engines have about 20% lower emissions than gasoline engines.

Diesel engines for passenger cars failed in the United States. Although they increased to 6.8% of the new car market in 1980, passenger diesels dropped to almost zero in 1988 (Flax 1989). This failure was the result of several factors: diesel engines failed to exhibit the expected reliability; both gasoline and diesel prices dropped sharply; and the gap in prices between diesel fuel and gasoline closed as motor fuel taxes were levied on diesel fuel. Particulate emissions standards also became too tight for the diesel engine. Nevertheless, diesels could easily be reconsidered again in the future if fuel prices rise as high as projected in the National Energy Strategy study. Further, if congestion increases and average speeds of driving in urban areas drop, the inherent and pronounced advantage of the diesel at idle and low speed (SAE 1981a) could lead to its revival.

The diesel's major advantage--fuel efficiency--is offset by several drawbacks, including cost, noise, and odor. Diesels are used in Europe partially because considerably higher taxes on gasoline create an economic incentive to use the more efficient fuel (SAE 1981a). Given the National Energy Strategy projections of a rising share of diesel fuel use in the national mix of transportation fuels, primarily because of demand by heavy trucks, it is doubtful that enough diesel fuel would be left from the national refinery product mix to allow substantial use of diesel fuel by passenger cars.

A Note on Fuel Switching

Santini's theory implies that a switch from one fuel to another is more likely to cause a depression in the vehicle manufacturing industry than is a jump in efficiency using the same fuel (Santini 1988). If this theory is correct, it implies that policies promoting fuel switching should be followed somewhat more reluctantly than ones promoting more efficient use of the same fuel. Santini's (1989) more recent statistical analysis of the effects of the process of fuel switching supports the theoretical model's prediction that fuel switching causes a contraction in the affected transportation sector and also supports the argument that contractions in the largest transportation sectors in the economy cause contractions in the economy as a whole. On a more optimistic note, Santini's empirical findings indicated that the problematic contractions did not occur until the new fuel had about a 50% share of the new vehicle market, and the affected market had to be large to have macroeconomic effects. Thus, a "market niche" sequence of progressive fuel switches in small segments of the overall transportation system should allow a smooth long-term aggregate switch of fuels without economy-wide disruption.

6.1.3 Mode Switching to Reduce Carbon Dioxide

The amount of fossil fuel consumed can also be reduced by adopting transportation modes that use less fossil energy per person-trip or per ton-mile. Options such as walking and bicycling do not require any fossil fuels. The need to travel may also be reduced by inducing adoption of telecommunications as a substitute. This section discusses opportunities for three mode-switching options: switch truck freight to rail, switch intercity air travel back to passenger cars, and switch short air trips to Maglev systems. The feasibility of altering the size mix of existing personal vehicles is discussed in Appendix F.

Freight: Heavy Truck to Rail

The projected growth of fuel use for freight purposes is concentrated in trucks (Mintz and Vyas 1991). As previously noted, the potential to reduce fuel consumption by trucks in freight hauling is physically limited by the high percentage of freight weight in the total loaded vehicle weight. Vehicle downsizing, which has been very effective for light-duty vehicles, has no effect on the freight weight that needs to be hauled. Further, sacrifices in acceleration, which are possible with light-duty vehicles, have already been made in the case of trucks. Further sacrifices in acceleration would jeopardize safety in mixed traffic. Finally, regulations requiring sharp reductions of particulate emissions from heavy-duty trucks appear to require particulate traps, which will incur a fuel consumption penalty of 3% to 4% (Needham et al. 1989). Two other factors that will tend to limit the effective increases in the highway fuel economy of trucks are the anticipated increases in congestion and the deterioration of highway surfaces.

One alternative to the truck on the highway is the truck on the railroad. On routes such as Detroit to Atlanta, truck trailers hauled by locomotives now are competing directly with trailers hauled by trucks (Keefe 1989). Citing General Motors' experience, Sobey (1988) indicated that freight hauled on a "RoadRailer" (a trailer designed to be hauled by rail or by truck) requires 20% of the energy required when the same freight is hauled by truck. This relationship of energy use per ton-mile for trucks and rail is about the same as that estimated by the TEEMS model. The RoadRailer technology is argued to be suitable for just-in-time manufacturing (Callari 1987). On many routes, the RoadRailer is also faster than trucks on highways, but is obviously not suited to small, dispersed manufacturing sites. Nevertheless, this technology, used in an integrated rail and local highway delivery system, clearly shows the most promise for reducing energy use in hauling freight in truck trailers.

Individual Travel: Air to Passenger Car or Rail

Study of freight energy-intensity information (Mintz and Vyas 1991) shows that air travel is far more energy-intensive than trucks or rail. However, the total weight of air freight and the total energy used are relatively minor. The vast majority of air transportation energy is devoted to passenger travel. On the average, U.S. passenger cars carry about 1.2 passengers per vehicle mile. This is less than 33% of the average capacity of passenger cars and trucks. Aircraft operate at a higher load factor, consistently above 50%.

On the average, the energy required to carry a passenger by car or air is about the same value. However, much of the use of the automobile is not directly competitive with aircraft (e.g., commutes and shopping trips). Thus, an appropriate comparison of aircraft and automobiles should consider the load factor for passenger cars on trips that might logically have been taken by air. Long trips taken by car were assumed to involve an average occupancy of 2 persons. Under such circumstances, the energy consumption per passenger for a car is almost half that for an aircraft. Thus, mode switches from air to passenger cars could reduce the energy consumption in the air transportation sector. Depending on the effects of altitude on greenhouse gas emissions, this mode switch should also reduce emissions.

As was the case with freight, rail is less energy-intensive than highway vehicles, so use of railroads for passenger trips would also reduce energy use and emissions. Johnson (1989) estimated that Maglev systems would use less energy than aircraft, but about the same amount as passenger cars with two passengers. However, Maglev systems would use electricity rather than petroleum-based fuels. Consequently, emissions would be a function of the type of electricity used to power the Maglev system. Similarly, an electric rail system in an area where nuclear power provided most of the baseload power would generate less emissions than aircraft.

6.1.4 Conclusions

In view of anticipated growth in population, personal income, vehicle ownership, personal miles of travel, and freight generation from industrial output and goods delivery, a policy promoting substitution of alternative fuels may not significantly affect greenhouse gas emissions. In addition, incremental modifications of gasolines through addition of MTBE should slightly increase effects per mile of gasoline vehicle travel (DeLuchi 1991).

Given a repeat of historical rates of fuel substitution, the emission effects (whether positive or negative) of substitutions of new transportation fuels are likely to be relatively small in the near term. Given the NES projections of current trends in transportation fuel use by mode and function, it appears likely that the only way to achieve emission reductions from the U.S. transportation system is to combine increased vehicle efficiency and the substitution of more energy efficient modes for those projected to experience rapid growth. An unpleasant complement to, and possible side effect of, these changes would be a slowing of U.S. economic growth.

6.2 NEAR-TERM OIL-BASED TECHNOLOGIES FOR IMPROVED FUEL ECONOMY

In this section the feasibility of reducing carbon dioxide emissions from motor vehicles by achieving higher mpg per vehicle is examined. However, it should be noted that mentioning various technologies and their ability to improve fuel economy is not an endorsement of *any* of the values claimed by the authors of the various studies, nor is it intended to indicate that all technologies could be applied to all vehicles or that the items in the following tables reflect a complete listing of fuel economy technologies.

The Department of Transportation (DOT), which has rulemaking responsibility in this area, is currently undertaking an analysis of feasible future fuel economy levels and has contracted with the National Academy of Sciences to analyze, among other things, the technological potential to improve light-duty fuel economy over the next decade. The Academy is due to complete its report by the end of calendar year 1991. The technologies and values shown in Tables 6.1 through 6.6 are listed solely to describe the range of fuel efficiency enhancing actions which could be taken and an order of magnitude estimate of their ability to reduce fuel consumption. The Academy's study will be used by DOT to help develop the Administration's views on the need for higher automobile fuel efficiency.

According to Amman (1989), improved fuel economy is "the only way to decrease the emission of carbon dioxide from automotive vehicles operated on gasoline." A complete examination of this subject would include passenger cars, trucks, aircraft, rail, ships and towboats, pipelines, and off-road vehicles. At this time, the information included covers only automobiles and trucks, with the greatest detail being provided for automobiles and light trucks. Information from several primary sources of information is summarized here: the book entitled *The New Oil Crisis and Fuel Economy Technologies* (Bleviss 1988); the report entitled *Characterization of Future Flexible Fuel Vehicle Attributes* (EEA 1988); the report entitled *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes* (EEA 1990); the report entitled *Potential for Improved Fuel Economy in Passenger Cars and Light Trucks* (SRI 1991); the paper entitled "Cost Effectiveness of Future Fuel Economy Improvements" (Difiglio et al. 1990); the "product/specifications" table from the *1988 and 1990 Market Data Book* (Automotive News 1988); the report entitled *Gas Mileage Guide* (DOE 1988, 1990b); and automotive product brochures and manuals.

Tables 6.1 through 6.6 provide information compiled from Bleviss (1988), Energy and Environmental Analysis,[(a)] and SRI International (SRI 1991), listing technologies that can improve vehicle mpg. This list has been compiled without critical review. Those technologies listed that did not include or allow an estimate of percentage improvement in fuel economy were not included in these tables. The quoted values are often from a secondary source. Generally original estimates are from vehicle manufacturers.

Bleviss, an advocate of relatively aggressive governmental efforts to promote fuel efficiency, generally gives the most optimistic estimates of the potential gains from various fuel economy technologies. EEA, a contractor to Oak Ridge National Laboratory, and SRI International, a contractor to the Motor Vehicle Manufacturer's Association, give generally similar estimates, with the SRI values being least optimistic overall. As discussed below, improving the fuel economy potential of a vehicle component by a given percentage does not mean that the actual fuel economy will be improved by that percentage if the technology is applied. Very often the improvement is devoted instead to improved performance. Sometimes, synergistic

(a) Energy and Environmental Analysis. (EEA). 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.

Table 6.1. Technologies for Improving Power and/or Efficiency: Gasoline Engines

Technology	Estimated Fuel Economy Gain (%)		
	Bleviss	EEA	SRI
Variable Valve Timing	10-20	6.0	2.6 (USC)[(a)]
Variable Valve Timing & Compression Ratio	NE[(b)]	14 (EU)	NE
Variable Engine Displacement	11 (USU)	NE	NE
Variable Turbocharger	11 (EU)	NE	NE
Turbocharger	NE	NE	5.0
Supercharger	5-13	NE	8.0
Dual Cooling Circuits	5-10	NE	NE
Electronic Temperature Control	5	NE	NE
Ultra-Lean-Burn	8-20	5-6	8.0
Compression Ratio up 0.5 units	NE	0.5	2.0
DAB Lifter for Hydraulic Lifter	NE	NE	1.5
Special Lubricants	NE	0.5	0.3
Friction Reduction	NE	2.0	2.0
Deceleration Fuel Shutoff	NE	NE	1.0
Overhead Camshaft (OHC) for Pushrod	NE	3.0	2.5
4 Valves for 2 Valves in OHC Engine	NE	5.0-8.0	2.6-3.0
Throttle Body Injection (TBI) for Carburetor	NE	3.0	2.6
Multiport/Sequential Fuel Injection for TBI	NE	3.0	2.0-4.0
Advanced Pushrod	NE	3.0	NE
Roller Cam Followers	NE	2.0	1.0-2.3
Split Port	NE	NE	2.6
Retuned Standard Intake	NE	NE	0.5
Reduced Cylinder Count	NE	NE	0-1.0

(a) If the driving cycle is specified, a notation on the type of cycle is given, as follows: USC = US combined city and highway cycle; H = US highway cycle; USU = US city (urban) cycle; EU = European Community cycle (an urban cycle); JU = Japanese city (urban) cycle.
(b) NE = comparable value not estimated or estimable from information given.
Sources: Bleviss 1988; SRI 1991; EEA (Energy Environment Analysis. 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.)

benefits are possible. The most important example of this is in the use of an improvement in the specific output of an engine technology. Such an improvement can allow the the size of the engine to be reduced in a vehicle of given interior volume, allowing a reduction of engine and vehicle weight while retaining the same level of performance and amount of useful space.

Often, however, there is a tendency by engineers working on a technology to report an optimistic contribution for the technology. For example, a

Table 6.2. Technologies for Improving Power and/or Efficiency: Diesel Engines

Technology	Estimated Fuel Economy Gain (%) Bleviss	EEA	SRI
Naturally Aspirated Indirect Injection (IDI) Diesel for Gasoline 2-valve	NE[(a)]	15-18	NE
Turbocharging Indirect Injection Diesel	NE	5-11	NE
Direct Injection for Indirect Injection	10-26	12-15	NE
Stratified Charge for Indirect Injection	15 by GM	NE	NE
Electronic Controls	10 @ 60 km/hr	NE	NE
10% Friction Reduction	NE	5 @ low load	NE
Flywheel Engine Stop/Start	7 (EU & JU)[(b)]	6	NE

(a) NE = comparable value not estimated or estimable from information given.
(b) If the driving cycle is specified, a notation on the type of cycle is given, as follows: USC = US combined city and highway cycle; H = US highway cycle; USU = US city (urban) cycle; EU = European Community cycle (an urban cycle); JU = Japanese city (urban) cycle.
Sources: Bleviss 1988; SRI 1991; EEA (Energy and Environmental Analysis. 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes.* Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.)

reduction of fuel consumption at idle or an improvement in EPA city fuel economy will not necessarily lead to the same improvement in combined EPA fuel economy. Consequently, to improve combined EPA fuel economy ratings by a given percentage, it will be necessary to improve either the city or highway fuel economy of the vehicle by a greater amount than the combined amount, or to improve every contributing component by a similar amount. Also, EPA test results are not the only mileage results that consumers will use to decide on a vehicle. *Consumer Reports* tests vehicles by operating them and recording the on-road results. The 195-mile test trip results used by *Consumer Reports* consistently give higher fuel economy results than EPA's highway test, and the city driving tests used by *Consumer Reports* consistently give mpg results lower than EPA's city mpg test (Markovich 1989).

Efficiency-enhancing alternatives can be mutually exclusive. For example, the continuously variable transmission (CVT) in the 1989 Subaru Justy clearly improves city fuel economy more than highway fuel economy. The advantage of the CVT is a continuously adjustable belt system that allows for some slippage. According to statistical estimates developed by Poyer and Santini (1990), four-speed lock-up transmissions provide a statistically significant improvement in highway fuel economy, but not in city fuel economy. This result is similar to that of Berger et al. (1990), whose combined coefficients for a four-speed and lockup also imply gains in highway fuel economy, but not city economy. The advantage of the lock-up transmission is that it almost completely eliminates slippage in high gear by "locking up" the transmission and driveshaft. The belt system on a CVT is not amenable to a

Table 6.3. Technologies to Improve Drivetrain Efficiency

Technology	Estimated Fuel Economy Gain (%)		
	Bleviss	EEA	SRI
Advanced Lock-Up Clutch	6-18	NE(a)	NE
4-Speed Lock-Up for 3-Speed Automatic	NE	7.5	2.8
4-Speed Lock-Up for 3-Speed Lock-Up	NE	NE	1.1
Increased Gears and Ratio Range	6 (JU), 8 (H)(b)	NE	NE
Electronic Transmission Control	6.6 (JU)	0.5	0.5-2.5
Fifth Speed with Automatic 5-4 Shifts	5 (H)	2.5	0.5
Sixth Speed over 5-Speed Automatic	NE	2.0	NE
Continuously Variable Transmission (CVT)			
CVT vs. 3-Speed Automatic	10-20	10	4.8
CVT vs. 4-Speed Lock-Up Automatic	NE	2.5	2.0
Front-Wheel for Rear-Wheel Drive	NE	5.0	0.5

(a) NE = comparable value not estimated or estimable from information given.
(b) If the driving cycle is specified, a notation on the type of cycle is given, as follows: USC = US combined city and highway cycle; H = US highway cycle; USU = US city (urban) cycle; EU = European Community cycle (an urban cycle); JU = Japanese city (urban) cycle.
Sources: Bleviss 1988; SRI 1991; EEA (Energy and Environmental Analysis. 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.)

lockup capability. Also, CVT belts take a great deal of stress and, at present, cannot take the stresses that occur in large cars. Thus, as a result of current engineering realities, the lock-up transmission makes more sense on a large car likely to be driven many highway miles, such as a family car intended for vacations, while a CVT makes sense in a small urban commuter car. The choice in this case is an either/or choice. In many cases, however, technologies to improve fuel economy can be added in "layers" to get better and better fuel efficiency.

When a potential percentage improvement in fuel economy is claimed, one should always ask, "Compared with what?" The CVT is an example. Bleviss (1988) cites a 10% to 20% fuel economy improvement for this technology. However, in 1988 in the United States, the only transmission available in a Subaru Justy had five forward speeds and was rated at 37 mpg city and 39 mpg highway. In 1989, the CVT became available in addition to the five-speed transmission. In 1989, the city mpg of the five-speed transmission was 34, the same as for the

Table 6.4. Technologies to Reduce Weight and Effects of Weight Reduction

Technology or Scaled Change	Estimated Fuel Economy Gain (%) Bleviss	EEA	SRI
Fuel Economy Improvement per 10% Reduction in Weight	7-8 City 4-5 Highway	5.4-6.4[(a)]	5.0
Aluminum Body	4-8	NE[(b)]	NE
Implied Car Weight Reduction Effects			
1% Reduction	≈0.6	0.54-0.64[(a)]	0.5
10% Reduction	≈6.0	5.4-6.4[(a)]	5.0
26% Reduction	≈15.6	14.6-16.6[(a)]	13.0
Light Valve Train	NE	NE	0.5
Aluminum for Iron Engine Head	NE	0.4-0.7[(a)]	1.0-1.5
Aluminum for Iron Engine Block	NE	1.5-1.8[(a)]	1.5
Magnesium Transmission Housing	<0.4[(c)]	NE	NE
Plastic Engine for Iron Block/Aluminum Head Engine	NE	2.6-3.9[(a)(d)]	NE

(a) Upper value assumes that the engine is also downsized, holding horsepower per pound of vehicle wight constant.
(b) NE = comparable value not estimated or estimable from information given.
(c) Uses EEA estimate of share of weight in drivetrain.
(d) Uses EEA estimate of engine weight share and engine weight reduction.
Sources: Bleviss 1988; SRI 1991; EEA (Energy and Environmental Analysis. 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.)

CVT, while the highway rating of the five-speed transmission was 37, which is 2 mpg better than the CVT's 35 mpg. Thus, while the CVT offers an improvement in fuel economy relative to an automatic transmission, it does not get better fuel economy than a manual transmission. In the case cited, the introduction of the CVT might have contributed to a reduction in the Subaru Justy's fuel economy.

These two examples illustrate the fact that the numbers presented in Tables 6.1 through 6.6 must be read with caution. The basis of comparison is very important. Further, several of the listed technologies are mutually exclusive, while many already have a significant share of the market. Consequently, the technical potential for fuel savings is likely to be *far* less than the sum of values in those tables.

6.2.1 Passenger Cars and Light Trucks

The technologies examined in Tables 6.1 through 6.6 relate primarily to passenger cars and

Table 6.5. Technologies to Reduce Rolling and Aerodynamic Resistance

Technology or Scaled Change	Estimated Fuel Economy Gain (%) Bleviss	EEA	SRI
Injection-Molded Polyurethane Tires	10	NE[a]	1.0
10% Tire Rolling Resistance Improvements	3-4	2.3	1.0
Potential Tire Improvement by 2010	NE	>0.5	NE
10% Aerodynamic Drag Reduction	2-3% USU[b] 5-6% H[b] ≈3-4% USC[b]	2.2	2.4
Model-Specific Potential Drag Reduction	NE	1.1-4.6	NE

(a) NE = comparable value not estimated or estimable from information given.
(b) If the driving cycle is specified, a notation on the type of cycle is given, as follows: USC = US combined city and highway cycle; highway cycle; USU = US city (urban) cycle; EU = European Community cycle (an urban cycle); JU = Japanese city (urban) cycle.
Sources: Bleviss 1988; SRI 1991; EEA (Energy and Environmental Analysis. 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.)

Table 6.6. Accessory Improvements

Technology	Estimated Fuel Economy Gain (%) Bleviss	EEA	SRI
Improved Alternator	0.7 to 3	NE[a]	NE
Electric Power Steering	4-8 @ 25mpg	1.0	1.4
2-Speed for 1-Speed Accessories	NE	NE	0.7

(a) NE = comparable value not estimated or estimable from information given.
Sources: Bleviss 1988; SRI 1991; EEA (Energy and Environmental Analysis. 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.)

light trucks. The three primary means of improving fuel economy are engine efficiency (Tables 6.1 and 6.2), drivetrain efficiency (Table 6.3), and weight reduction (Table 6.4). Smaller gains are possible through reduced rolling resistance in tires (Table 6.5) and increased efficiency of accessories such as air conditioners, alternators, and power steering (Table 6.6). Very expensive long-term options include flywheel storage (Table 6.2), a technology that should be particularly attractive for diesel-powered urban vehicles that stop and start very frequently. However, it is technically unsuitable for gasoline vehicles. In the event that congestion worsens substantially, the diesel flywheel storage technology, which shuts the engine off when it would otherwise be idling, could become comparatively attractive. Note that the diesel has a comparative advantage over the gasoline vehicle in congested conditions, even without the flywheel technology.

Engine Efficiency

The technologies Bleviss cites for improving gasoline engines (Table 6.1) are variable turbochargers, pressure wave superchargers, variable engine displacement, variable valves, dual cooling circuits, electronic temperature control, and ultra-lean burn. Supercharging has recently been introduced as a performance enhancing technology; variable valve timing has been introduced on some luxury cars; and "variable engine displacement" (turning cylinders off during low engine load) was tried in the early 1980s by Cadillac and dropped because of reliability problems. A problem with variable engine displacement is differential thermal loading between the cylinders that are on and off. Variation of thermal stresses within the engine block increases substantially with this technology. Compared with the technologies cited by EEA and SRI, Bleviss' estimates are optimistic implying big gains with few technologies. EEA and SRI present estimates for more numerous technologies, each offering a smaller contribution.

Various forms of fuel injection have been adopted over the last few years. *Automotive News* passenger car specifications tables list four types of fuel injection: electronic, throttle body, sequential, and multipoint. Difiglio et al. (1990) list throttle body and multipoint fuel injection, indicating that the less efficient throttle body fuel injection had 24% of the passenger car market in 1987, while the more efficient multipoint type had 48%. EEA and SRI estimate that adoption of throttle body fuel injection over carburation increased efficiency by about 3%, while switching to multipoint fuel injection added about another 3%. Most of these gains have already been implemented.

Technologies cited for diesel engine efficiency improvement (Table 6.2) are electronically controlled diesels; direct injection diesels (which have environmental problems); and a stratified charge diesel. The adiabatic diesel, once thought promising, has so far failed to live up to early expectations (Needham et al. 1989; Amman 1989). Amman's summary article lists the *potential* for improvement at 4% and notes that even the 4% has not been confirmed experimentally. Reporting on research by Ricardo Consulting Engineers, Needham et al. reported that experiments with a single-cylinder low-heat-rejection diesel, when optimized for emissions reduction, resulted in a fuel economy *penalty* of 9%. Electronic controls for diesels (Table 6.2) are now being implemented by manufacturers. The most optimistic fuel efficiency estimates presented by Bleviss and EEA rely on the use of diesels. Thus, the most optimistic energy conservation technologies can only be introduced with a fuel switch.

Drivetrain Efficiency

Technologies listed for improving drivetrain efficiency include various combinations of advanced lockup clutches, extra speeds for transmissions, electronic controls, and gear ratio changes. Belt-driven CVTs are also included. Many new cars with automatic transmissions already have lockup clutches in the high gear, while many of the newer automatic transmissions have four speeds rather than three. Five- and six-speed automatics are now available on a few cars. Gear ratio changes have long been an option for gaining fuel efficiency, as have more speeds in transmissions. A very good example of experimental estimation of these relationships can be found in Weidemann and Hofbauer (1978). In that case, an approximate 40% decrease in final top gear drive ratio led to about a 17% increase in highway fuel economy.

The CVT is currently an option only on cars with low inertia weight. If sharp weight reductions were implemented in the future, it would probably see widespread use. The CVT was made available by Subaru in the 1989 Justy model and is advertised for its ability to improve acceleration in comparison to a "conventional automatic." Unfortunately, in *Consumer Reports'* 1991 Annual Auto Issue (April 1991), subscribers who owned the Justy CVT caused its rating to be "much worse than average." It should be noted, however, that the introduction of ultimately successful new technology is often initially accompanied by poor reliability.

Weight Reduction

Bleviss (1988, Table 3-2) gives a number of examples of prototype passenger car models whose design objective was to improve fuel economy primarily through weight reduction. Four of the 11 models Bleviss cites have gasoline engines--the rest use diesels. Two of the 11 are products of American manufacturers. The four gasoline models are the TPC of General Motors, the ECV-3 of British Leyland, the VESTA-2 of Renault, and the ECO 2000 of Peugeot. The average EPA combined fuel economy of these four vehicles is about 70 mpg and the average number of passengers these cars can carry is about 3.5 persons. The weight-reducing materials substitutions cited in Table 6.4 include use of plastics, aluminum, and magnesium.

Effects of Other Regulatory Actions

EEA[a] asserted that new safety and emissions standards expected in the 1987-1995 time frame can be expected to cause a 3% decline in fuel economy.

6.2.2 Heavy-Duty Vehicles

In its National Energy Strategy analysis, Argonne National Laboratory assumed relatively little percentage improvement in fuel efficiency for heavy trucks and railroads compared with that for light-duty vehicles. Duleep (1991) has also estimated that the potential gains in fuel economy for heavy trucks are well below those of passenger cars and light trucks. The base scenario projected a 22% improvement in the efficiency of hauling freight by heavy and light trucks from 1985 to 2010. Heavy truck fuel economy is projected to increase by 14%, while commercial light truck fuel economy is projected to increase by 38% (see Mintz and Vyas 1991). The annual miles traveled of most heavy trucks and locomotives are so great that the most fuel-efficient technologies are found to be economical at higher first cost than for light-duty vehicles because the savings accrue much faster. Accordingly, advanced technologies are found in heavy trucks before they are found in light trucks and passenger cars.

One reason that light-duty vehicle purchasers do not purchase economically efficient technology, considering market interest rates and full vehicle life, is the tendency of the new vehicle purchaser to hold the vehicle only for a limited percentage of the miles of its life (Difiglio et al. 1990). In the case of heavy trucks and locomotives, purchasers, who are businesses, would likely hold the vehicle for a far

(a) Energy and Environmental Analysis. (EEA). 1990. *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*. Draft Final Report. Energy and Environmental Analysis, Arlington, Virginia.

larger proportion of its useful life and would, in any case, apply pure economic reasoning to the selection process to a greater degree than would households.

A second problem in the case of households is the high percentage of households that drive a limited number of miles per year, making expenditures on fuel efficiency less of a virtue than if the vehicle were used intensively. Businesses would probably schedule the use of the vehicle with multiple drivers such that most new vehicles are driven frequently. With an assumption of consistent intensive use, one can expect average business purchasers to be willing to pay more for fuel efficiency than households would. Consequently, an argument cannot be made for regulation of business purchasers on the basis of an assumption that a substantial increase in fuel efficiency is justifiable because of probable departures from the best technology available. One cannot expect as much "slack" in the technology with which fuel efficiency can be improved. However, the Btu used per ton-mile of freight hauled by heavy truck is about five times as great as that for rail, while freight in aircraft is estimated to be five times more energy-intensive again (Mintz and Vyas 1991). Of course, to the consumer of transportation services, energy is only one of the values affecting the merits of a mode of shipping.

Heavy Class-8 trucks were switched to diesel fuel for fuel efficiency purposes after World War II and are now almost exclusively diesel-fueled. Turbocharging to improve efficiency has since become predominant in heavy-duty diesel compression ignition engines; the technology has had limited use in passenger cars. Further, the use of four valves per cylinder is probably more common in new heavy-duty direct-injection diesel compression ignition engines sold today than is two valving. According to the Southwest Research Institute,[a] the efficiency gained by adding four valves to current turbocharged two-valve compression ignition engines is very small, partly because better port design has been emphasized in such engines. As a result, the better inlet airflow needed to improve efficiency has been obtained.

In any case, the state of technological development and the complexity of U.S. heavy-duty compression ignition engines is clearly well in advance of that for light-duty spark-ignited engines, as one would expect from economic considerations alone. Accordingly, further percentage efficiency gains can be expected to cost more for heavy-duty engines than for light-duty engines.

Environmental legislation and high energy prices in the 1970s led to turbocharging of diesel engines to reduce fuel consumption, reduce rated speeds, and lower specific weight of the engine (SAE 1981b; Anderton and Duggal 1975). In gasoline engines, turbocharging an engine of a given displacement leads to a substantial increase in fuel consumption. In contrast, turbocharging a diesel direct-injection compression ignition engine of a given displacement can both increase power and decrease specific fuel consumption, while also lowering the engine speed at which peak power can be obtained (Anderton and Duggal 1975); also compare turbocharging effect estimates in Tables 6.1 and 6.2. The potential improvement in efficiency at lower operating speed of these engines was found to create a transitional problem for drivers at one trucking company. Because drivers had become used to operating engines at 2,100 rpm, they failed to operate the new fuel-efficient engines at the required 1,500 to 1,600 rpm until a training program was instituted (Millian and Broemmer 1981).

A number of fuel efficiency technologies are steadily working their way into the heavy-truck fleet, including fan clutches, radial tires, aerodynamic devices (wind deflectors and reshaped cabs), smoothside trailers, and variable opening radiator covers to avoid overcooling in winter (compare this latter technology to the "dual cooling circuit" technology in Table 6.1). Much of the economic gain from these technologies has already been achieved. The Pauls Trucking Company reported fleet fuel economy gains from 1973 to 1981 of 3.8 to 5.6 mpg.

(a) Personal communication with C. D. Wood, October 30, 1989.

Oil and diesel fuel prices peaked in 1981 and dropped thereafter. In 1985, the national estimate of Class-8 truck fuel economy was 5.8 mpg.

A theme of the 1981 Society of Automotive Engineers' (SAE) report on voluntary efforts to improve truck and bus fuel economy was the need to use driver training to realize some of the fuel savings technically achievable with new technologies (SAE 1981c). Another theme in that publication was the lack of concern for fuel economy by owner-operators. In 1981, when real fuel prices were at their peak, anecdotal evidence implied that many owner-operators still purchased decorative features rather than fuel-efficient technologies. Driver education programs that proved successful for corporations included reporting results and creating peer pressure to achieve good fuel consumption. In the article on owner-operators, the effects of the CB radio and on-road peer pressure to speed were cited as causes of poor fuel economy. Another point involved the energy needed to stop and accelerate at toll booths. In the case of heavy-duty trucks, the experts' estimates in the Patterson (1989) survey implied that government promotion of driver training could save 0.10 quads over the free market case.

In the near term, the 1991 and 1994 particulate emissions standards for heavy-duty engines are creating extreme pressures on engine designers (Needham et al. 1989; Wood).[a] According to Needham et al. (1989), even a number of technological innovations and fuel modifications improving combustion and reducing lubricating oil consumption may not be sufficient to meet the 1994 standard, thereby requiring use of the particulate trap, a costly aftertreatment device that is estimated to reduce fuel economy by 3% to 4% in urban operation.

Wood,[a] whose views are cited in the remainder of this paragraph, notes that engine customers and designers see the particulate trap as a performance-robbing device that is likely to cost a few thousand dollars. The view is that a considerable amount of technological innovation improving the engine could be bought with those few thousand dollars, so research on technical improvements to the engine is receiving substantial attention. To meet the 1991 standards, the addition of intercooling to all heavy-duty engines is very likely. A zero to 2% mpg improvement should result at a cost of up to $1,000. Air-to-air intercoolers should give the best gains, but are most costly, perhaps as much as $1,000. Water-to-air intercoolers, which take up less space, are a second-best solution and cost a few hundred dollars. Improved fuel injection systems will receive a great deal of emphasis to meet the more stringent 1994 standards. Computer-controlled electromechanical injection pumps for the direct-injection diesel engine are being investigated and show great promise for emissions reduction, but at an estimated mass-produced cost of $1,500 to $2,000. Although the new fuel injection systems are being considered for emissions reduction and little fuel economy gain is anticipated by 1994, some learning about possible improvements in fuel efficiency is likely to occur. Twin turbochargers and intercooling systems, which will lower cylinder inlet air temperature to near the freezing point of water, are also being examined. Friction reduction and improved port design are two other areas where some small efficiency gains may be expected in the future. Unfortunately, it is possible that all of the fuel economy gains through regulation-forced improvement in heavy-duty engines could be lost if the technological improvements cannot reduce emissions to the 1994 standards. In that event, particulate traps may be necessary and any fuel economy gains obtained as side effects of the effort to meet the standard could be wiped out by the fuel economy penalties of particulate traps.

The experts Patterson surveyed also projected a gain in efficiency of engines as a result of government intervention: a reduction of 0.19 quads due to adiabatic diesels, gas turbines, and ceramic parts. Ceramic parts are critical to the success of the gas turbine. Amman (1989) has noted the poor fuel consumption of the idling gas turbine as a

(a) Personal communication with C. D. Wood, Southwest Research Institute, October 30, 1989.

drawback, but in certain over-the-road truck applications where cruising is predominant, this would not be much of a drawback. The absence of evidence to support earlier claims for 25% to 30% efficiency gains for the adiabatic (low heat rejection) diesel was noted earlier. Competition for the gas turbine in applications where most of the time is spent cruising include turbocompounding and Rankine bottoming, the two purportedly capable of theoretically achieving about a 10% gain over an intercooled turbocharged diesel (Amman 1989). In light-load urban driving however, the turbocompounding technology penalizes fuel consumption (Amman 1989), so it is likely to be a very specialized technology for limited markets. In the Patterson survey, government incentives to use more aerodynamic devices and radial tires were estimated to create an additional 0.15 quad of savings.

In total then, the incremental improvement the government has projected to be able to support through behavior modification, more efficient engine technology, better tires, and better aerodynamics was about 0.44 quads. In percentage terms this was a greater gain than the experts projected for government intervention into light-duty vehicle technology development. The seriousness of the problem of growing truck traffic makes this a key point of that survey.

The experts' estimation of the potential effect on oil savings through government intervention in fuel substitution was similar, amounting to 0.5 quads for heavy trucks and fleets. This savings included the use of methanol, electric vehicles, hybrid vehicles (electric plus fossil fuel), and compressed-natural-gas vehicles. The predominant contribution was from promoting methanol use, amounting to 0.34 quad. This 0.34 quad reduction would be in addition to the 0.14-quad saving projected for the $1.50 per gallon gasoline case in the first round of the Patterson survey, for a total of 0.48 quads of reduction in oil use in heavy trucks and fleet vehicles. If accomplished, this would be a useful reduction in oil use. Consumption of oil-based transportation fuels in heavy-duty trucks and fleet vehicles would be reduced from 6.4 quads in 2010 to 5.9 quads, a reduction of only 7.5%. This reduction, however, could be of little value as far as greenhouse gas emissions are concerned.

The greenhouse gas emission effects of fuel substitution can be positive or negative, depending on the feedstocks, processing efficiencies, and the engine efficiency of the vehicle. Unlike spark-ignited engines in automobiles whose energy efficiency improves when using methanol, a compression ignition engine does not increase in energy efficiency to any notable degree when methanol is introduced. The substitution of methanol for diesel oil fuel in compression ignition engines is less likely to reduce carbon dioxide emissions. The estimates of Unnasch et al. (1989) and DeLuchi (1991) indicate that switching from diesel fuel in compression ignition engines to compressed natural gas or methanol fuel in spark-ignited engines would increase greenhouse gas emissions.

6.2.3 Air Transport Technology

In the projected 1990 to 2010 National Energy Strategy base case, the 1.7 quad expansion in diesel fuel use in heavy trucks greatly exceeded the 0.8 quad expansion in nonmilitary aircraft use of jet fuel. This occurred for several reasons. First, high fuel prices resulted in a projected shift from gasoline to diesel fuel in trucks. If the share of gasoline and diesel fuel had remained the same in 2010 as in 1990, there would have been 0.7 quads less diesel fuel consumed and 0.7 quads more gasoline consumed.

Second, the projected fuel efficiency gains for the aircraft fleet were well in excess of those projected for the truck fleet. From 1990 to 2000, the energy use per air revenue passenger-mile was projected by Argonne National Laboratory to drop by 27%, a percentage drop identical to that of the light-duty vehicle fleet energy use per vehicle-mile. The effects of congestion, however, were anticipated to be even more severe for trucks than for passenger cars because most truck deliveries are projected to occur during peak urban travel periods, while many more passenger car trips will occur during off-peak periods. The Argonne National Laboratory estimate of this effect reduces the gain in efficiency for trucks to a 17% reduction in Btu per ton-mile.

A third reason for the higher growth in diesel fuel use was the fact that rail energy use was projected to increase by 0.4 quads, a reversal of the declining use of fuel by railroads over the last decade. This shift is consistent with historical patterns of distillate use by railroads. Although the long-term trend has been slowly downward, railroads clearly increased their use of distillates in the years of the two major oil price shocks in the last 20 years (API 1990).

The success of air travel relative to other forms of travel is projected to continue in spite of rising fuel costs. Revenue passenger-miles are projected to increase at a rate of 3.3% per year, while vehicle-miles of household travel are projected to increase at an average rate of 1.3% per year. Ton-miles of truck travel are projected to increase at 2.5% per year. The 27% improvement in energy efficiency for household vehicles and aircraft amounts to about 1.6% per year. These efficiency gains offset travel increases in ground transportation (by household light-duty personal vehicles), leading to a reduction in energy use there, but do not offset air travel revenue passenger mile increases, leading to increased demand for jet fuel. Similarly, the efficiency gains for trucks are about 0.9% per year and do not offset increased truck traffic.

Since the Maglev technology (Johnson 1989) was not regarded as on-the-shelf technology, the development times before substantial introduction precluded projection of any fuel substituting technology in the air transportation sector. The ultimate potential of this technology for jet fuel use reduction was estimated to be from 0.26 to 0.37 quads. The first U.S. Maglev routes are already in the late stages of planning. It is likely that a short route will soon begin construction in Orlando to connect the Orlando airport to Disney World, and a more lengthy route from Los Angeles to Las Vegas could begin construction before 2000. Thus, some of the ultimate potential may be realized in the 2000 to 2010 time frame. The level of carbon dioxide emissions that would result depends on the mix of fuels used to generate the electricity to run the Maglev systems.

In the case of air transport technology, Argonne National Laboratory expected a substantial improvement in fuel efficiency in the National Energy Strategy base case. The rate of increase in efficiency per revenue passenger mile for Argonne's projections amounts to about 1.5% per year from 1990 to 2010. This estimate, which is related to rapidly rising real fuel prices, is substantially less than Boeing's (1989) optimistic assumption of a 2% per year gain through 2000 in conjunction with constant real fuel prices. It is also about the same as Argonne's base estimate of a 1.6% per year fuel efficiency gain in automobiles. As a result of good knowledge of potential cost-effective fuel efficiency-enhancing technologies for light-duty vehicles, in Argonne's optimistic scenario the rate of improvement in fuel-efficiency was increased from 1.6% to 2.8% per year. In view of the Boeing's optimism (1989) under a projection of constant fuel prices, Argonne judged that an assumption of an increase in rate of fuel efficiency gain from 1.5% to 2.5% per year would be a reasonable "optimistic" value to use in conjunction with the very high fuel price projections.

A number of technologies could contribute to such a gain in fuel efficiency. The use of fewer, larger airplanes could reduce congestion. Successful development and implementation of a retrofittable ultrahigh bypass ratio engine with counter-rotating advanced propellers for MD-80 aircraft and other aircraft with pairs of fuselage-mounted rear engines could reduce fuel consumption by existing aircraft. Orders for such aircraft, however, have recently been cancelled because the high first-cost of the engines cannot be justified with current fuel prices. Advanced ducted high bypass ratio engines could be retrofit on airplanes using wing-mounted nacelles. Stricter maintenance procedures for older aircraft could cause earlier retirement of older, less fuel-efficient aircraft. Jet fuel taxes for the purpose of building the proposed "wayport" remote airport concept and feeder systems could push less fuel-efficient aircraft out of the market sooner, while reducing congestion in the system.

Even with the optimistic assumption concerning aircraft fuel efficiency gains, the total jet fuel use in commercial passenger aviation increases to 2 quads in 2000 and 2.1 quads in 2010. Relative to Argonne's base case projections, this reduces energy consumption by 0.55 quads, about 20% of the 2.7 quad reduction relative to the base case achieved in the optimistic case for light-duty household and fleet vehicles.

6.2.4 Rail and Marine Technologies

Railroad fuel consumption in Argonne's National Energy Strategy base transportation case was projected to buck the recent declining trend and to expand its share of the market for freight, partly because of its inherent efficiency and partly because of a DRI model projection that industries historically dependent on rail will once more expand in the United States. Because rail uses about 20% the energy per ton-mile that trucks use, Argonne's FRATE computer model projected that the high energy costs of this scenario would force some reversal of the trend toward the "just-in-time" manufacturing emphasis on truck use. Rail gained market share in this case partially because of its inherent efficiency, not because it achieved greater improvements in efficiency than other sectors. In fact, rail was projected to lag in this respect, improving efficiency only at a low rate of about 0.3% per year from 1990 to 2010.

Marine fuel use for freight shipments also was projected by Argonne to increase, but at a lesser rate than for trucks or rail. Jet fuel use to haul freight also increased at about the same rate as for trucks. Pipelines were projected to be the only "freight" category that will not exhibit a continuous increase. Energy use for pipelines rose in the National Energy Strategy base case from 1990 to 2000 and declined thereafter.

There is some basis for reevaluating the pessimistic estimates for marine and rail. For trucks, such technologies as turbocompounding and Rankine bottoming may not make it into the marketplace because they offer improvements only at steady speed and high engine load. Such operating conditions are more common in locomotives and ships, so a greater gain than has been projected may be possible for rail and marine applications. The overall transportation sector error introduced by the pessimism in these two sectors is small.

6.3 LONG-TERM TECHNOLOGY OPTIONS FOR HIGHWAY VEHICLES

The best way to think about long-term engine/vehicle options for reduction of carbon dioxide emissions is to think about the total pathway from energy production to conversion and, potentially, to reconversion. One of the implications of reducing carbon dioxide emissions through the internal combustion engine is that the costs of added units of mpg begin to rise sharply as the 40 mpg value for the existing size mix is approached.

There are three ways to attack this problem. One is to develop new engine/drivetrain technologies that can achieve much higher levels of efficiency (mpg) at a lesser cost than for the continually modified/advanced internal combustion engine. The second is to use substitute fuels for gasoline, a course which can sharply reduce the magnitude of net carbon dioxide emissions per mile from gasoline engines. Some combination of these first two is also possible. The third possibility is to continue to rely on gasoline engines of the types just examined, but to sharply alter the size mix of vehicles and the way that vehicles are used. This last possibility is given the least attention in this report, because, by definition, the orientation is toward a technological solution.

Using a vehicle choice model, Difiglio et al. (1990) estimated that the next decade's technological options for fuel efficiency gains (including some weight reduction for current sizes of vehicles) would be exhausted at 39.4 mpg, and any further gains would have to be met by shifts in the sizes of vehicles. That valuation led to an average estimate of $480 per CAFE mpg gain by shifting sizes to achieve the 7 mpg gain, implying that consumers would pay to avoid switching to smaller cars. Presumably, this also provides a measure of their willingness (or lack of willingness) to accept smaller vehicles to reduce emissions. The numbers used to develop these estimates are from the academic literature and are therefore measures of past preferences of consumers. This leaves open the possibility that the estimates reflect consumers' lack of knowledge of the environmental consequences of their choices, rather than an unchangeable desire for current vehicle sizes. Accordingly, it is reasonable to at least consider the possibility that consumers may in the future become far more willing to purchase smaller vehicles in order to reduce the greenhouse gas emissions associated with their actions. Such a possibility might be realized if ongoing scientific analysis of the effects of emissions reached a solid conclusion that such effects would undoubtedly be severe, and if information on these findings was disseminated to the public.

6.3.1 Much Smaller Vehicles

Before proceeding to a detailed discussion of the former two approaches, a brief examination of the latter is in order, to the extent that it implies emphasis on selected technological pathways. The nature of this report is to discuss the modification of existing light-duty vehicles with little modification of the system in which they operate and little modification of the amount of weight and passenger volume. However, if the scope of thinking is widened to include a modification of the system, as recommended by Garrison (1991), then other options emerge for consideration.

One vehicle option proposed by Sobey (1988) is the "lean machine," essentially an enclosed one- to two-passenger motorcycle-sized three-wheel vehicle that leans into turns. Sobey's estimate of the potential of such a vehicle to improve fuel economy, at different levels of performance, is illustrated in Figure 6.3.

Sobey estimates that a lean machine with the acceleration of an economy car would be capable of well over 100 mpg, without an air conditioner.

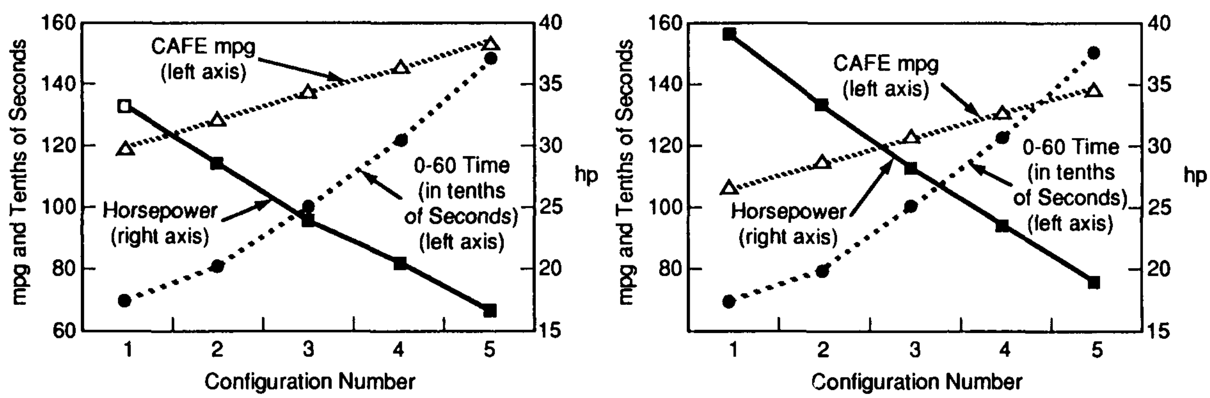

Figure 6.3. Performance and Fuel Economy Tradeoffs for Single- and Double-Occupant "Lean Machines," No Air Conditioning

When it has the acceleration of a performance car and an air conditioner (not shown), its fuel economy would drop below 100 mpg.

In the context of earlier estimates of what is necessary, the numbers in this figure clearly indicate that it is not technically unthinkable that a society still heavily dependent on gasoline vehicles could reduce carbon dioxide emissions from light-duty vehicles by 50%. However, the estimates of Difiglio et al. make it clear that consumers may value current sizes of vehicles far too highly to accept this method of reduction. Implicitly, the National Energy Strategy choice of alternative fuels, which have the long-term potential to realize the needed reductions, takes this into account.

A concern with making vehicles lighter is safety in collisions. For example, studies by the National Highway Traffic Safety Administration of the effects of the vehicle size and weight reductions that took place between the 1970s and early 1980s indicated that the reduction of the average weight of new cars from 3,700 to 2,700 lb resulted in increases of nearly 2,000 fatalities and 20,000 serious injuries per year. Thus, a careful analysis of safety consequences is needed before undertaking policy initiatives that would stimulate development of smaller, lighter vehicles. Perhaps the introduction of a vehicle like the lean machine would occur in conjunction with both transportation control measures which reserve existing lanes, streets, and parking spots for these small, light-weight vehicles and with construction of new streets and roads dedicated only to very light-weight vehicles (Garrison 1990). Such streets and roads might be considerably cheaper per lane mile to build and maintain and might be more cheaply elevated in congested areas.

Assuming that lighter vehicles would allow cheaper construction of roads and highways exclusively for those vehicles, the introduction of integrated vehicle highway systems in conjunction with these light commuter vehicles might be made easier. Such systems will more readily pay for themselves in densely populated areas where traffic volumes are high, and such areas should be an attractive market for very small, light-weight vehicles. The Japanese already provide lower taxes and less onerous parking regulations to cars in the mini-compact category.

6.3.2 A Reexamination of Oil-Based Options

Alternative engines that have historically depended on petroleum derivatives are diesel engines, rotary engines, two-stroke engines, and automotive gas turbines. The rotary engine is a technologically successful engine used in the Mazda RX7 sports car. It is highly reliable, but is not as efficient as a four-stroke engine and will not receive attention as a means of improving vehicle efficiency.

As mentioned, the passenger car diesel has been estimated by Acurex to cause approximately 12% less carbon dioxide emissions than a gasoline engine of equivalent performance, partly because it does not use as much energy to produce a Btu of fuel and partly because each Btu of fuel can be converted more efficiently in a diesel than can gasoline in an otto-cycle engine (Unnasch et al. 1989). In principle then, a switch to diesel engines in passenger cars could reduce greenhouse gas emissions as much as a switch to DOHC 4V (double overhead camshaft four-valve per cylinder) technology.

Like another technology being actively considered--the gasoline two-stroke--the problem for the diesel is the strict emissions standards passed in the Clean Air Act Amendments of 1990. Nevertheless, the diesel deserves to be considered as an option, especially since the quality of crude oils worldwide is declining.

One reason for the greater emphasis on use of diesel fuels in Europe, where the diesel has historically been popular, is the crude oil from which the products are refined. So-called natural product yields for Nigerian, Arab light, and North Sea crudes range from 19% gasoline to 23%, while the West Texas Sour from the United States yields 35% gasoline (Owen and Coley 1990). Thus, to the extent that the United States becomes more dependent on imports of these crudes, more energy will be required to produce the same amount of gasoline. Consequently, the option of using diesel oil from such crudes in diesel-engined passenger cars should continue to be given consideration.

The National Energy Strategy calls for research on advanced diesel engines, high-temperature ceramic materials, and friction-reducing technologies. High-temperature ceramics have been argued to theoretically improve the efficiency of diesels, but the results in tests have so far been disappointing. Ongoing DOE-funded research is addressing this problem by trying to develop friction-reducing coatings for ceramic materials that could be used in diesel engines. New technologies to deposit molecule-thick coatings on a ceramic surface are being developed.

The two-stroke is not a new engine concept, having been used in diesels in urban buses and gasoline-engine motorcycles. It has been used in Eastern Europe for years. Its problem is the control of pollution. Significant advances in addressing this problem may lead to its introduction in the mid-1990s. If not, the more advanced versions will likely be used in marine applications where emissions control is not as strict and where the new technologies offer significant emissions benefits.

The diesel engine and the two-stroke engine have in common a reduced rate of fuel consumption at low engine load and at idle, relative to a four-stroke gasoline engine of similar peak load power. On these grounds, they are competing for the urban commuter car market. It is important to keep in mind that the two-stroke is being developed to be a spark-ignition gasoline engine and not a compression-ignition diesel engine. Consequently, the ability of the diesel to use fuel which takes less energy to process has to be included in a proper evaluation of how the two compete in congested urban traffic as technologies to reduce carbon dioxide emissions.

In a certain sense, the automotive gas turbine has the opposite behavior of the diesel and two-stroke engines. Specifically, it consumes much more fuel at part load and idle than does a four-stroke gasoline engine of similar peak power. Its advantages relative to the gasoline engine are two-fold: first, it can easily burn lower quality fuel, like the diesel, and second, it can have a considerably higher efficiency if running steadily at optimum load. It has a disadvantage in the sense of the scale at which it can efficiently compete with four-stroke engines. It is easier to retain the inherent efficiency of a four-stroke engine as it is reduced in size than to do so with a turbine engine. This is due to the fact that the distance between the turbine blade tips and the housing of the engine have to be a very small fraction of the length of the blades if high efficiency is to be maintained. As the engine is downsized, the absolute distance between the blade tips and the housing must also decline. For very small engines this becomes a manufacturing challenge, requiring the maintenance of very close tolerances. Another problem is the need to operate the turbine engine at very high temperatures, thereby tending to create nitrogen oxide emissions in excess of standards.

The automotive gas turbine has been tested in automobiles in the 1960s and 1970s. As a result of the fuel consumption realized in these tests, researchers concluded that redesign and development of high-temperature ceramics were necessary to allow the engine to realize its theoretical potential. It was also concluded that transmissions capable of keeping the engine in its efficient operating range had to be developed. Ceramics would allow the engine to operate at higher temperatures, would decrease the weight of the engine, and would decrease reliance on scarce materials (McLean and Davis 1976).

Because it is important to keep the gas turbine operating at a high percentage of its peak load to ensure efficient operation, a continuously variable transmission is, in principle, an optimum transmission. Alternatively, an automatic transmission with numerous speeds would allow efficient operation. The introduction of automatic transmissions with electronic controls and as many as six speeds (see Table 6.3) has moved transmission design closer to an ability to translate theoretical gas turbine efficiency into actual on-road efficiency. Such transmissions can also address the problem of turbine lag, a delay in throttle response. With many speeds set electronically to keep the turbine at a high rpm, the transmission itself would cause a higher proportion of the acceleration by changing gears than would the engine by changing rpm.

The key problem at this time is the development of low-cost durable ceramic parts that will not fail catastrophically. Much progress has been made, and a commitment to continue the development of this engine and its ceramic components was made in the National Energy Strategy. The turbines being developed are in the 100-hp range, a reasonable size for compact cars. The design goal for the Allison Gas Turbine AGT 100 engine in a 2700-lb car was initially indicated to be 36.4 mpg in 1980 (Polack 1980), but was increased to 42.5 mpg in 1984 (Helms et al. 1985).

The costs of achieving a goal of 42.5 mpg in a vehicle of 2700-lb-curb weight with a conventional gasoline engine would be extremely high if the calculations here are correct. Even the Toyota turbocharged, supercharged, intercooled, multipoint fuel-injected four-valve per cylinder combination was estimated by the methods used here to achieve only 39 mpg in a 2700-lb car with 13-second 0 to 60 acceleration (to match the AGT theoretical value stated by Polack).

If the AGT were to obtain 42.5 mpg on diesel fuel, then the carbon dioxide emission reduction benefits would be even greater than if the engine used gasoline. The AGT can easily be modified to run on gasoline, jet fuel, diesel fuel, methanol, or any other liquid fuel. Since the Toyota technology mentioned above is a gasoline technology, the possibility to use less refined fuels does not exist in that case. Although the AGT continues to experience setbacks in the effort to reach its stated design goals, the rewards of success with the technology may be considerable, if both technical and economic success can be achieved.

6.3.3 Non-Oil-Based Options

The prior discussion showed that fuel substitution among petroleum derivatives might reduce carbon dioxide emissions and should be considered as one point of evaluation of engine technologies. There are two very productive ways of reducing carbon emissions by switching away from petroleum-based fuels. These are to switch to fuels derived from advanced nuclear power technologies or to switch to renewable fuels.

DeLuchi (OTA 1991, p. 160) has estimated that nuclear-electric pathways could achieve an 80% reduction, while woody biomass as a source of alcohol or natural gas could achieve a 60% to 70% reduction. Reemergence of nuclear power technologies promoted through the development of reactors with enhanced safety features could sharply reduce the burning of fossil fuels. Such power can be used either to power electric vehicles or to produce hydrogen from seawater.

Renewable fuels include solar-generated electricity, biomass-generated electricity, and hydropower-generated electricity. Use of solar or hydropower-generated electricity would reduce net greenhouse gas emissions by 85%, according to DeLuchi (OTA 1991). Thus, any of these power sources for electric vehicles could sharply reduce net carbon dioxide emissions. Another way of using biomass as a renewable fuel is to make liquid fuels such as ethanol or methanol from the biomass feedstock and burn the liquids directly in vehicle engines or to make natural gas from the biomass, also for use in vehicles. The carbon dioxide generated by burning biomass-based alcohols is recycled as carbon is fixed by new growth of biomass on the land which grew the original fuel source.

Bleviss (1988) has pointed out the potentially positive synergistic interaction between attainment of greater fuel efficiency and use of biomass. A problem with using biomass is that its use has environmental side effects. In Brazil, the sugarcane-based ethanol program is contributing to the cutting down of the rain forests, which is itself contributing to increased greenhouse gas emissions. Thus, one has to be cautious about how biomass-based alcohols might be produced and how much would be needed. As Bleviss points out, greater fuel efficiency means that less biomass feedstocks will have to be used to produce a given amount of miles of travel. The problem with biomass-based fuels is that they are quite costly to produce. Consequently, if they prove to be made economically viable by a high carbon tax on fossil fuels, then it will also be economic to introduce more engine technologies that enhance fuel efficiency.

The use of fuel substitution to reduce net carbon dioxide emissions can occur more readily if two types of engine research are undertaken. To use the electric option, considerable research on battery technologies and the vehicle package in which they are used will be needed. Both are stated goals of the National Energy Strategy (DOE 1991).

To use biomass-based fuels, also a projection of the National Energy Strategy, it will be necessary to introduce alternative-fueled engines and vehicles that can use these fuels. Such engines include the automotive gas turbine, redesigned conventional internal combustion engines, and the fuel cell.

The fuel cell can use alcohol from biomass or hydrogen from nuclear power. It generates electricity from these fuels and converts it at a very high efficiency. Acceleration capability and weight are problems for the fuel cell. Weight and the ability to accelerate repeatedly are problems that have to be addressed in the development of battery-powered electric vehicles.

An important point is that use of alcohols and compressed natural gas in heavy-duty engines is being developed. Given the high rates of growth of fuel use in the heavy-duty sector, the ability to switch to fuels ultimately producible from woody biomass is potentially a very valuable contributor to reduction of carbon dioxide emissions. The gains with these vehicles will not be as large because they currently use diesel fuel in compression ignition engines. As noted earlier, alcohols can be burned more efficiently in spark-ignition engines than gasoline, while alcohols used in converted compression ignition engines burn with about the same efficiency. Accordingly, greater percentage gains are possible by substituting woody biomass-based alcohols in spark-ignition light-duty engines than in compression-ignition heavy-duty engines.

Alternative Fuels in Conventional Engines

The "methanol engine" concept proposed by Gray and Alson (1989) of the EPA, and/or the automotive gas turbine technologies being investigated with DOE support by General Motors and by Allied Signal both are potentially suitable engines for use of biomass-based alcohols. The automotive gas turbine has the potential advantage of running on a variety of fuels with very little modification.

The methanol engine proposed by Gray and Alson (1989) would be a downsized supercharged engine without a traditional cooling system. This engine would be even better than those of similar technology using gasoline because the compression ratio would be higher and the cooling system weight would be eliminated. Deluchi's most recent estimates indicate that an advanced methanol engine using natural-gas-based methanol produced by advanced production processes could reduce greenhouse gas warming effects by 17%, a little more than the 14% estimated for an advanced short-range compressed natural gas vehicle (OTA 1991, p. 160).

There is little doubt that methanol or ethanol can be introduced in current technology engines, as can compressed natural gas. When used in dedicated vehicles with a much shorter range than current gasoline vehicles, compressed natural gas has the potential to reduce emissions by a few percent, while methanol from natural gas (in current, thoroughly tested engine designs) has a bit less potential to do so (see Santini et al. 1989).

Because fuel system weight is such an important consideration in compressed natural gas vehicles, significant gains in mpg are possible when range is sacrificed. This property also holds for electric vehicles, but not for vehicles whose engines run on alcohol, gasoline, or diesel fuel. In the long-run, however, introduction of alcohol-powered vehicles will create an ability to introduce alcohols produced from woody biomass. In that case, significant emission reduction benefit will result through a recycling of carbon dioxide such that net atmospheric loading will change far less than when alcohols or petroleum products are produced from fossil fuels.

Methanol is unlike gasoline or diesel fuel in the sense that it is being successfully burned in both spark-ignition and compression-ignition engines. This fact suggests that the fuel does have unique properties of its own, as Gray and Alson (1989) contend, which would make the ideal engine designed for this fuel considerably different from current engine designs. As in the case of the automotive gas turbine, however, the proposed optimized methanol engine is not likely to be available until after the year 2000.

Both of these engine options should be considered long-term options that could not make a large contribution to the reduction of carbon dioxide emissions in the intermediate term. Other engine designs may emerge or reemerge in the future, but these are two that merit current attention because they can be biomass-based in the long term. These are two liquid-fuel-based engine/fuel concepts that are currently considered promising by the DOE and the EPA.

Systems With Electric Drive

The introduction of electric and hybrid vehicles using a variety of battery technologies would displace much of the emissions from the location of the vehicle to the vicinity of the utility power plants that provide the electricity to recharge the batteries. Insofar as carbon dioxide emissions are concerned, the use of electric vehicles in place of gasoline vehicles can be either beneficial if nuclear power or renewable fuels are used to generate the electricity or very detrimental if coal is used. With fuel cells, which are likely to use natural gas, hydrogen or methanol as a fuel, the system efficiency has the potential to result in a significant reduction (nearly 50%) of emissions of greenhouse gases relative to current internal combustion engines modified to use those same fuels or gasoline.

The Energy Information Administration (1990) projects the mix of power plants in the United States in 2010 would consist of coal (60.4%), petroleum (3.5%), natural gas (14.1%), and nuclear (14%), with the remaining 8% a mix of hydropower, geothermal, petroleum coke, biomass, wood, waste, solar, and wind.

Dowlatabadi et al. (The Energy Daily 1991) suggest that the introduction of electric vehicles up to 15% of the transportation mix would not boost aggregate utility emissions, assuming that new fossil-fueled power production technologies using advanced designs and combustion technologies would reduce the emission of carbon dioxide per unit of power generated. Overall, on a per mile basis, Wang and DeLuchi (1991) estimate a greater than 90% reduction in petroleum usage per mile of personal vehicle travel by 2010 by an electric vehicle rather than a gasoline vehicle. As Wang and DeLuchi note, however, significant reductions of net carbon dioxide emissions are only likely if electric vehicles are recharged by power generated from nuclear or renewable (biomass, hydro, wind, and solar) fuels.

Battery Technology Development. The potential of electric vehicles to displace emissions from highly polluted urban areas and to displace oil use has contributed to an increased interest in these vehicles. A consortium of U.S. vehicle manufacturers has been formed to conduct battery research in hopes of a technological breakthrough.

Such a breakthrough is needed for several reasons, but the most significant is the high weight per unit of horsepower for a battery storage system. To illustrate, the General Motors "Impact" prototype vehicle has a lead acid battery power pack weighing 7.63 lb/hp delivered by the electric motors (this does not include the weight of the motors). This contrasts with a weight of 1.77 lb/hp for GM's Saturn double overhead camshaft four-valve-per-cylinder engine (not including fuel system weight). The newly formed electric vehicle consortium consisting of government agencies and major vehicle manufacturers is focusing its attention and resources on three types of battery systems, with hopes of greatly reducing the weight per unit of power deliverable and energy storable by commercially viable batteries.[a] The battery types being considered are

- Beta batteries
  - sodium/sulfur
  - sodium/metal chloride batteries using iron chloride, nickel chloride, or copper chloride

- Molten salt batteries
  - lithium/iron sulfide
  - lithium/iron disulfide, bipolar lithium/iron disulfide

- Ambient temperature batteries
  - lead/acid
  - nickel/iron
  - lithium/polyethylene oxide.

Over an estimated 12-year life of the consortium, the above battery systems have been classified as follows:

- present term
  - lead acid
  - nickel/iron

- near term
  - sodium/sulfur

- intermediate term
  - lithium/iron sulfide
  - lithium/iron disulfide, bipolar lithium/iron disulfide
  - sodium/metal chloride batteries using: iron chloride, nickel chloride, or copper chloride

- far term
  - lithium/polyethylene oxide.

Both DOE and the consortium are focusing on batteries with high specific energy (for range), high power capability (for acceleration), and long service life (to minimize replacement costs). The consortium would like the nominal working voltage of the battery system to be around 340 volts (the maximum voltage for the Impact prototype is 400). The characteristics of each of these battery systems are discussed in the following section and are listed as defined by the consortium grouping. The overall issue which needs to be addressed relates to the development of appropriate materials for batteries.

Other battery types that have been funded by DOE include the zinc/bromine, lithium, aluminum/iron sulfide, and iron/air batteries (DOE 1990a). Batteries that two western utilities are promoting for present- to near-term use are the nickel-cadmium and zinc-air batteries, which have been used in combination (Cook 1991).

- Present-term systems

  Recently, General Motors has described the Impact, an electric vehicle powered by commercially available lead-acid batteries and developed by their vehicle development group. This vehicle is reported to have a range of 120 miles at a steady 55 miles per hour [a practical range of 75-80 miles (*Alcohol Week* 1991)] and can accelerate from 0 to 60 mph in 8 seconds, though repeated rapid accelerations would significantly shorten range (Amman 1989). This is probably the least initial cost system.

(a) Personal communication with D. R. Vissers and with J. F. Miller, Argonne National Laboratory, March 19, 1991.

Disadvantages include a change of a $1000-2000 battery system over every 20-25,000 miles (4-10¢/mile) of travel and the need for regular maintenance. These cost figures are somewhat low in comparison to one source's quoted $5000 battery replacement cost per 3 years for the Volkswagen diesel-electric hybrid vehicle (J. E. Sinor 1991, p. 162), which will be field tested in Switzerland in 1992. Perhaps the Volkswagen value is a current cost, while the GM value is a projected cost for the date of introduction of the vehicle. Concerns over environmental safety and health and the high toxicity of lead make this battery less desirable for long-term use, although recycling could reduce these concerns.

As a point of reference, a car of 1550-lb curb weight would roughly have an curb weight equal to the 114-hp Impact, assuming the weight of the battery pack is deleted [2200 lb less 870 lb (J. E. Sinor 1991)] and addition of the weight of the 124-hp Saturn DOHC engine [220 lb (Reilly et al. 1991)]. Such a car would realize about 42 mpg with essentially the same acceleration as the Impact. At a cost of $1.20/gallon, gasoline costs per mile for the performance equivalent gasoline vehicle would be about 2.9¢/mile, less than the Impact's battery replacement costs alone (ignoring recharging costs). Assuming that the 42 mpg gasoline vehicle had a $25 oil change every 3000 miles and went 25,000 miles in 2 years, its undiscounted monthly operating costs would be $38/month compared with an estimate of $80/month including electricity for the Impact (J. E. Sinor 1991). Assuming GM used 12,500 miles/yr in its calculations of the $80/month figure, then at roughly $2.90/gallon [a price exceeded in Japan, France, Italy, and Sweden (Davis and Hu 1991)], the battery replacement and electricity costs of the Impact would be about the same as for fuel and oil for an equal performance gasoline vehicle. Differences in initial cost of the vehicles are ignored in this comparison, and the costs for the Impact would vary according to the rates charged for electricity. Nevertheless, these crude estimates put the Impact's fueling costs into perspective. Note that the Impact is a two-passenger commuter vehicle. The 1550-lb curb weight estimated above for a gasoline vehicle of comparable performance to the Impact can be compared to the 1620-lb curb weight for a Geo Metro, a four-passenger car.

The electric vehicle is likely to be introduced first as a niche vehicle; that is, a vehicle with a well-defined repetitive pattern of use. The Impact is designed to be attractive as a commuter car, while much of the other electric vehicle work focuses on use of vans in commercial fleets.

The most likely immediate alternative to the lead acid battery is the nickel/iron battery. This battery system has the advantage of long life but the disadvantage of a higher initial cost, which may be offset in the future by a salvage value for the nickel. Charging inefficiencies in this system and the resulting production of hydrogen make adequate ventilation during charging essential. Commercial facilities with central recharging stations seem more likely than households to have the incentive to build proper recharging facilities for these batteries. The advantage of this battery system is that it has demonstrated a long cycle life (over 1000 cycles) and adequate specific energy and power for normal operations over a 100- to 120-mile range. The low life-cycle cost of this system, combined with a moderate range of 100 to 120 miles makes this battery potentially attractive to a group of fleet operators. However, nickel is a strategic material, which may make widespread use of this system somewhat questionable.

The recent success of a modified Honda CRX (Cook 1991) using a combination of nickel-cadmium and zinc-air batteries has created interest in these batteries. At steady speeds of 50 to 60 mph, this electric vehicle went 124 miles with a reported reserve of 50 miles of range. The battery pack for this electric vehicle was reported to weigh 1100 lb, cost $1500 to $2500, and require replacement every 20,000 miles

(Cook 1991). Weight and cost are higher than those for the Impact. Without a battery pack, a Honda CRX weighs 2000 lb, so even the gutted CRX (with the 1100-lb battery pack) must have weighed more than the Impact.

- Near-term systems

The sodium/sulfur battery is receiving the maximum attention worldwide as a near-term battery for electric vehicle propulsion. Chloride Silent Power Limited in Britain is probably the closest to building a pilot facility for the manufacture of this system. A high specific energy battery (140 W-hr/kg), the system operates at about 300°C with all the reactants and products in the liquid state. The open circuit voltage of the system ranges from 1.8 to 2.1 volts, depending on the state of charge. The discharge needs to be interrupted partway to avoid the formation of a solid product which could render the cell inactive. A solid electrolyte beta´´ (read as beta double prime) alumina is used. The beta family of electrolytes is an aluminum-oxide-based ceramic defined as having specific electrical properties (a transference number of unity for the sodium ion). This electrolyte has a high conductivity of sodium, yet the conductivity is low enough that very thin electrolyte must still be used. The main risks of this system are the fragility of the electrolyte and the possibility of shorting through the electrolyte by the sodium, which results in the rapid release of heat (Sen 1988).

The 45-60 kWh capacity and high voltage requirements would require the assembly of several hundred cells in a series/parallel array within each battery. The reliability of such a system in actual operation within the battery remains to be demonstrated. It is estimated that failure of less than 2% of the individual cells could result in overall battery failure. A corrective approach may be to have an adequate excess of cells and appropriate electronic diagnostic sensing and cell replacement measures to avoid a premature breakdown of the system. In addition, questions of battery safety and thermal management need to be addressed, as this system operates at over 300°C. While these system maintenance measures might be acceptable to fleet operators, they might be a drawback for sales of the battery for personal use vehicles. The materials required for this system are readily available.

- Intermediate-term systems

The other beta batteries such as the sodium/metal chloride batteries are in the early stages of development. Further research and development is required to increase the power capabilities and reliability of these systems. These systems operate at 200°C to 250°C and, therefore, the probability of and risks associated with electrolyte failure are less than with the sodium/sulfur system. In contrast with the sodium/sulfur cells which fail in the open circuit mode, these cells fail reliably in the short-circuit mode, which makes battery design simpler. Further, the slow reaction of the sodium with the metal chloride results in a safer system. The nickel current collector does not corrode and results in greater electrode stability, and the higher density of the sodium/metal chloride systems makes the design more compact. Except for nickel, the materials availability is not envisioned as a problem (Sen 1988).

The lithium/metal sulfide systems now being developed at Argonne National Laboratory also operate at above ambient temperatures. The lithium/iron sulfide battery is closer to manufacture than is the disulfide system. When developed, the disulfide system will be a reliable system with several advantages as described for the sodium/metal chloride systems, with the added bonus of higher specific energy and power. The batteries are inherently safe even under crash conditions. The disadvantages of this system, such as the high cost of lithium and the positive current collector, are expected to be addressed in further development work in progress (Sen 1988)

- Far-term systems

  The lithium/polyethylene oxide ambient temperature system is at a very early stage of development at the University of California at Berkeley. The electrolyte is an organic polymer that can be made from readily available materials. Cycle life and power capabilities of the system need to be improved. Very little data are available on this system (J. E. Sinor 1991, p. 163).

  Examination of the lithium-sulfur phase diagram identifies a high temperature lithium/sulfur system that has potential for high specific energy and power. Argonne did some early work on this system in the early to mid-1970s (Miller[a]). Further developmental work may identify a reliable, safe, low-cost propulsion system.

Fuel Cell Development. Fuel cells directly produce electricity from the hydrogen available in fuels and are identified by the electrolyte used in the system. Because it generates electricity, a fuel cell is an alternative power source for the battery in vehicles using electric motors. The direct energy conversion results in higher fuel utilization with lower emissions of criteria pollutants and greenhouse gases. Anticipated low maintenance costs and long life are further attractive features.

While current technologies are expensive, heavy, and voluminous and rely on a nonrenewable resource when powered with fossil fuels, further development to meet transportation needs may make these systems attractive. Potentially, they may reduce the amount of fossil fuel required per mile. Further, to the extent that hydrogen is provided from biomass (as alcohol or natural gas) or nuclear-powered dissociation of water, fuel cells will also sharply reduce carbon dioxide emissions from transportation, as discussed at the outset of this section.

(a) Personal communication with J. F. Miller, Argonne National Laboratory, March 19, 1991.

The developmental efforts are now concentrated on the following three systems:

- phosphoric acid
- proton exchange membrane (PEM)
- solid oxide (SOFC).

The phosphoric acid fuel cell technology is the most mature of the three listed above. An ongoing joint program funded by DOE, DOT/UMTA, and SCAQMD is designed to demonstrate the technical feasibility of using a methanol-fueled phosphoric acid fuel cell in combination with a battery system to provide low emission propulsion for large transit buses. In Phase II the evaluation will be extended to the evaluation of the system in three smaller 27-foot buses. This fuel cell uses methanol as a fuel.

The use of methanol as a fuel requires reformer hardware to dissociate the hydrogen from the methanol for use as fuel for the operation of the fuel cell. The reformer adds weight and bulk, both detrimental attributes in transportation applications. Another current problem with the reformer is its inability to vary hydrogen production quickly enough to allow the fuel cell to alter its power output to accelerate the bus at rates needed for operation in normal applications.

There are two solutions to this problem. One is to redesign the transportation system to ensure smoother flow and fewer acceleration/deceleration sequences. Approaches such as integrated vehicle highway systems are attempts to implement this solution. The second approach is to adopt a hybrid power system for the vehicle, with a power source which is highly efficient in steady-state operation (the fuel cell) and a second power source which can be operated intermittently to provide bursts of power. This conceptual approach was used in the recently tested Honda CRX electric vehicle, where 350 lb of nickel-cadmium batteries were used for bursts of power and 750 lb of zinc-air batteries were used for efficient cruising (Cook 1991).

In the bus, the second approach is also used. A battery system is used in combination with the fuel cell to meet the power requirements for acceleration and grade climbing. Under steady-state cruising, the fuel cell provides the power, with any unused power providing a charge to the battery. Unless the bus is used on a route which repeatedly requires rapid acceleration or hill climbing, the battery will be close to a 100% state of charge. Fewer discharges and less "deep" discharges extend battery life, so batteries in a hybrid system such as this one would last far longer than those in vehicles relying only on a single power source.

In general, one of the tradeoffs in use of fuel cells in transportation is the cost and weight of the fueling system. This is also true for the internal combustion engine, but the system interactions are different. Fundamentally the tradeoff is between use of liquids and gases. At atmospheric pressure, the liquids hold more energy per unit volume and weight than do the gases. This can be overcome to some extent by pressurizing the gases, but this requires energy for the pressurization and fuel system bulk (weight and volume) for the containers holding the gases. That bulk, in turn requires energy to carry it around and sacrifice of storage space (carrying capacity) in the vehicle.

In the case of the fuel cell, hydrogen is the ultimate fuel. Its direct use on the vehicle in pressurized containers requires bulky storage systems, but does not require a reformer. Natural gas can carry the hydrogen, but requires both pressurized storage systems and a reformer to dissociate hydrogen and carbon. Methanol, being a liquid, can be contained relatively compactly in fuel tanks, but requires the reformer to dissociate the hydrogen.

The proton exchange membrane fuel cell is potentially capable of meeting transportation needs early in the 21st century. As with the phosphoric acid fuel cell, reformer technology is required, except when hydrogen is used directly as the fuel.

Current concerns with this system are primarily its high cost and the management of the accumulated water produced by oxidation of hydrogen during operation. Under ambient conditions surface deposits of the water produced in liquid form may result in cell failure. Other systems, which operate at higher temperatures, produce water as a gas which does not coat the cell surface. The system requires significant use of platinum, a relatively scarce and expensive metal. For use in passenger cars, its volume and weight need to be reduced, without sacrificing its power output.

Tests of the proton exchange membrane fuel cell in an automobile are reportedly being planned by the Pennsylvania Energy Office (J. E. Sinor 1991, pp. 109-111.) This technology has been estimated by R. H. Billings to cost $3500 per cell for mass production of a cell which could give a hydrogen powered version of a car a 300-mile range. This cost may not include the cost of the metal hydride hydrogen storage system. Even so, it is about half the cost of the least expensive economy car available and compares to costs of a few hundred dollars to produce internal combustion engines.

Nevertheless, the fact that a stationary fuel cell (one sitting on the ground and not used to move its own weight and the weight of its associated tanks of fuel) can be twice as efficient as a gasoline-powered internal combustion engine makes this technology worth careful evaluation. According to the American Academy of Science, the weight of this cell per horsepower generated is about 2 lb/hp, (J. E. Sinor 1991, p. 110), a weight comparable to the Saturn double overhead camshaft four-valve-per-cylinder engine (Reilly et al. 1991). Tests of this cell and its associated hydride refueling system in prototype vehicles will allow comparisons such as those made above for the GM Impact. Cell life, acceleration capabilities, and fuel consumption on EPA CAFE test cycles will be very valuable.

The solid oxide fuel cell made of ceramics and operating at close to 1000°C is capable of reforming fuels such as methanol to produce hydrogen. However, significant development problems need to be addressed. These include approaches to control inter electrode and electrolyte ionic diffusion (which may be difficult at the high operating temperatures), as well as to protect the ceramic system from failing during thermal cycling. A major issue with this system when used as a propulsion system for passenger cars would be the startup time required to bring the system to its operating temperature. Ideally, this system may be most useful in trains and ships, which run almost continuously.

This system would need a long development and evaluation time and is probably most likely to debut sometime in the mid 21st century. Current development work on this system is aimed at identifying electrode and electrolyte materials that are capable of operating at lower temperatures. This system is far from ready for testing in vehicles.

Hybrid Systems. Another approach would be to implement a high power density battery of nominal specific energy and low cost as used in the GM Impact (to conserve volume) in combination with a high efficiency internal combustion engine running off regular fuels. As with the fuel cell battery hybrid currently under evaluation for buses, the internal combustion engine could be used for steady-state highway cruising with the battery providing power for acceleration and climbing. In highly populated and polluted urban areas, the battery power may be used exclusively in selected zones for shorter ranges. Volkswagen, AG has announced a fleet demonstration of 40 hybrid vehicles running on diesel fuel and electricity (J. E. Sinor 1991). Depending on the usage profile, the hybrid system may result in a lower emission of greenhouse gases (Kalberlah 1991).

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7.0 INDUSTRIAL TECHNOLOGY

Unlike energy technologies in the building and transportation sectors, those in the industrial sector cannot be treated generically to yield reliable estimates of conservation potential and costs. Energy use in manufacturing depends primarily on the production processes in each industrial sector. Applications such as motors and process heating are very process-specific. Therefore, the analysis presented here is quite different from the technology characterizations for buildings and transportation, where a generic analysis can be successfully applied.

Unfortunately, nongeneric (i.e., process-specific) information on conservation technologies is not available for many sectors. For example, an examination of the electricity conservation supply curve data produced for the Michigan Electricity Options Study (Battelle 1987) and for Bonneville Power Administration (Resource Strategies 1985) shows 1) a lack of information on conservation opportunities tied to specific production processes and 2) a lack of information relating to high energy-price regimes. These shortcomings are not due to poor study methodology but simply reflect the state of the art of industrial energy analysis. Similarly, Energetics (Babcock et al. 1988) has performed valuable studies for the DOE's Office of Industrial Programs on textiles, pulp and paper, cement, glass, and iron and steel. Yet, even these detailed, sector-specific studies do not systematically address the information requirements for a conservation supply curve, since economic data are not provided for most of the technologies.

Given this lack of process-specific information two alternatives were considered: 1) perform a generic analysis in spite of its shortcomings and 2) rely on process-specific analysis of a few narrowly defined sectors, assuming that the conservation supply curves thus obtained can be used to estimate the overall conservation supply curve for manufacturing. The later approach is expected to produce more realistic results. However, it must be recognized that currently available information is not adequate for any approach to be used with confidence. The use of specific process cost and energy data at least is anchored in actual industrial experience. It is thought to be the most effective means of estimating conservation supply curves which extend into higher energy price regions.

This chapter, then, discusses technologies and their conservation potential and the construction of conservation supply curves. The subjects are some what disjointed, however, in that the general descriptions of technologies do not lead to conservation supply curves. The supply curves are instead built from analysis of specific processes or even specific plants. Because the technology descriptions are not the basis of the conservation supply curves, they do not include detailed information on cost and performance. They are intended, instead, to show examples of the variety of technologies involved in industrial energy use and to point out areas of potential energy savings.

7.1 INDUSTRIAL STRUCTURE

The role of manufacturing industries is to transform materials. These transformations are accomplished through energy-consuming processes such as heating, mixing, and shaping. When process energy is derived from the combustion of fossil fuels, carbon dioxide is a by-product of industrial activity. Production of this greenhouse gas can be reduced through energy conservation, fuel switching, and process modifications. An example of the latter is recycling, which reduces the need to consume energy in primary material transformations such as ore reduction. An outline of industrial energy use and the potential to reduce greenhouse gas emissions through energy conservation is provided in the following pages. As noted above, the approach taken is to develop energy conservation "supply curves," which correlate the potential industry-wide savings with investment in conservation measures.

The industrial sector includes manufacturing, mining, agriculture, and construction. Of these four subsectors, manufacturing is the largest overall consumer of energy. In fact, manufacturing industries are responsible for over 80% of all industrial energy consumption. These investigations are limited to the manufacturing industries (i.e., Standard Industrial Classifications 20 through 39 as listed in Table 7.1). Of these 20 industries, four stand out as the largest energy users: Paper and Allied Products (SIC 26), Chemicals and Allied Products (SIC 28), Petroleum and Coal Products (SIC 29), and Primary Metal Industries (SIC 33). With the exception of Food and Kindred Products (SIC 20) and Stone, Clay, and Glass Products (SIC 32), other manufacturing industries each consume less than 15% as much total energy as one of these four major energy users. Together, the six largest energy consumers account for over 84% of total manufacturing energy consumption.[a]

Industrial energy use can be further classified according to energy source. The *Manufacturing Energy Consumption Survey* (DOE 1988) identifies consumption of net electricity, residual fuel oil, distillate fuel oil, natural gas, liquid petroleum gas, coal, coke and breeze, by-products, and other fuels. The energy source distinction is important because the rate at which greenhouse gas is produced (e.g., pounds of carbon dioxide per million Btu) is fuel-specific. Energy use by fuel is summarized in Figure 7.1. To simplify the figure, both fuels and industries have been aggregated. Primarily, this involves assigning petroleum coke and by-products to petroleum-based fuels and coal and coke by-products to coal. Biomass energy is not included in Figure 7.1 because its contribution to carbon dioxide emissions is canceled by growth from replanting. Process industries include SIC 26, 28, 29, and 32. Fabrication includes all other industries except SIC 33, Primary Metals.

The dominant position of the process industries as energy consumers and of natural gas as an energy source are clear from this figure. The process industries include three of the four largest industrial

(a) References to energy consumption do not include fuels used in non-energy applications, only energy consumed for heat and power.

Table 7.1. 1985 Manufacturing Industries Energy Consumption

Industry	Code	End-Use Energy Consumption[a] (Trillion Btu/yr)	Energy Use Contributing[b] Carbon Dioxide (Trillion Btu/yr)
Food and Kindred Products	20	946	1,180
Tobacco Manufactures	21	19	29
Textile Mill Products	22	248	452
Apparel and Textile Products	23	30	62
Lumber and Wood Products	24	333	210
Furniture and Fixtures	25	48	82
Paper and Allied Products	26	2,198	1,470
Printing and Publishing	27	76	165
Chemicals and Allied Products	28	2,407	3,360
Petroleum and Coal Products	29	2,631	2,896
Rubber and Miscellaneous Plastics Products	30	212	418
Leather and Leather Products	31	13	21
Stone, Clay, and Glass Products	32	896	1,141
Primary Metal Industries	33	2,391	4,608
Fabricated Metal Products	34	298	512
Machinery, Except Electrical	35	239	467
Electric and Electronic Equipment	36	209	455
Transportation Equipment	37	317	579
Instruments and Related Products	38	73	133
Miscellaneous Manufacturing	39	31	56
Total	590	13,615	18,296

(a) This column displays the energy directly consumed in industrial processes. It does not include coal used to reduce iron oxide (in steelmaking) and reports electricity use on the basis of electrical energy, not the chemical energy required to generate power. In addition, biomass, which contributes no net carbon dioxide, is included.
(b) This column reports electricity in terms of primary energy input for generation. Because it generates carbon dioxide, coal used to reduce iron ore is included. Biomass is not reported.
Source: Manufacturing Energy Consumption Survey (MECS) Table 3, DOE (1988)

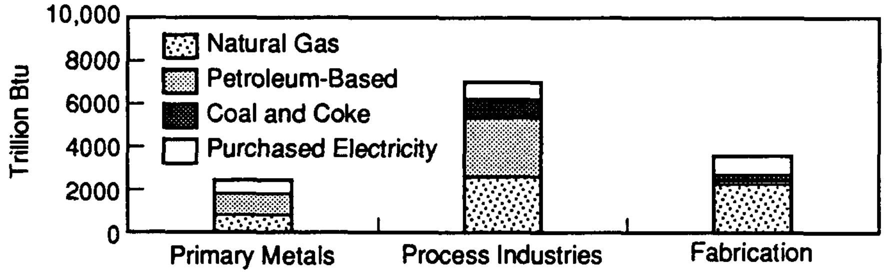

Figure 7.1. Energy Use by Fuel

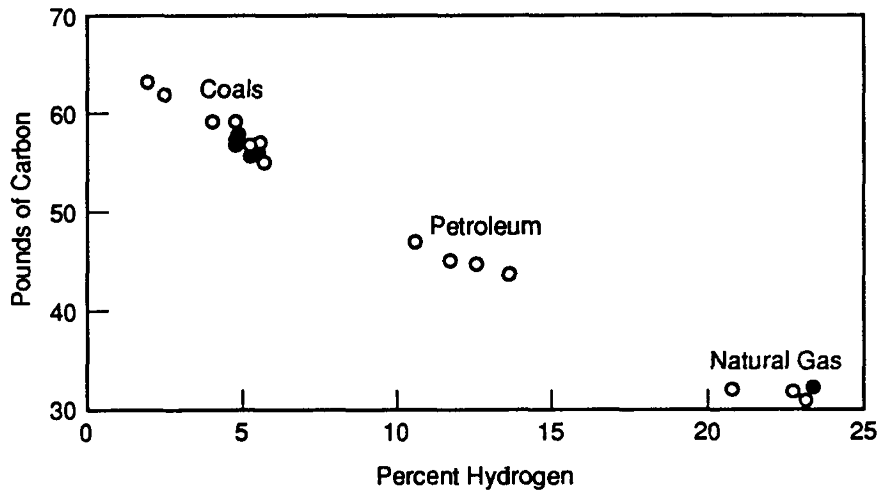

Figure 7.2. Carbon Emission Versus Composition

energy consumers: petroleum, chemicals, and paper. Each of these consumes well over two quadrillion (10^{15}) Btu per year for heat and power. Primary Metals, SIC 33, is the only other industry group in this high consumption range.

7.2 POTENTIAL FOR REDUCING GREENHOUSE GAS EMISSIONS

As noted above, greenhouse gas emissions are fuel specific. Higher carbon content fuels generally produce more carbon dioxide per unit of energy than lower carbon content fuels. Coal combustion, for instance, can release as much as twice the carbon dioxide per million Btu as natural gas combustion. Unit emissions are often expressed as pounds of carbon per million Btu. Twelve pounds of carbon are released for every 44 pounds of carbon dioxide. Figure 7.2 is a plot of carbon release per million Btu versus hydrogen content for various fossil fuels. The composition of any natural fossil fuel spans a range that is reflected in a range of emission factors as shown. Emission estimates in this report are based on the following representative emission factors:

Kilograms (Pounds) Carbon per Million Btu

Coal	26 (58)
Fuel Oil	20 (45)
Natural Gas	15 (32)
Electricity	50 (110)

The high carbon dioxide emissions associated with coal combustion are of particular importance because most electrical energy is generated by coal-fired power plants. This and the fact that such plants are today only about 33% efficient make the electricity portion of industrial energy consumption a significant source of carbon dioxide. This fact is emphasized by Figure 7.3, which compares the percent of industrial energy consumption for various fuels to the percent of carbon dioxide produced by those same fuels. While purchased electricity accounts for only 17% of manufacturing energy use, it accounts for 35% of greenhouse gas emissions. In addition, a portion of the fuel used by industry is for self-generation. This suggests a strong incentive to reduce industrial electricity consumption.

Energy consumption can be reduced through conservation, changes in operating practices, fundamental process changes, and changes in industrial activity. Conservation, which is the focus of this discussion, generally involves capital investment in conservation measures. Operating practice includes activities commonly considered housekeeping or energy management. Fundamental process change (e.g., direct steelmaking) is motivated more by overall cost, design, or marketing considerations than by energy use. In this context, changing industrial activity refers to the movement of economic activity from energy-intensive industries. Energy intensity is the ratio of energy use to some measure of production, such as value added. Sectoral shift affects the overall energy intensity of manufacturing. Conservation, operating practice, and process change affect the energy intensity of specific sectors or even specific products. Because this investigation is intended to provide data for estimates of conservation potential, the discussion will focus on conservation measures.

7.3 CONSTRUCTION OF CONSERVATION SUPPLY CURVES

As defined here, conservation is the reduction in the energy intensity of production associated with investment primarily motivated by the energy savings. The technologies involved save energy compared with currently used equipment and also typically have important ancillary benefits. These technologies should be distinguished from fundamental process change (including new products and product redesign), which may have quite large ancillary impacts on energy use, but which are not adopted for their energy impacts as such.

The likely extent of energy conservation is a function of energy prices. This conservation or savings

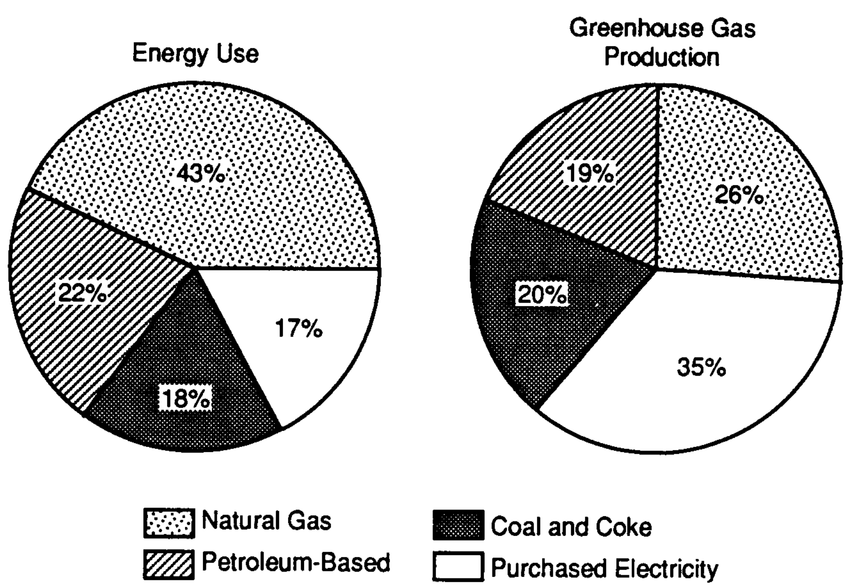

Figure 7.3. Energy Use and Greenhouse Gas Production by Energy Source

potential is conveniently described with a conservation supply curve, which expresses the cumulative energy savings (as percent of base year consumption) as a function of energy price. Such conservation supply curves are the focus of this chapter. Although the functional relationship is one of savings as a function of price, conservation supply curves are typically drawn with percent savings on the horizontal axis. Figure 7.4 follows this convention and reveals the key features of a conservation supply curve. The vertical axis is energy price. As price increases, investment in conservation measures increases, resulting in additional energy savings. Thus, the cumulative savings increases continuously, subject to diminishing returns, as the easiest conservation opportunities are exploited first. Two different situations are shown, curve A and curve B. In the latter, diminishing returns set in early and limit savings to a modest level. In the former, just a hint of diminishing returns is evident toward the end of the curve. Historical experience supports a type A curve. That is, as prices rise, new technology is introduced, preventing an asymptotic end to the conservation potential. To avoid this asymptotic effect, conservation supply curves should be based on an adequate inventory of conventional, new, and even advanced conservation measures.

Conservation supply curves can be estimated by analytical or empirical means. The analytical approach applies engineering and cost analysis to an inventory of conservation measures. These measures can then be implemented in a least-cost order, with the estimated savings accumulated a each technology is introduced and penetrates the market.

With the analytical approach, it is important to recognize the relationship between the cost of a conservation measure and the energy price at which such a measure is likely to be implemented. Industrial managers have historically implemented conservation measures only if the resulting energy savings guaranteed payback in 2 to 4 years. This decision criterion suggests a high implicit discount rate for such investment. This discount rate relates the cost of a conservation measure to the energy price at which the measure is likely to be implemented.

The empirical approach compares energy intensities for a cross section of industrial sites with various energy prices. Lower energy consumption at sites with higher energy prices provides a direct correlation between energy prices and savings potential. Figure 7.5 summarizes these approaches. Both the

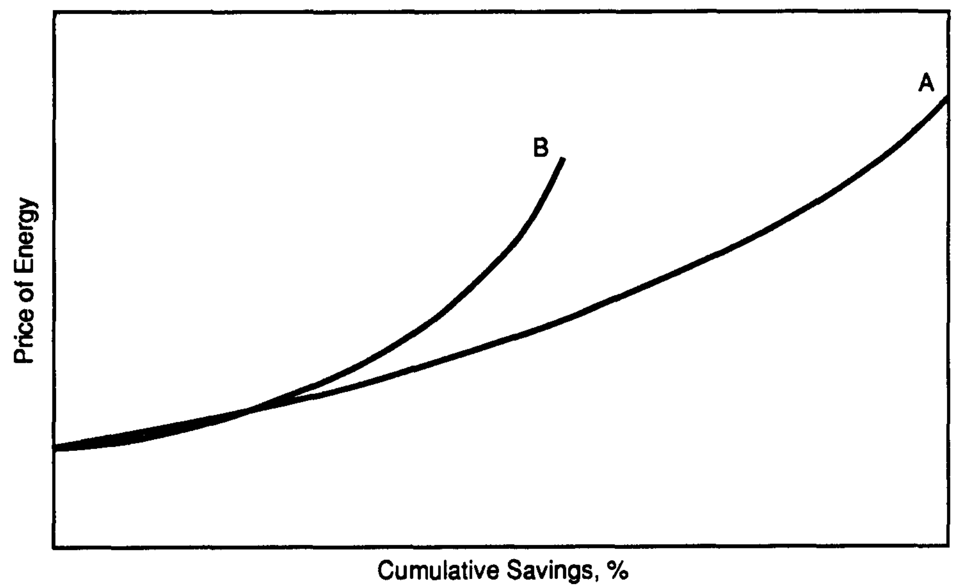

Figure 7.4. Conservation Supply Curves

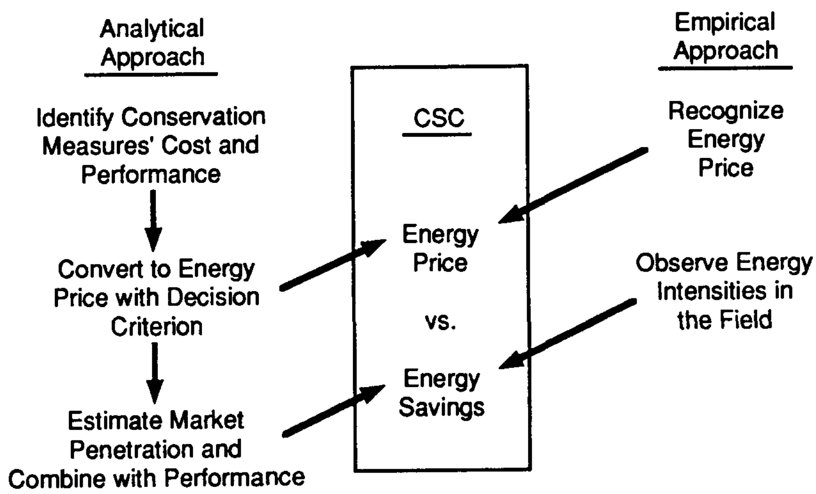

Figure 7.5. Comparison of Empirical and Analytical Approaches to Developing Conservation Supply Curves

empirical and the analytical approaches have been used to develop the curves recommended here, though the empirical approach is favored.

The analytical approach can be difficult to apply because reliable, consistent data on representative conservation measure performance and cost are not easily obtained. This is especially true for advanced technologies, which must be included in the analysis to avoid sharply diminishing returns on conservation investments. In addition, investment criteria are not well understood. As noted, these criteria relate conservation measure costs to energy prices and tend to be conservative in typical industrial practice, reflecting a high implicit discount rate. The complexities of plant investment decisions cannot be accounted for by strictly analytical methods. The empirical or cross-sectional analysis implicitly accounts for these decision processes, but the method is not without pitfalls of its own. Notably, few plants have experience in the high energy price range that is of interest for policy analysis. In fact, some industries, such as primary aluminum, simply are not active in high energy price regions and, therefore, provide no cross-sectional information. Actually, this raises doubts about the fundamental adequacy of any approach that employs a single conservation curve for diverse industries.

Ideally, sites used for the empirical approach should host similar industries and manufacturing processes. Only then can energy use differences be confidently attributed to energy price differences and price-motivated conservation. For example, Kahane (1986) has obtained data for Japanese electric arc steelmaking, cement making, and auto manufacturing. Electricity prices in Japan have long been at about twice the U.S. level. The Kahane data thus provide both a price and an energy consumption level, but care must be taken that process, product, and decision-making differences are taken into account. Detailed data at the lower end of the price scale have been obtained on U.S. auto manufacturing (Price and Ross 1989). Process and product similarities give more assurance here that energy consumption differences are from price-induced conservation.

7.4 THE CONSERVATION SUPPLY CURVES

Conservation supply curves are needed for four energy services: industrial use of electricity, steam, other fuels used for heat, and cogeneration. For electricity, new conservation supply curves have been developed for key manufacturing industries using actual plant experience (the empirical approach) where possible. This section constructs such curves for each energy service.

7.4.1 Industrial Machines

The individual industry curves for electricity have been weighted and combined to yield an overall curve for the manufacturing sector. The weighting is based on the relative fraction of total manufacturing electricity consumption. Although curves have not been developed for all industries, those industries for which curves have been developed are responsible for 34% of electricity consumed by the manufacturing sector. In addition, process similarities suggest that the curves can be reliably applied to additional industries representing 26% of total manufacturing electricity consumption.

Relative electricity consumption by industrial subsectors is summarized in Figure 7.6, which is based on the *Manufacturing Energy Consumption Survey for 1985* (DOE 1988). The shaded areas on the chart correspond to industries for which component cost curves have been developed. This is the 34% mentioned above. Industries to which these curves can be directly extended are indicated by dotted areas. The remaining 40% is shown unshaded.

As shown on this figure, representative industrial-electricity-conservation supply curves have been developed for the following industries:

- Fabrication and Assembly of Metals, SIC 34, 35, 37
- Primary Aluminum, SIC 3334
- Energy-Intensive Process Industries
  - Chlor-Alkali, SIC 2812
  - Stone, Clay, and Glass, SIC 321,323,3296
  - Cement, SIC 324.

A conservation supply curve for all of manufacturing electricity use has been constructed from a

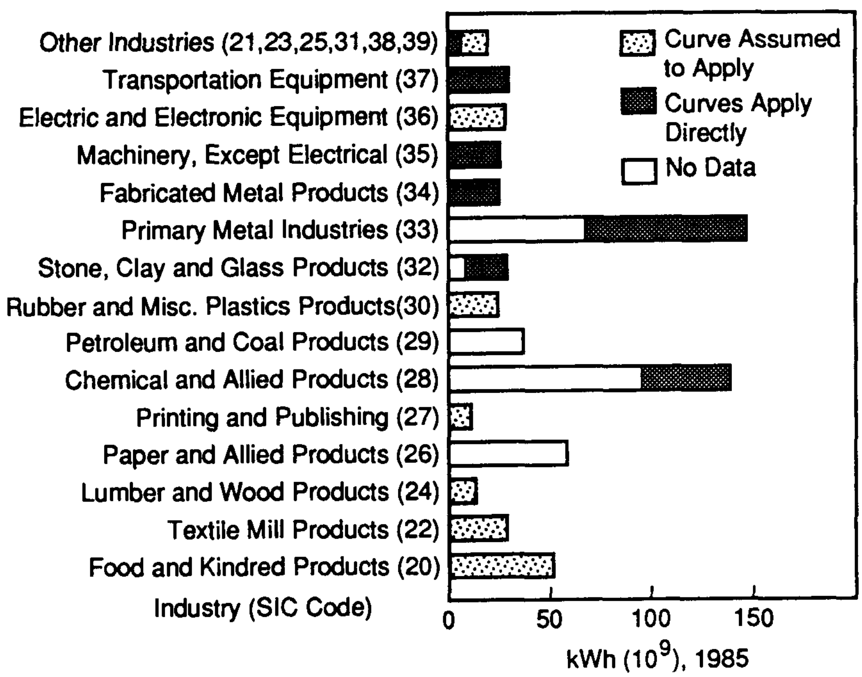

Figure 7.6. Electrical Energy Use by Manufacturing Industries

weighted combination of these three curves. The weighting is based on the relative contribution of each to total electricity consumption for all three. The proposed conservation supply curve has been constructed from price data and actual implementation data. Therefore, it displays the savings likely to be realized at a given price or equivalent incentive.

The most carefully developed conservation supply curve is that for electricity in fabrication and assembly industries, which is based on the automotive manufacturing sector. Process-specific as well as generic technologies are involved. Even a technology that analysts often treat as generic, such as variable speed motor drives, may have major process-specific elements in many applications. Thus, more than half of the cost of many variable speed drives is production-specific engineering costs. Variable speed drive applications continue to be the subject of articles in specialized engineering journals. This is noted simply to emphasize the point that in all major areas of manufacturing energy use, including fabrication and assembly industries and all energy-intensive materials manufacturing, there are important conservation technologies specific to each production process. The new conservation supply curves presented here include this information for sample sectors. Rather than limiting the description of all sectors to a list of generic technologies, we have assumed that the same curves would apply in all sectors. This conservation supply curve is shown in Figure 7.7.

7.4.2 Industrial Steam and Industrial Other Heat

These supply curves will be roughly estimated from ambitious proposals created at 1) a petroleum refinery and 2) an integrated steel mill. The overwhelming virtue of this information is its completeness within its context. After suitable adjustments, the petroleum refinery data are used to determine the conservation supply curve for steam. The steel mill data are used to determine the conservation supply curve for other heat. Only one point is determined in each case, the data not justifying further exploitation. Based on the experience obtained from the more extensive information for the electricity conservation supply curve, conservation supply curves can then be drawn as discussed below. The conservation supply curves presented here are for natural-gas-fired boilers and other heaters.

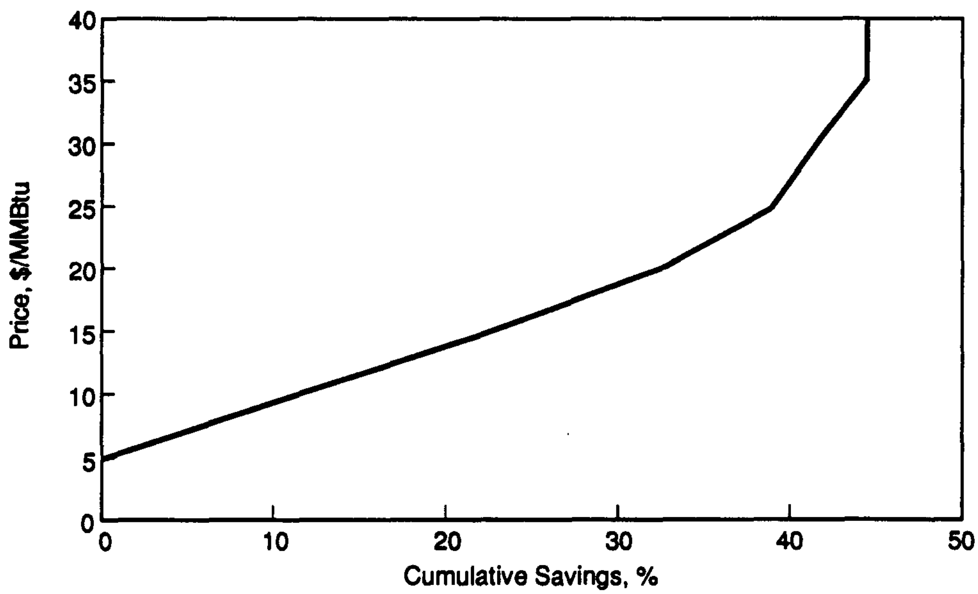

Figure 7.7. Conservation Supply Curve for Industrial Machines

The steam conservation supply curve is based on a conservation plan for a particular refinery as shown in Figure 7.8 (Larsen 1990). When the steam trap maintenance and adjustable speed motor control programs are omitted from this plan, the cumulative savings up to the cogeneration proposal are 12%, with a marginal simple payback of 3 to 4 years for gas costing $4/million Btu (1983$). If we correct for inflation to 1988$ and to a marginal willingness to invest in such projects at a simple payback of 3 years, the marginal price of gas is $5.50/million Btu for 12% savings. Another point is obtained from the judgment that the best investments would be marginally justified at a price of $2.50/million Btu, somewhat under today's (all-industry) average price of about $3.00. The curve is assumed to be a straight line (i.e., not to show an acceleration of costs with increasing savings in the interval to 30% savings). This assumption is based on the typically very large opportunities for reducing steam use through 1) powerful new methods of steam system analysis, 2) the effectiveness of control systems, and 3) the extraordinary scope for redesign of steam systems that were originally designed at a fuel price of about $1.00/million Btu (1988$). The steam conservation supply curve is shown in Figure 7.9.

The curve for industrial other heat was derived from arguments similar to those just noted for the industrial steam curve. Steel mill data were used to produce the conservation supply curve shown in Figure 7.10.

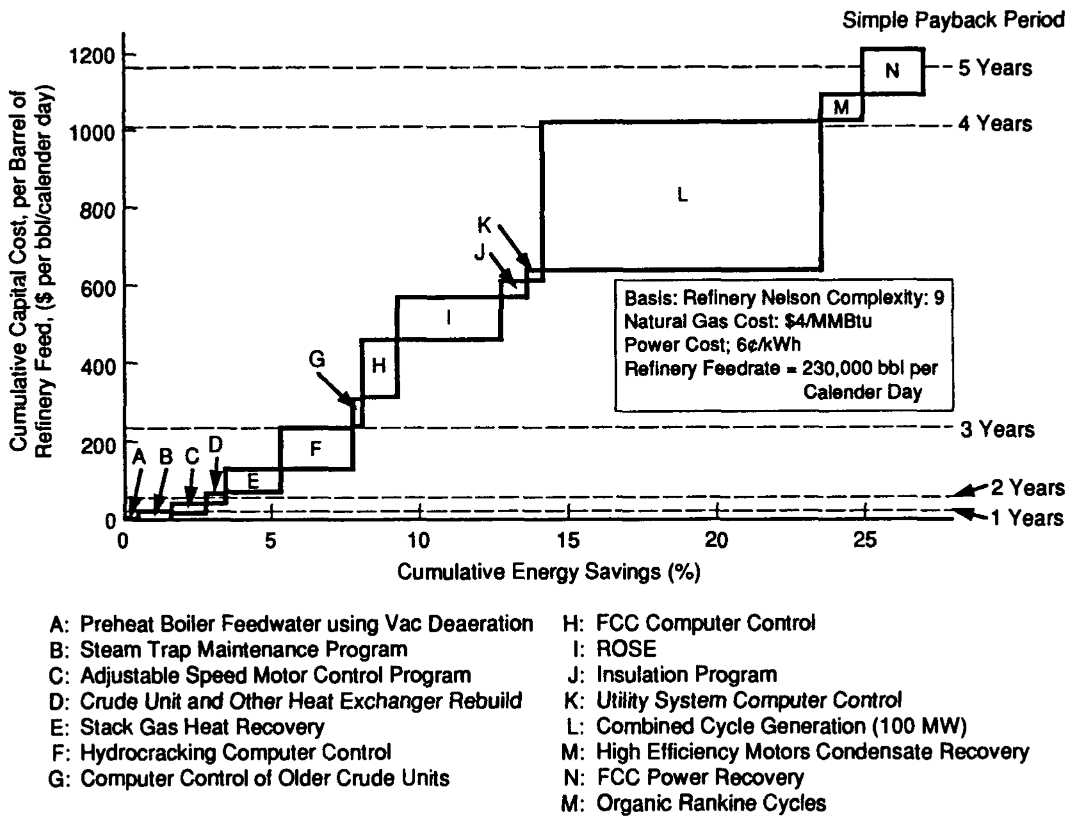

Figure 7.8. Sample Refinery Energy Conservation Plan: Capital Cost, Energy Savings, and Economic Performance

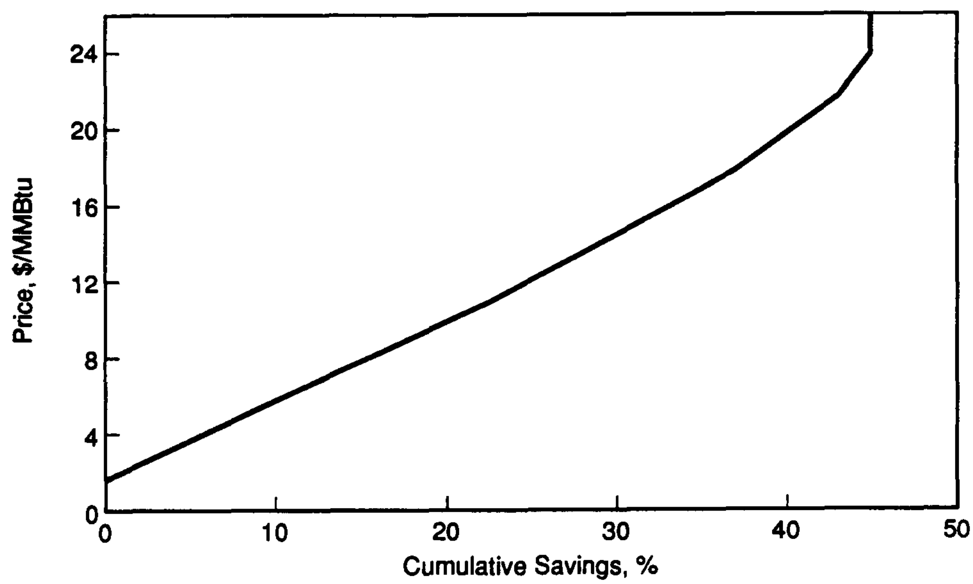

Figure 7.9. Conservation Supply Curve for Industrial Steam

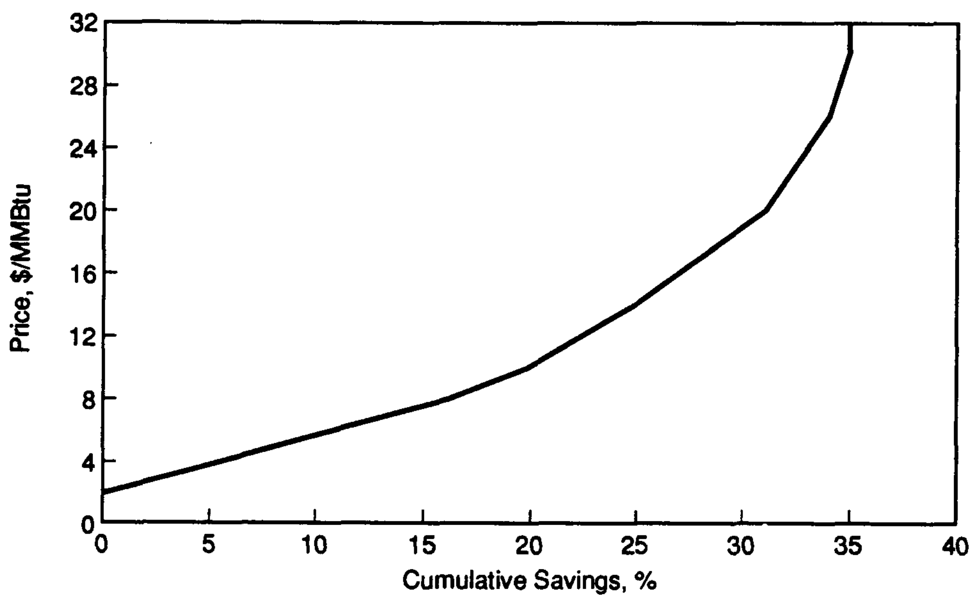

Figure 7.10. Conservation Supply Curve for Industrial Other Heat

7.5 CONSERVATION TECHNOLOGIES

Some important industrial conservation technologies are briefly described below. (These technologies may not be explicitly included in the conservation supply curve data.) As noted in the introduction, adequate data are not generally available to estimate the conservation potential of specific processes. The conservation supply curves developed above are not based on explicit ranking and costing of industrial energy technologies. However, it is useful to put the cost and performance of some key energy conservation technologies into context.

This section describes and gives some example cost and performance figures for generic conservation technologies and incremental process change. Generic technologies are those that provide energy services found throughout manufacturing. Incremental process change can be viewed as "upgrades" or "add-ons" to existing processes in specific industries. Examples of fundamental process change are also given in this section, but cost data are not. Fundamental process changes involve major improvements in productivity, totally new processes, product redesign, or major industrial restructuring. Investment in fundamental process change is rarely for energy reasons, but may have far-reaching impacts on energy use. The investment and adoption incentives for this change may be part of a global climate policy, so some discussion of fundamental process change is clearly warranted. Although fundamental process change involves major investment and industry restructuring, both generic conservation and incremental process change may also involve significant investment by industry, and the impact of investment-related policies should not be ignored.

7.5.1 Generic Technologies

Tables 7.2 and 7.3 illustrate the potential savings from several generic conservation technologies. The sample installed cost [in ($/kWh)/yr for electricity and ($/million Btu)/yr for fossil fuels] represents a broad cost distribution in most cases. A typical value is shown; e.g., mid-range in size and hours of use. Thus, across all applications only one-half to two-thirds of the savings would be achieved at this cost. To

Table 7.2. Characteristics of Sample Generic Conservation Technologies - Electrical

Sample Technology	Sample Installed Cost per Energy Savings Capacity [$/(kWh/yr)]	Energy Savings (% of Applicability)	Applicability (%)
Generic			
High-efficiency lighting (fluorescent system)	0.10	40	3
Energy management system	0.10	7	60
Variable speed motor controls[(a)]	0.20	30	15
High-efficiency motor[(b)]	0.08	4	40
Pump modifications	0.12	20	17
Cogeneration	0.13	20	50

(a) It is misleading to show all adjustable speed drives as generic; aside from HVAC and plant utility applications, most applications are custom-designed process upgrades.
(b) At retirement of existing motors. The estimated total savings potential is $0.4 \times 4 = 1.6\%$ of all electricity.

Table 7.3. Characteristics of Sample Generic Conservation Technologies - Natural Gas

Sample Technology	Sample Installed Cost per Energy Savings Capacity [$/(10^6 Btu/yr)]	Energy Savings (% of Applicability)	Applicability (%)
Generic[a]			
Steam systems improvements	4.0	7	20
Fired heater stack heat recovery[b]	9.0	2.5	40

(a) Based on refinery experience.
(b) Including use of new higher-temperature materials for heat exchange.

determine the price at which the user would be motivated to invest, multiply the number shown by the user's behavioral capital recovery rate. Applicability in the generic category is the percentage of all energy types purchased by industry.

High Efficiency Lighting

An estimated 5% of industrial electricity energy is consumed for general lighting and miscellaneous applications. Although widely used in industry, fluorescent lighting seldom exists in its most efficient form. Efficient fluorescent lighting, which involves high-reflectance fixtures, electronic ballasts, and high-efficiency bulbs, can reduce electricity requirements by 40% or more, compared with standard installations. For area lighting where color rendition is not important, ultra-efficient high-pressure sodium lamps can reduce electricity consumption by up to 50% over mercury lamps.

Energy Management Systems

Energy management systems refer to automatic control systems that can turn off equipment and lighting in nonproduction hours and make adjustments in periods of low production. Submetering and time-of-day records can also enable accounting systems and procedures that lead to further savings. Extensive rewiring of existing plants is typically needed and accounts for the major portion of the costs.

High Efficiency Motors

This technology is established and is expected to have a continuing impact on improved electricity efficiency as older motors are replaced with new, more efficient ones (Baldwin 1988).

Electric Motor Controls

The use of variable speed control for motors is increasing. The potential for energy savings is significant because 70% of industrial electrical energy use is for motor drivers. The most common form of variable speed control is based on semiconductor rectifiers that create a simulated alternating voltage composed of square pulses of modulated time (width). In recent years, the first cost of electronic controls for motors of up to several hundred kilowatts have been significantly reduced. Very large savings have been achieved in specific applications, but the overall savings opportunity is not well known because it depends on the amount of variation in the load, the relative sizing of the motor to load, and the amount of part-load operation. No systematic surveys are available on these characteristics.

Pump Modifications

There are three possible methods of energy savings in pump modifications: 1) improving the pump design to minimize internal losses, 2) improving the selection process so that higher efficiency pumps are implemented, and 3) improving the design with respect to predicting the proper head-flow requirements to reduce system-induced losses (Baldwin 1988; A. D. Little 1980). High-efficiency pumps are available, but at higher costs.

Cogeneration

Cogeneration, the simultaneous generation of process heat and electricity, is largely used by energy-intensive industry with significant joint steam and electricity demand. The "savings" shown, and used in the cost estimate, is from the user's perspective: the electricity generated on site (which replaces purchases). The societal energy savings (of cogenerating rather than centrally generating) is roughly 35% of the electricity generated (heat rate of 7500 Btu/kWh instead of 11,000 Btu/kWh delivered).

Similar benefits, in the form of societal energy savings, may also be realized via a district heating approach, in which waste steam from electric power plants is used at collocated industrial facilities. The greenhouse gas emissions reduction benefits would be greatest if the district heat were provided using nuclear or renewable fuels.

Fuel/Air Controls

Controlling combustion close to the ideal stoichiometric mixture of fuel and air improves the efficiency of operation of a boiler or fossil-fired heater. Accurate sensing equipment allows automatic control of fuel and air flows. Fuel/air controls is a well-established area of technology with considerable further opportunities for improved applications.

Steam System Improvements

Much progress has been made in reducing steam use and fuel use at boilers. However, steam trap maintenance programs and the use of modern pinch analyses to identify opportunities for optimal heat recovery and use continue to offer a substantial opportunity.

High-Temperature Heat Exchangers

The development of advanced heat recovery equipment that would extend temperatures at which heat can be recovered has been an activity at the DOE Office of Industrial Programs. The development of such equipment is potentially important for industries such as glass and steel with very high-temperature heaters.

7.5.2 Incremental Process Change

Tables 7.4 and 7.5 show some example costs and applicability for several incremental process change technologies. As in Table 7.2, the estimates represent a broad cost distribution in most cases. The applicability, however is only for the energy use in the sector in question. There can be much double counting between process upgrades and so-called generic technologies. Among the following, process controls are important but do not significantly overlay energy management. Motor-related "generic" technologies are included in the cement example but not in the other examples.

Primary Aluminum

Existing technology improvements that have not yet been fully included in most U.S. plants include increased anode size, lower current-density, improved automatic process controls, continuous aluminum feeding, and new-design cathodes (Galambas et al. 1988).

Electric Arc Furnace Steelmaking

Electric arc furnace steelmaking is being rapidly improved in terms of electricity intensity (with a 10 kWh/tonne or 2% annual decline). Major further improvement is practical for the average U.S. facility (Center for Metals Production 1987). Among the technologies are preheating, improved insulation, higher power, and improved physical and electrical control of the electrodes.

Table 7.4. Characteristics of Sample Incremental Process Change Technologies - Electrical

Sample Technology	Sample Installed Cost per Energy Savings Capacity [$/(kWh/yr)]	Energy Savings (% of Applicability)	Applicability (%)
Process Upgrades			
Primary aluminum	0.12	8	80
Electric arc furnace steelmaking	0.20	22	80
Cement making	0.25	25	90

Table 7.5. Characteristics of Sample Incremental Process Change Technologies - Natural Gas

Sample Technology	Sample Installed Cost per Energy Savings Capacity [$/($10^6$Btu/yr)]	Energy Savings (% of Applicability)	Applicability (%)
Process Upgrades			
Replace reheat furnaces[(a)]	8.0	60	9
Blast furnace gas to fire Coke ovens[(b)]	12.0	3	80

(a) Including use of new higher-temperature materials for heat exchange.
(b) An example of recovery and efficient reuse of combustible effluents.
Adapted from Larsen and Ross. 1985. "Energy Conservation in Petroleum Refining." Unpublished report. University of Michigan.

Cement Making

Electricity consumption per ton has been rising, as fuel has been conserved (e.g., in switching to dry processing and introducing suspension preheaters) and stiffer environmental standards are met. Some technologies to reduce the intensity are roller, instead of ball-mills, for grinding; better sorting or classification of the materials for grinding and regrinding; computer controls to reduce excessive grinding; and more efficient fan systems (Kahane 1986).

Computer Process Controls

Computer process controls are widely used in several industries and applications are increasing as sensing and computer technologies develop. Development of on-line sensing of the chemical makeup of product streams is, for example, greatly expanding the potential of computer process controls.

Microwave Drying

Microwave technology, a multi-billion dollar market in the residential sector, is slowly emerging in the industrial sector. Microwave drying is geared toward applications that heat or dry moist materials; it can be much more efficient than fuel-fired ovens. The food industry has successfully incorporated many microwave drying applications, and other industries could do so. Recent success with lumber drying provides another example.

Ladle Chemistry

The refining of hot metal and liquid steel is increasingly being conducted in separate steps in ladles. The benefits are closer control of alloy chemistry and fewer constraints on the operation of steelmaking furnaces and blast-furnaces so they can be optimized for their principal functions. This makes it possible to avoid inclusions and create clean steel. The accompanying increase in ladle use requires energy-conserving techniques for heating, drying, and insulating ladles. These techniques are being widely implemented.

Automatic Controls

Through direct rolling (e.g., of steel) and the use of automatic controls, product yield is increased for a given input of materials. Energy and other inputs per unit of production are thus decreased. For example, the thickness of product is controlled on-line with feedback through hydraulic pressure on the rollers and through the current to the motors that control the tension in the sheet. In this way, excess thickness is almost eliminated. Another example is the immediate identification of variations in thickness and shape and of surface imperfections. The immediate correction of these problems reduces both the number of rejections and the need to remelt and reroll.

Surface Treatment with Electromagnetic Beams

Electromagnetic beams can improve surface properties of metals through evaporation, melting, or hardening (Schmidt 1984). Lasers, ultraviolet, and electron beams can be used. The high degree of control possible with the beams and the specificity of their interaction with the product result in improved production and energy savings.

Induction Heating

Induction heating is a well-established technology that still has potential for substantial growth. Because of its speed, induction heating can be much more energy efficient than heating in fuel-fired ovens. This technology is highly controllable (Schmidt 1984).

Black Liquor Recovery/Electric Generation with Turbines

Black liquor is a by-product of the chemical pulping of wood chips in the manufacture of kraft paper. Over a quad of energy annually is obtained from such waste products. Much of the cogeneration is now accomplished with the use of giant recovery boilers, so-called because in combustion of the black liquor, the pulping chemicals are recovered. However, if the liquor can be gasified and then used in a gas turbine, a much higher ratio of electricity to steam would be obtained. This improved ratio better matches mill needs and improves safety because it does not rely on recovery boilers, which are subject to explosions (Kelleher 1987).

Advanced Turbine Systems for Cogeneration

The use of aircraft-derivative gas turbines to generate electric power is receiving increasing interest (Williams and Larsen 1989). The principal variations being considered involve generating steam from the gas turbine exhaust heat and injecting that steam back into the turbine, thus increasing the turbine power output and improving the overall thermal conversion efficiency.

Two types of systems currently being discussed are the steam-injected gas turbine and a variation of this cycle known as the intercooled steam-injected gas turbine, where cooling occurs between two compressor stages. Intercooling decreases the energy used to compress the turbine inlet gas because the energy required to compress a gas increases with the temperature of the gas. The advantage of these systems is that efficiencies approaching that of combined-cycle systems may be achieved with a simpler, modular, single-cycle system.

Recovery and Efficient Reuse of Combustible Effluents

Recovery of organic effluents is half the job. The other half is to develop valuable uses for which the demand is high enough to guarantee the use. The example shown in Table 7.3 is one for steel furnace by-products.

7.5.3 Fundamental Process Change

Fundamental process change can have far-reaching impacts on energy use; however, it is not adopted for its energy impacts, per se. Two examples of this in recent history are the penetration of electric arc furnaces (EAF), which replaced open hearth and basic oxygen furnaces in the steel industry, and thermomechanical pulping (TMP), which replaced conventional pulping processes in the paper industry. Both of these are electrotechnologies that replace conventional fossil-based processes.

In a study of the impact of these technologies, Boyd et al. (1990) estimated three electrotechnology coefficients: A) the effect on the purchased electricity intensity of pulp and papermaking of a 1% shift to thermomechanical pulping,[a] B) the effect of the same shift on the fossil fuel intensity, and C) the effect on the purchased electricity intensity of iron and steelmaking of a 1% shift to electric arc furnaces.[b] The estimated coefficients are in surprisingly good agreement with engineering estimates as shown in Table 7.6. While the coefficients show that the technologies have a large impact on the electri fication of those industries, the same analysis found that energy prices had no significant impact on the rate of adoption. A more detailed analysis[c] of electric arc furnaces found that a doubling of electric prices would delay the optimal adoption date by only eight days.

(a) SICs 261, 262, 263, and 266.
(b) SICs 331, 332 and 339.
(c) Carlson, S., and G. Boyd. 1989. *Adoption of Competing Inventions by United States Steel Producers: The Impact of Energy Prices.* Draft report, Northern Illinois University Department of Economics.

Table 7.6. Coefficients as Estimated Compared with those from Engineering Analysis

Coefficient	Electrotechnology	Intensity	Estimated Coefficient[a]	Engineering Analysis
A	Thermomechanical pulping	Electricity	4.5	3.1[b]
B	Thermomechanical pulping	Fossil fuel	-65	between 0 and -200
C	Electric arc furnace	Electricity	1.0	0.75[c]

(a) The intensities being modeled are in units of trillion Btu per $100 million (1972$) of output.
(b) Based on 2000 kWh/ton for thermomechanical pulping as compared with other pulping.
(c) Based on 700 kWh/ton of steel mill products for electric arc furnace steelmaking as compared with other steelmaking.

Given the importance of the energy impacts of process change, several emerging processes an trends in the energy intensive industries are discussed below. The policy to promote this change, however, is likely to be demonstration programs and incentives to capital stock turnover, rather that energy prices.

Membrane Separation Processes

Membrane processes can be much less energy-intensive than conventional separation technologies. Currently, membrane processes are finding some applications in the food, pulp and paper, chemical petroleum refining, and textile industries, as well as in waste water treatment. Membrane fouling is a problem that may limit the potential of this technology.

Freeze Concentration

Freeze concentration is another separations technology being applied in the food and beverage industry. Freeze concentration and crystallization can be less energy-intensive than evaporation and can improve the quality of the product.

Waste Reduction Using Closed Water Systems

The main energy conservation benefit of this environmentally motivated technology is based on the recovery of material (i.e., water does not have to be re-treated). Currently the main application of closed water systems is in the pulp and paper industry; however, technology development could enable broader application.

New and Improved Catalysts for Chemical Processing

Catalysts have long been used in the chemicals industries. Methods for designing catalysts and predicting their performance are improving. Continuing improvements in existing applications, as well as important new applications, will be possible.

Recycling

Recycling is expected to affect energy-use patterns primarily by reducing energy-intensive manufacturing. A substantial portion of steel, aluminum, and other metals is recycled. Currently, 30% of the input to aluminum making is scrap, and 40% of the input to steelmaking is scrap iron and steel. The challenge is to develop new process technologies and markets for recycled material at the post-consumer stage. Aluminum beverage cans are made from roughly 50% post-consumer scrap. Currently, however, recycled post-consumer steel is used to make metallurgically undemanding products. If the deleterious materials, especially copper, could be removed from the post-consumer scrap during the recycling process, the recycled scrap could be processed into a broader range of products. Substantial amounts of paper are now being recycled, but much higher levels of paper, glass, and plastics can be recycled if markets for the recycled material are strengthened. As for steel, technologies for incorporating recycled material into higher quality products are especially needed to strengthen the markets. Research and development into processes and investments in plant and equipment are needed.

Continued Improvement in Strength and Formability of Plastics, Ceramics, and Other Materials

Much research effort is focused on these technologies. The development of stronger, longer-lasting materials will improve both the performance of energy-using equipment and the longevity of materials-intensive products.

Direct Near-Net-Shape Casting and Direct Rolling

Direct near-net-shape casting, or directly casting into thin shapes, extends continuous casting technology. Recent studies have proposed two direct strip casting technologies: the double roller process and the single roller process. Major technical challenges to be addressed in developing these processes include good surface finishing, dimensional control, uniform thickness, and uniform width. The potential savings in energy, capital, and labor costs are substantial.

Direct and Continuous Steelmaking

The application of direct and continuous steelmaking results in indirect but potentially significant energy conservation. Additional advantages of the technology are lower capital costs and improved control. Development of this technology (replacing the blast furnace, supporting coke ovens and agglommeration mills and, perhaps, steelmaking furnaces) would enable industry to replace antiquated steel mills. Without new technology, the front end of the steel industry in the Unites States will not be replaced in the foreseeable future. Modernization would lead to sharply reduced energy intensities, especially because of coal use.

Increased Corrosion Resistance in Products

This technology extends the useful life of products, so fewer resources would be needed for replacement. It is an example of technology's potential to change the relationship between services provided to final consumers by manufactured products and the rate of manufacturing output.

7.6 NEW TECHNOLOGIES AND IMPACTS

The impact of adopting any new technologies will likely be a reduction in greenhouse gases. The mechanism by which this impact is realized differs for each technology. To forecast total energy use and end-use energy mix (e.g., electric versus fossil and fossil fuel type for different industrial processes), these technologies have been categorized as to the mechanism by which the energy-use changes may be realized and greenhouse gases emissions reduced.

We have categorized the technologies that may mitigate greenhouse gases production into one (or more) effects:

- direct conservation of fossil fuel or electricity consumption
- direct substitution of electricity for fossil fuel in a production process
- indirect conservation of fossil fuel or electricity by changes in use or production of industrial materials
- indirect substitution of electricity for fossil fuel by changes in the use or production of industrial materials.

One can see that there are really two pairs of effects in two categories: 1) conservation versus substitution, and 2) direct versus indirect. Each category is discussed below.

The first mechanism for reducing greenhouse gas emissions is energy conservation. The impact on carbon dioxide is obvious. Lower direct use of fossil fuel reduces direct emissions from the industrial sector. Similarly, lower electric demand reduces carbon dioxide emissions from the electric utility sector.

The effect of the second category, substitution of electricity for fossil fuel, on greenhouse gases emissions depends on the technology and the utility sector. If the technology is highly efficient in its use of energy, which is often the case in electricity-using processes, then the substitution will make up for the thermal losses that occur when electricity is generated from fossil fuel. However, even when the technology does not have a significant efficiency gain, the behavior of the utility sector may result in decreased greenhouse gases emissions. Shifting to nuclear or solar power would also significantly reduce greenhouse gases emissions. Further shifting away from direct fossil-fuel use in the industrial sector to electricity would only amplify this impact.

The above effects may occur directly within the production process; thus, their associated technologies are relatively easy to analyze. Indirect effects may be more difficult. Changes in the use of industrial materials, which tend to be energy-intensive products, may have large effects on energy use. Recycling tends to use less energy than making virgin materials. Using less of a material, through better engineering or design, lowers energy use. These are examples of indirect conservation. Current efforts to minimize waste could also reduce energy consumption in manufacturing processes by encouraging new technology development and implementation. Switching materials may substitute an electric-based material for one based on fossil fuel. A good historical example is substituting aluminum for steel in cans.

Modeling indirect effects requires some care. One cannot model the energy use decision in isolation. One needs to look at the demand for industrial materials and the product mix of specific industries. These indirect effects are captured, in part, by analyzing the shifts that occur in each industrial sector (Boyd et al. 1987). What drives these indirect effects may vary significantly--pollution regulations for disposal of wastewater and solid wastes, consumer demand shifts, international competition, or increased efficiency in the entire product cycle.

The last two columns of Table 7.7 summarize the effects of a selected list of technologies in terms of their energy impacts. Energy conservation is designated by E, electricity, and F, fossil fuel. In a few cases, shifting to lower carbon fossil fuels, such as natural gas, may reduce greenhouse gas emissions. The case of lower carbon fuels is represented by L. Electric substitution is represented by S. The type of mechanism, either direct conservation or process change, and indirect changes in material use are indicated in the last column.

Before a new technology can have any impact on greenhouse gas emissions in the industrial sector, it must be a mature commercial technology. Table 7.7 indicates whether the technology is commercially mature, emerging, or under development. The scale of maturity is gray, not black and white, so some technologies are listed in more than one column. Energy auditing programs have been implemented by the DOE and by utilities to help industrial plants identify opportunities for conserving energy through use of mature technologies and changes in operating practices.

When the technology is not mature, it may be worthwhile to encourage the commercialization process with additional research and development or technology demonstration programs. While the private sector may have market reasons for developing these technologies, e.g., potential cost savings or efficiency, government assistance may be warranted for technologies that have the additional benefit of reducing greenhouse gas emissions. The following technologies from Table 7.7 might benefit from increased research and development funding:

- natural-gas-based ethylene
- recycling steel and plastics
- nonchlorine bleaching
- thin casting
- direct steelmaking
- corrosion-resistant products
- black liquor gas turbines.

Other technologies are closer to the commercial stage and could benefit from an aggressive demonstration program. Industry tends to be reluctant to adopt technologies that might hinder the production process, while "only saving energy." Demonstrations jointly funded by government and the private sector, like the current DOE demonstration project, would help prove the commercial viability of new industrial technologies in what is an increasingly competitive world marketplace. Technologies listed in Table 7.7 that might benefit from demonstration are the following:

- high-efficiency lighting
- motor controls

Table 7.7. Technologies with a Potential Impact on Greenhouse Gas Emissions

Generic	Established	Emerging	Under Development	Impact on Energy-Use Patterns	Mechanism of Effect
Generic					
High-efficiency lighting (fluorescent, high-pressure sodium)	*	*		E	Direct
Energy management systems for factories		*		EF	Direct
Electric motor controls (variable drives)		*		EF	Direct
High-efficiency motors	*			E	Direct
Pump modifications	*	*		E	Direct
High-temperature recuperators		*	*	F	Direct
Fuel/air controls	*			F	Direct
Incremental Process Change (Upgrade)					
Computer process controls	*		*	EF	Direct
Microwave drying		*	*	S	Direct
Ladle chemistry	*			F	Direct
Direct rolling and automatic controls	*	*		EF	Direct
Surface treatment with electromagnetic beams		*		D	Direct
Induction of electrical resistance heating	*			D	Direct
Black liquor recovery/electric generation with turbines			*	EF	Direct
Advanced turbine systems for cogeneration (steam-injected gas and intercooled steam-injected gas)		*	*	E	Direct
Fundamental Process Change					
Separation based on new membranes, absorbing surfaces, critical solvents, & freeze concentration		*	*	S	Direct
Ethylene chemistry based on natural gas feedstocks			*	L	Direct
Waste reduction using closed water systems		*		EF	Direct
New and improved catalysts for chemical procedures	*	*	*	EFL	Direct
Recycling paper and plastics (i.e., new products)		*	*	EF	Indirect
Nonchlorine bleaching of pulp	*		*	F	Indirect
Continued improvement in strength and formability of plastics and ceramics	*		*	EF	Indirect
Recycled scrap (e.g., scrap separation technology)		*	*	EFS	Indirect
Thin casting			*	EF	Indirect
Direct and continuous steelmaking			*	F	Direct
Coal-based aluminum smelting			*	S	Direct
Increased corrosion resistance in products	*		*	EF	Indirect

Notes: E = Improved electricity efficiency, F = Improved fuel efficiency, L = Lower carbon fuels, S = Switching electricity for fuel.

- separations applications
- direct rolling of steel
- electromagnetic surface treatment
- corrosion resistant steels
- advanced gas turbines.

The technology impacts for the industrial sector's contributions to reduction of greenhouse gas emissions may be broadly categorized into the four groups used earlier to describe technology impacts on energy use:

- E - improved efficiency in direct electricity use (or cogeneration of electricity)
- F - improved efficiency in direct fuel use

- L - lower carbon (hence, lower emissions of greenhouse gases) fuel types
- S - substitution of electricity generated from lower-carbon-emitting sources for fossil fuel use in the industrial sector.

These impacts may be achieved through direct and indirect mechanisms in the industrial sector. The types of policies that may be used to achieve the direct and indirect impacts discussed above will vary. Broad fiscal and regulatory policies to reduce greenhouse gas emissions are described in Volume II of this report.

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8.0 RESIDENTIAL AND COMMERCIAL BUILDING TECHNOLOGY

This section focuses on the potential for energy conservation in the buildings sector because of this sector's large contribution to total U.S. carbon emissions. To put building energy use in context, we first briefly discuss trends in total energy use in the United States. U.S. energy use and GNP grew in step until the first major oil crisis in 1973. From 1973 to 1985, energy use remained constant, despite a 35% increase in GNP and significant increases in the building stock (Rosenfeld et al. 1991). From 1984 to 1986, energy use remained essentially constant at 74 quads (1 quad = 1×10^{15} Btu). The collapse of oil prices in 1986 reduced efforts to improve energy efficiency. Between 1986 and 1989, energy use in the United States increased by 9.4% (from 74.2 to 81.2 quads) (EIA 1990).

8.1 ENERGY USE IN BUILDINGS

In discussing building end-use energy, we will use data from 1985, as that is the last year for which we have a comprehensive breakdown. Total energy consumption in the United States in 1985 was 73.9 quads. Total energy production was only 64.8 quads, leading to a net import of 9.1 quads. In 1985, the United States imported 2.4 quads of coal and 10.6 quads of petroleum products. Energy use by sector is shown in Table 8.1.

Table 8.1. 1985 U.S. Primary Energy Consumption

Sector	Energy Consumed (quads)
Residential Buildings	15.3
Commercial Buildings	11.6
Industry	27.0
Transportation	20.0
Total	73.9

Source: EIA 1988a.

Buildings use as much energy as industry and more than transportation. In 1985, 36% of the energy used in the United States went into buildings. This amounted to 26.9 quads, which cost building occupants approximately $173 billion (BNL 1988). In 1985, energy used in buildings in the United States released approximately 370 million tons of carbon into the atmosphere. Building energy use as a percent of national energy use has increased from 32.7% in 1979 to 36.3% in 1985. During this period, commercial sector primary energy use has increased 9.1%, and residential energy use has increased 0.7%. Industry and transportation shares of energy use have declined 17% and 1.7% respectively.

The decentralized nature of the construction industry hinders efforts to increase building energy efficiency. Thousands of contractors construct buildings, but the contracting companies are not large enough to justify research or monitoring facilities devoted to energy efficiency. Buildings are generally unique and their energy performance is site-specific and weather-dependent. The lack of consistent building efficiency rating systems also increases the difficulty of assessing energy performance. Changes in construction techniques or more expensive equipment are difficult to justify when energy savings are uncertain. Thus, improvements in building energy efficiency have generally lagged far behind that of centralized industries.

In addition, the landlord-tenant problem is a significant structural barrier to energy efficiency in both residential and commercial buildings. This widespread and pernicious market failure occurs because tenants who do not pay the energy bill have no incentive to use energy efficiently. Alternatively, if the tenants do pay the energy bill, the landlord has little direct incentive to retrofit a building or construct an efficient building in the first place.

Energy use in commercial and residential buildings is broken down by end use in Table 8.2.

Table 8.2. 1985 Primary Energy Consumption for Commercial and Residential Buildings

Building Type	Electricity	Gas	Oil	Other	Total	%
Residential						
In Quads						
Space heating	1.77	2.96	1.10	0.40	6.16	40.3
Water heating	1.57	0.84	0.10	0.06	2.57	16.9
Refrigerators/ freezers	1.85				1.85	12.2
Lighting	1.02				1.02	6.7
Air conditioners	1.06				1.06	7.0
Other	1.79	0.76		0.03	2.60	16.9
Residential totals	9.06	4.56	1.11	0.49	15.26	100.0
Commercial						
In Quads						
Space heating	0.90	1.98	0.78	0.18	3.84	33.2
Lighting	2.95				2.95	25.5
Air conditioning	1.00	0.11			1.11	9.6
Ventilation	1.39				1.39	12.0
Water heaters	0.32	0.18	0.08	0.58	5.0	
Other	1.38	0.24	0.01	0.010	1.71	14.8
Commercial totals	7.93	2.51	0.86	0.28	11.58	100.0
Total Residential and Commercial Consumption 1985	17.01	7.08	1.98	0.77	26.84	100.0

Source: BNL 1988.

Electricity is the dominant fuel in both the residential and commercial sector. In 1985, 794 billion kWh were used in residential buildings and 605 billion kWh were used in commercial buildings. These totals account for 60% of the total electricity use in the United States for that year (EIA 1987). Space heating, water heating, and refrigerator/ freezers account for almost 70% of residential primary energy. Space heating, lighting, and air conditioning are the largest commercial energy end uses.

Space heating is the largest commercial end use because retail sales, not office buildings, have the largest floor area. (See the section below that describes the commercial stock.) Retail buildings usually have smaller internal heat gains than offices and consequently require significant space heating. Large office buildings have large internal gains and low surface-area-to-volume ratios and consequently have large cooling loads (even in cool climates).

Lighting and HVAC systems are extremely important commercial end uses because they contribute most to utility system demand. Utility rates have two incentive structures to reduce peak loads. Electricity rates can be as much as double during daytime peak demand periods. Additionally, about one third of the electricity bill for a large building is a peak demand charge to pay for the generating capacity that the utility must keep on line to meet its largest load.[a] Space heating peak demand generally receives less attention because it is usually provided by natural gas, which is not subject to hourly price variations.

8.1.1 Description of Commercial Stock

In the United States in 1986, there were approximately four million commercial buildings with over 58 billion square feet (bsf) of floor area. Mercantile and service and office space are the largest categories in both square footage and number of buildings. The breakdown of commercial buildings by type and floor area is given in Table 8.3.

Table 8.3. U.S. Commercial Building Stock 1986

Building Type	Number of Buildings	Floor Area (bsf)
Assembly	575	7.34
Education	241	7.32
Food Sales and Service	303	1.99
Health Care	52	2.11
Lodging	123	2.18
Mercantile and Service	1,287	12.81
Office	614	9.55
Warehouse	549	9.00
Other	171	3.01
Vacant	238	2.93
Total	4,153	58.2

Source: EIA 1988b.

(a) Personal communication with Joe Eto, Lawrence Berkeley Laboratory (LBL), April 1989.

8.1.2 Description of Residential Stock

As of 1987, there were 90.5 million households in the United States. The breakdown of the housing stock by ownership and number of units is shown in Table 8.4.

Table 8.4. Residential Housing Stock

Type	Owned (millions)	Rented (millions)	Total (millions)
Single-family	51.6	8.9	60.5
2 to 4 unit buildings	2.0	8.1	10.1
5 or more unit building	1.0	13.9	14.9
Mobile home	4.3	0.9	5.1
Total	58.9	31.8	90.5

Source: EIA 1986.

Implementation of conservation measures is heavily dependent on climate, residence size, and ownership. Buildings in cold climates can achieve dramatic heating energy savings. In the 1979 Community Services Administration/National Bureau of Standards weatherization demonstration program, cost-effective space heating savings of 43% were achieved with shell and heating system retrofits (Cohen et al. 1991). Energy conservation measures are more likely to be employed in single-family residences that are occupied by the owners. Rental properties often use excessive amounts of energy because the owner does not pay the energy bill, and the tenant is not willing to invest conservation money in property owned by someone else.

Single-family homes dominate the new construction market. The South is the area of fastest growth. Since 1966, over 40% of new homes have been built in the South (BNL 1988).

8.2 RESIDENTIAL BUILDINGS

The data shown below for residential equipment and appliances are the latest that are publicly available. In the context of the Department of Energy's appliance efficiency standards analysis, data are currently being collected on fluorescent ballasts (both residential and commercial), pool heaters, ranges/ovens, space heaters, mobile home furnaces, room air conditioners, televisions, and water heaters. When collected and made available in late 1991 or early 1992, these more recent data will supersede some of that presented below.

8.2.1 Space Heating

Space heating consumed 40%, or 6.16 quads, of the primary energy used in residences in 1985 (BNL 1988). Residences in the United States use a wide variety of fuels for space heating: 55.4% use natural gas, 16.8 % use electricity, 12.4% use fuel oil, and 7.5% use wood (EIA 1989).

Technology Description

Since gas-fired warm air furnaces are the most common type of residential space heating, this section will analyze the first cost and energy savings of efficiency improvements for this type of furnace. Heat pumps for electrically heated houses are discussed in the section on residential air conditioning.

The standard measure of efficiency for furnaces is called the annual fuel utilization efficiency (AFUE). The AFUE rating includes steady-state operation as well as on and off cycling tests. The average lifetime for a central furnace is 23 years (DOE 1982a). Thus, a typical central furnace in a U.S. residence is 10 or more years old and has an AFUE rating of approximately 66%.

The energy efficiency options for gas furnaces are intermittent ignition devices (IID), two-stage burners, induced draft, and a condensing heat exchanger. The technologies are described below and the thermal performance and cost data are given in Table 8.5.

An intermittent ignition device provides an on-demand spark and replaces a continuously burning pilot light. Induced draft furnaces use a fan after the heat exchanger to exhaust the combustion

Table 8.5. Cost and Performance Data for an 80 kBtu/hr Gas-Fired Forced-Air Furnace[a]

Option Number	Design Option	Consumer[b] Purchase Cost (1988$)	AFUE (%)
0	Inefficient baseline	370	62
1	Level 0 +IID	415	71
2	Level 1 + 2 Stage Burner	560	74
3	Level 1 + Induced Draft	555	80
4	Level 3 + Additional Insulation	570	80.5
5	Level 4 + Condensing Heat Exchanger	900	92

(a) Engineering information on efficiency measures is from DOE (1988).

(b) Does not include installation costs, which are on the order of $500.

gases. With induced draft, a larger heat exchanger can be used and consequently more heat is removed from the exhaust gases. A condensing heat exchanger condenses the water vapor in the exhaust gases to recover the heat of vaporization.

Condensing furnaces, which have entered the residential space heating market in large numbers (more than 300,000 per year) over the past several years, are the most efficient, with AFUE ratings of up to 97% (DOE 1988). More typically, AFUEs of 92% to 95% are achieved. In the pulsed-combustion condensing furnaces, a spark ignites the initial natural-gas-air mixture. Ignition of the mixture forces the intake valve shut. The ejection of the hot gases creates a vacuum to draw in more gas and air to be burned. After the first mixture burns, the gas and air are ignited by residual heat from the previous combustion cycle. Shock waves occur in the pulse combustion cycle, resulting in efficient transfer of heat to the metal wall and then to the supply air.

Energy Performance and Costs

Cost data in Table 8.5 are from the Lawrence Berkeley Laboratory appliance standards research project.[a] Note that the consumer purchase cost assumes a markup of 190% over manufacturing costs and $15 dollars for shipping.[b] Installation costs are approximately $500 for all models. An extra $100 to install a polyvinyl chloride condensate drain has been included in the purchase price of Option 5 (condensing furnace) in order to make its price comparable with the other options. However, in new construction, condensing furnaces are cheaper to install than conventional furnaces because exhaust gases are cool and a high-temperature chimney is not necessary.

The costs given above assume low tooling costs per furnace (mass production) and a competitive market to avoid overcharging. Consequently, the furnace prices given above are representative for the large market-share furnaces (i.e., efficiencies of 80% or less). The installed cost for a condensing furnace is $1500-1600 in the north-central United States.[c] Costs for condensing furnaces may be higher in regions where few are sold.

Early model condensing furnaces had corrosion problems and failed far short of the 23-year average furnace life. Nitric acid in the condensed water vapor corroded the stainless steel heat exchangers. Improved stainless steel alloys with seamless construction in areas likely to corrode seem to have solved the problem.

8.2.2 Water Heating

Water heating consumed 17% of the energy used in residences in 1985 (BNL 1988), or 2.6 quads of primary energy. The only larger residential energy use is space heating. Almost 100% of U.S. residences have hot water heaters (EIA 1986), and typical residential hot water use is 16 gallons per person per day (Usibelli 1984). Forty- to fifty-gallon tanks are typical. The predominant fuel

(a) Personal communication with Isaac Turiel (LBL), March 1989.

(b) LBL Residential Energy Model. (Cited hereafter as LBL Residential Energy Model.) Personal communication with Jim McMahon, LBL, March 1989.

(c) Personal communication with Jeff Schlegel, Wisconsin Energy Conservation Corp., July 1990.

types for residential water heating are natural gas (54.4%) and electricity (35.3%) (EIA 1989). Energy efficiency options specific to these two types will be analyzed in this chapter.

Technology Description

Gas, electric, and oil water heaters all have average lifetimes of 13 years (DOE 1982a). Thus, the average water heater in the United States is 6 to 7 years old. Water heater efficiencies have changed only a few percent in the last 10 years. The national average energy factors for new gas and electric water heaters are approximately 55% and 88%, respectively.[a]

A 55% efficient gas water heater typically has an energy cost of $191 per year assuming that natural gas costs $0.60/therm. An 88% efficient electric water heater has an energy cost of $430 per year (at 7.6 cents/kWh) (GAMA 1985). These numbers are averages for comparison; actual energy use will depend on the number of occupants and how much hot water they use. However, electric water heaters cost more to operate for a given amount of service than gas water heaters. Therefore, for identical measures, payback times for electric water heaters will be shorter than those for gas water heaters.

Savings from design options depend heavily on the use patterns. If standby losses are reduced but the water is in constant demand, the percentage savings will be less than for a water heater with occasional demand. Conservation measures are discussed below. Energy savings and costs are summarized in Tables 8.6 and 8.7. The baseline gas and electric water heaters have 0.75 inches of fiberglass insulation (0.5 lb/ft^3). These numbers are based on Department of Energy estimates from the early 1980s and are currently being updated.

Energy used to heat water can be reduced independently of efficiency by decreasing water use. Low-flow showerheads and more efficient clothes washers and dishwashers will reduce water use.

(a) Personal communication with Jeff Schlegel, Wisconsin Energy Conservation Corp., July 1990.

Table 8.6. Gas Water Heaters

Level	Design Option	Consumer Purchase Cost[a] (1988$)	Energy Factor (%)
0	Baseline	245	47
1	1.5" Fiberglass insulation (2 lb/ft^3)	260	54
2	2.0" Foam	265	59
3	Level 2 + Heat trap	270	61
4	2" FG ins. + IID and Flue damper	510 [b]	67
5	Level 2 + IID and Flue damper	510 [b]	70
6	Level 5 + Multiple flues	610 [b]	73
7	Pulse condensing	1,010 [b]	82

(a) Cost data from LBL.
(b) The cost for Levels 4, 5, 6, and 7 does not include an estimated $125 to provide electrical power.
Source: DOE 1982b.

Table 8.7. Electric Water Heaters

Level	Design Option	Consumer Purchase Cost (1988$)	Energy Factor (%)
0	Baseline	256	76
1	1.5" Fiberglass insulation (2 lb/ft^3)	271	87
2	2.0" Foam	280	89
3	Level 2 + Heat trap	284	90

Source: DOE 1982b.

Several free or low-cost steps can be taken after installation to improve the efficiency of installed gas or electric water heaters. Standby losses can be reduced if the water temperature can be turned down from 140°F to 120°F or even 110°F. A booster coil can be used if there is a dishwasher so that the water temperature can still be turned down. Increasing the amount of insulation surrounding the tank by up to a factor of 5 to reduce standby losses usually has a payback period of less than 1 year. Installing a U joint or one-way valve in the hot water outlet pipe will prevent convective flow into the distribution piping. The distribution pipes can also be insulated, though this is difficult to do except during construction.

For both gas and electric water heaters, increased jacket insulation and heat traps can be designed in, rather than retrofitted. For gas water heaters, there are many design options for higher efficiency. The pilot light input can be reduced by using a smaller orifice for the pilot jet. Electronic ignition combined with a flue damper eliminates the constant flow of heat up the flue from an idle pilot light. Submerged combustion chambers eliminate the central flue. The chamber is surrounded by water and therefore heat cannot escape from the bottom or sides of the combustion chamber without heating the water. The recovery efficiency of a water heater can be improved by increasing the flue baffling and using a forced draft to remove the subsequently cooler, less buoyant air. Multiple flues provide more surface and thus transfer more heat. Pulse combustion and flue gas condensation are furnace technologies that could be applied to water heaters, but are not yet commercially available. For a description of these technologies, see the discussion under residential space heating.

Development Needs

Heat pump water heaters have the potential to increase electric water heater efficiency beyond 100%, and save substantial amounts of energy. Further research is needed to make these devices commercially viable on a large scale.

8.2.3 Windows

Technology Description

The basic types of residential windows in use today are single-glazed, double-glazed, and double-glazed with a low-emissivity (low E) coating. Windows insulate because of the dead air space on either side of the glass or between the panes. Glass itself has a high conductivity. Thus, the thickness of the glass has little effect on the thermal performance of the window. However, windows can be produced with coatings that reduce radiative losses by reflecting selected wavelengths. Additionally, windows with multiple glazings can be filled with heavier-than-air gases or solids to reduce thermal conductivity across the window.[a]

The shading coefficient and R-value are measures of a window's energy performance. The shading coefficient is the ratio of solar heat gain through a particular window system to the solar heat gain through a reference window system (1/8 in. glass) under the same conditions. The R-value is the thermal resistance of the window (hr-ft^2-^{o}F/Btu). An ideal residential window has a high shading coefficient, a high transmissivity of visible light, and a high thermal resistance. For most multiple-pane windows, the lifetime is limited by the durability of the glazing seal. Typically, seals are assumed to last 20 years. Single-glazed windows have essentially infinite lifetimes if properly installed and maintained. Commercially available windows and promising designs under development are listed in Table 8.8. Not listed there are the so-called "spectrally selective" glazings, which cost no more than double paned, low-emissivity glass, but block all infrared and ultraviolet radiation. This property is especially valuable in warm climates because roughly half of solar radiation is not in the visible spectrum. When this invisible radiation is blocked, significant cooling savings can be achieved without reducing the transmissivity of the window to visible light.

Note that the window R-values listed in Table 8.8 assume one-dimensional heat transfer across the window surface. The center-of-glass R-values do not incorporate one- and two-dimensional heat transfer effects of the window frame. These effects are most significant for small windows with high-conductivity frames. Except in the case of a single-glazed window with a wood frame, overall window R-values are lower than center-of-glass R-values.

The windows cost data are from NAHB (1986). Window costs in Table 8.8 assume standard 3 by 4 foot models with wood frames. The absolute

(a) See technical discussion of these types at the end of this section.

Table 8.8. Residential Windows

Type	Center-of-Glass R-Value ($hr\text{-}ft^2\text{-}^\circ F/Btu$)	Commercially Available?	Incremental Cost over Single Glazing ($1988\$/ft^2$)
Single-glazed	1	Yes	0
Double-glazed	2	Yes	2-5
Double-glazed, low E	3	Yes	3-7
Double-glazed, low E with argon fill	4	Yes	3-9.50
Triple-glazed, 2 low E coatings, krypton-argon fill	8	Yes	8-14.50[a]
Double-glazed, silica aerogel filled and evacuated to 0.1 atmosphere	8-12	No	--

(a) As a result of economies of scale in manufacturing, the incremental cost of triple glazing with 2 low E coatings, krypton/argon fill is likely to drop to a range of \$5.50-\$12 compared with single glazing by the mid-1990s.

cost data have a large degree of variation because there are many different frame types, qualities, and shapes of windows. However, the incremental costs are reasonable.

Development Needs

1. Simulations and testing have shown that windows with R-values of 8 to 10 are more energy efficient than an insulated wall, even on the north side of a building, because they admit more useful solar gain than the heat that they lose. Further research is needed on selective coatings, low-conductivity fills, and durable window seals in order to realize these high R-values in a low cost, commercially available window.

2. Testing and analysis methods need improvement in order to evaluate window performance accurately and to compare window products in specific locations and building types.

Market Penetration

Between 1972 and 1988, insulated glass windows went from a 17% to a 78% market share of the residential sector (Cunningham 1989). Low E glass production increased from 42 million square feet in 1986 to 120 million square feet in 1988 (Cunningham 1989). In the next few years, gas fills (coupled with low E coatings) will expand their market share from currently low levels. Most other high-tech windows will not have a significant share of the market within the next few years, though some may expand their market share rapidly in the mid-1990s.

Description of Energy Efficient Windows

Low-Emissivity Coated Windows. For a typical double-glazed window, approximately 75% of the heat transfer between the two panes of glass is radiative.[a] Low-emissivity coatings reduce this heat transfer because they reflect infrared radiated by the warm room while still transmitting visible light. Consequently, winter heating loads are significantly reduced. Summer cooling loads are reduced slightly by low-emissivity coatings because infrared energy radiation from the warm surroundings to the cooler room is blocked.

Two types of low-emissivity coatings are currently used on windows: sputter and pyrolitic. Sputter coatings are applied after the glass is produced. The resulting film can be scratched and will oxidize in a humid environment. Thus, sputter-coated glass must be used in a sealed unit.

(a) Personal communication with Darieush Aresteh, LBL, April 1989.

However, sputter coatings usually have a lower emissivity and are thus generally found to have better thermal performance than pyrolitic coatings.

Pyrolitic coatings have many processing advantages over sputter coatings. They are applied during the float process, and a molecular bond forms between the coating and the glass. The resulting film is scratch resistant and will not oxidize when exposed to air. Pyrolitic coated glass can also be cut or heat treated after coating. Because pyrolitic coatings are scratch resistant and will not oxidize when exposed to humidity, they can be used on single sheets of glass. Thus, pyrolitic coatings can be used for storm windows or add-on panels to retrofit for higher thermal performance. Currently, the majority of low E windows sold are sputter coated.

Low Conductivity Windows. With low-emissivity coatings reducing radiative losses, conduction becomes the main heat loss mechanism in a double-glazed window. Windows can be filled with heavier-than-air inert gases to reduce the glass-to-glass thermal conductivity. Because of cost limitations, argon is the primary gas used, although gases such as krypton and xenon would yield better performance.

Future windows may use hard vacuums or silica aerogel fills to reduce the thermal conductivity of the window. Vacuums reduce conductivity because fewer molecules are present to transfer heat through molecular collisions. Silica aerogel consists of long chains of fused silica molecules occupying approximately 5% of the volume of the material. Air pockets trapped in the silica matrix give the material its insulating properties. The air spaces in the material are smaller than the wavelength of light. Thus, scattering is limited, provided that the thicknesses of the silica aerogel is half an inch or less. Silica aerogel is a brittle material that fails easily in tension, but is strong in compression. Therefore, it is used under vacuum to place it in compression. At 0.1 atmospheres, silica aerogel has an R-value of 20 hr-ft^2-^{o}F/Btu per inch.

8.2.4 Building Shell Insulation

Technology Description

Standard insulating materials work by trapping an air layer in a porous material. Two predominant types of insulation are used in buildings today: fiberglass and rigid foam. In 1985, foam accounted for 66% of the insulation used in new commercial building construction, half the insulation in new single-family residences, and roughly one third of the residential retrofit use (Shea 1988). Fiberglass insulation accounted for most of the rest. The saturation of blown cellulose insulation is not well known, but seems to have increased in the past few years. Radiant barriers, which reflect infrared radiation using metallic foil surfaces, have also become more popular in some applications.

Styrofoam insulation is often blown with chlorofluorocarbons (either CFC-11 or CFC-12), which deplete the ozone layer. (See the discussion on the environmental impact of chlorofluorocarbons in the section on refrigerators.) The Montreal Protocol, which calls for large reductions in chlorofluorocarbons production, was signed by 24 nations in 1987. Reductions in CFC use have been proceeding more rapidly than those called for in the 1987 agreement. Thus, styrofoam use in buildings may decrease drastically in the near future, unless blowing agents are found that do not cause ozone depletion. Nonetheless, this report will discuss fiberglass and styrofoam insulation, since much work is now under way to replace ozone-depleting chlorofluorocarbons in such processes.

Fiberglass building insulation consists of strands of silica fibers backed with aluminum foil and paper. The foil reflects heat back to the interior space while air trapped in silica reduces conduction losses. Fiberglass is used inside exterior walls or in ceilings because of its low cost (see Table 8.9), ease of installation, and minimal environmental hazard. It is not used in foundations or outside of the exterior walls because of its inability to stand up to

Table 8.9. National Average Contractor-Installed Cost of Insulation in New Residential Construction

Insulation Type	Thickness (inches)	R-Value (hr-ft^2-°F/Btu)	Installation Method	Cost (1988$/ft^2)
Fiberglass[(a)]	3.5	11	Batts	0.40
Fiberglass[(a)]	5.5	19	Batts	0.54
Polystyrene	1.0	5	Rigid sheets	0.55
Polystyrene	2.0	8	Rigid sheets	0.90
Urethane	1.5	10	Rigid sheets	0.86
Urethane	2.0	14	Rigid sheets	1.00
Isocyanurate	0.5	4	Rigid sheets	0.48
Isocyanurate	1.5	8	Rigid sheets	0.74
Cellulose (ceiling)	3.5	11	Blown[(b)]	0.30
Cellulose (ceiling)	3.5	19	Blown[(b)]	0.43
Cellulose (ceiling)	8.7	30	Blown[(b)]	0.61

(a) Fiberglass data assume that studs are 16 in. on center.
(b) NAHB 1986.
Source: Kiley (1988).

the weather. Typically fiberglass insulation is assumed to have an effective 20-year lifespan. Fiberglass can be blown in through small holes to retrofit uninsulated walls and ceilings (cellulose insulation can also be used in these applications).

Energy Performance and Costs

The retrofit wall insulation costs given in Table 8.10 have a large degree of uncertainty. They are from the SERI report (1982) and are adjusted to 1988 dollars. All labor costs are union costs, which are typically 30% higher than nonunion costs. Labor costs represent 66% of the total cost. The highest costs are values for Anchorage, Alaska, while the lowest costs are for Miami, Florida. The retrofit ceiling insulation costs are derived from the Michigan Electricity Options Study, adjusted to the national average based on MEANS cost indices, adjusted to 1988 dollars.

Proper installation of blown insulation in walls will, in many cases, reduce infiltration. In addition to reducing heat transfer through walls, insulation

Table 8.10. Range of Regional Contractor-Installed Costs of Insulation for Residential Retrofits

R-Value (hr-ft^2-°F/Btu)	Location	Access	Cost (1988$/ft^2)
11	Wall	Wood, aluminum, stucco siding	0.48-0.92[(a)]
11	Wall	Painted gypsum	0.79-1.63[(a)]
11	Attic	Unfinished crawl space	0.33
19	Attic	Unfinished crawl space	0.43
30	Attic	Unfinished crawl space	0.60

(a) If fixing siding anyway, cost for retrofit wall insulation will be lower.
Source: SERI 1982; Krause et al. 1988b.

will increase the mean radiant temperature of walls, ceilings, and floors. Increased mean radiant temperature implies that for a given air temperature, occupants will be more comfortable. Alternatively, air temperatures can be reduced while maintaining the same level of comfort.

Development Needs

Development needs are research on

1. non-chlorofluorocarbon blowing agents for foam insulation

2. Swedish low-energy and zero energy home construction techniques, including "I-beam" construction, which drastically reduces thermal breaks in walls, while cutting capital costs of walls

3. the capital cost benefits of reducing the size of the heating system or eliminating it altogether through use of tight building shells, mechanical ventilation, and high insulation levels.

8.2.5 Lighting

Lighting consumed 7%, or 1.02 quads, of the primary energy used in residences in 1985 (BNL 1988). The breakdown of residential lighting by lamp type and billions of kilowatt hour use is given in Figure 8.1. Purchase cost and technical data for residential lighting are shown in Table 8.11.

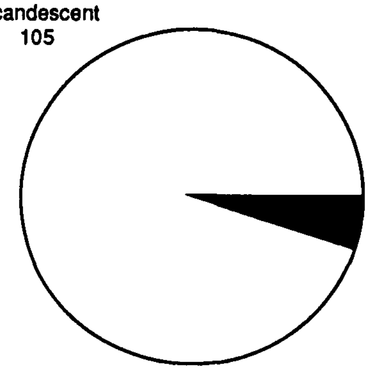

Figure 8.1. 1985 Residential Lighting (Trillion Wh)

Technology Description

Most lights in residences are standard, low-efficacy (15 to 17 lm/W) incandescents. There is a large potential for saving electricity and money with high-efficacy light sources that replace higher wattage bulbs. The best choice for high-usage residential lights is compact fluorescent bulbs, which have efficacies of 40 to 60 lm/W. Compact fluorescent bulbs typically cost 10 to 20 times more but last 10 times longer and use 25% of the electricity of incandescents. Standard fluorescent bulbs have a limited residential market share because of a poor coloring index (CRI) and inconvenient 4-foot length.

Compact fluorescent bulbs are available in modular or integral units. Integral units contain the

Table 8.11. Purchase Cost and Technical Data for Residential Lighting

Type	Efficacy (lumens/ watt)	Bulb Lifetime (hrs)	Color Rendering Index (CRI)	Consumer Price (1988$)
Standard Incandescent	15-17	750-1,000	93	0.75
Halogen	20-30	2,000-3,5000	~100	3.00-4.00
Compact Fluorescent	40-60	7,500-10,000	82 average	20.00

lamp, ballast, and adapter all in one package, which is discarded when the lamp burns out. Modular units have a separate lamp that plugs into an adaptor/ballast. The reusable ballast can last as long as 5 to 15 bulbs. Ballasts are either magnetic or electronic. The magnetic types are larger, heavier, and less expensive than their electronic counterparts. The electronic ballasts offer instant starting and flicker-free light and are the preferred choice.

Compact fluorescent bulbs screw into conventional Edison-type sockets. They are available in bare-tube, globe, reflector, and decorative designs. Dimmable ballasts are also becoming commercially available. The major drawback of compact fluorescent bulbs is that they are larger than incandescent bulbs and do not fit in some standard fixtures, even though they fit in the socket. Compact fluorescent bulbs may require a special harp when used in some lamps. The cost for the larger harp is $1 to $3. Compact fluorescent bulbs (like any fluorescent bulbs) contain a small amount of mercury, which should not create a problem if handled properly.

Twenty dollars is a low-end retail cost for electronically ballasted, compact fluorescent bulbs. Costs would be lower if the market share increased, but expanded market share is inhibited because consumers are not familiar with compact fluorescents and are reluctant to pay $20 for a light bulb.

The cost of conserved energy (CCE) is a function of the duty factor. The duty factor is the fraction of time that the light is on. More energy will be saved and, consequently, the payback time is shorter if the duty factor is large.

Cost of Conserved Energy Versus Duty Factor for a Philips SL-18 Bulb. Note that even with a duty factor of 0.1 (equal to usage of 2.4 hours/day), the cost of conserved energy is less than 4.7 cents/kilowatt hour or about two-thirds of the national average residential electricity price. These calculations assume that an OSRAM EL-18 replaces a 60-watt incandescent bulb, though the lumen output of an EL-18 is actually closer to that of a 65-watt bulb. The EL-18 is an 18-watt, electronically ballasted, compact fluorescent bulb. It is assumed to cost $20 (retail) and have a lifetime of 10,000 hours. The incandescent bulb has a lifetime of 750 hours and is assumed to cost $0.75. The real discount rate is 7%. These calculations do not include labor costs for changing bulbs and do not reflect the fact that many utilities now offer substantial rebates to consumers who install the bulbs.

Where bulbs are used less than one hour per day, Halogen lights can replace incandescents. They cost less than compact fluorescents and are less efficient, but are still significantly more efficient than incandescents.

Environmental Hazards of Mercury (Lovins 1988)

Mercury is present in all fluorescent lamps. Free mercury at ambient temperature evaporates rapidly into the air and far exceeds the toxic limit. Mercury vapor is more dangerous than ingested mercury because it crosses the blood-brain barrier more readily and damages the nervous system. Ingested mercury reacts to form organic compounds that damage the kidneys.

Mercury in a lamp is deposited into the glass and phosphor by ion bombardment. Mercury depletion is designed to be the failure mechanism in many fluorescent lamps. Thus, mercury release from failed lights is extremely slow. However, group relamping can be dangerous because discarded lamps contain free mercury that is rapidly released into the atmosphere.

Modern fluorescent lights contain approximately 21 milligrams of mercury. The 1.2 billion fluorescent lights manufactured worldwide in 1980 contained about 25 tons of mercury. For comparison, 6,000 tons per year of mercury are used worldwide for various purposes. Seven thousand tons per year are released naturally and 3,000 tons of mercury per year are released by burning coal. If we were to replace fluorescents lights with less efficient incandescent lights, 300 tons of mercury would be released by burning coal to generate the additional required electricity.

In conclusion, with proper handling and disposal techniques, mercury lamps represent minimal health risks for the benefits they confer. However, care must be taken not to break the lamps in occupied spaces. Additionally, lamps should not be replaced until they burn out and should be disposed of in well-ventilated areas away from living areas.

Development Needs

Development needs are

1. efficient incandescents that can be cost effectively used in lamps that are only turned on one hour per day or less

2. better lighting controls (occupancy and light-level sensors).

8.2.6 Air Conditioning and Heat Pumps

Air conditioning consumed 7%, or 1.06 quads, of the primary energy used in residences in 1985 (BNL 1988). In some areas of the country, air conditioning is the largest residential energy end use. Air conditioning efficiency is particularly important because in warm climates use of air conditioning creates peak loads for utilities on summer afternoons. More efficient air conditioners result in lower rates if the utility does not have to build extra power plants. Consequently, it is often worth investing more money to save a given amount of energy using a more efficient air conditioner than to save the same energy in a non-peak-demand appliance.

Technology Description

Almost 60% of all residences in the United States have air conditioning. Residential air conditioning is accomplished with room air conditioners, central air conditioners, or heat pumps. Half of the air conditioned residences have central units and half have room units (EIA 1986). Most air conditioners and heat pumps are air cooled (as opposed to evaporatively cooled or water cooled).

Air conditioners come in two configurations: split and package systems. Split systems have physically separated indoor and outdoor coils, while packaged systems contain all the hardware in one unit. Approximately 85% of central air conditioning and heat pump sales are split system units. Most room units are air conditioners only (not reversible heat pumps) with side louvers. Approximately one quarter of the central units are heat pumps that can be reversed to provide space heat (Krause et al. 1988a). Therefore, this analysis will deal with technology for 1) room air conditioners with side louvers and 2) split system, air-cooled central air conditioners and heat pumps.

Air conditioners come in room (through the wall or window) or central units. Room air conditioners are generally rated at 4,000 to 35,000 Btu/hr, while central air conditioners are generally 16,000 to 65,000 Btu/hr. Residential sized heat pumps are 65,000 Btu/hr or less. Central heat pump units are typically 35,000 Btu/hr, and room units are approximately 10,000 Btu/hr.

Reversible heat pumps have slightly lower efficiencies than comparable central units because both coils must be able to operate as evaporators and condensers. The coil design cannot be optimized for either the heating or cooling mode. During the heating season, the outside coil acts as the evaporator and must be designed to limit frost buildup.

In 1984, 30% of new single-family residences were equipped with heat pumps. Between 1978 and 1984, 66% of the heat pumps installed in new single-family residences went into homes in the South (O'Neal et al. 1987). Heat pumps show a strong regional bias because they do not operate well at temperatures below freezing. Before heat can be absorbed at low temperature, the outside coil must be cooler than the outside air. Moisture from the air condenses on the coil and freezes;

consequently, efficiency decreases because energy is needed for defrosting, and backup electric resistance heat must be used to heat the house.

Air conditioner efficiency can be increased by improving the heat transfer of the heat exchanger, improving fan and compressor efficiencies, switching to electronic expansion valves, and using multiple or variable speed compressors. Heat exchanger performance can be improved by increasing the heat exchanger surface area, the heat transfer coefficient, or the number of circuits. The surface area can be increased by going to a larger frontal area, more tube rows, or a higher fin density. The heat transfer coefficient can be increased by changing the fin shape. Parallel flow circuits in the heat exchanger lower the pressure drop of the refrigerant after evaporation, thereby reducing compressor work. Electronic expansion valves controlled by a microprocessor result in better control of the refrigerant flow. Variable speed compressors run at the minimum speed necessary to satisfy cooling requirements.

Central air conditioner and heat pump efficiency ratings are given by a seasonal energy efficiency ratio (SEER), which is calculated under operating conditions that approximate the cooling season. The SEER is the ratio of the heat extracted (kBtu) to the kWh put in. Room air conditioners are rated by an energy efficiency ratio (EER) that is calculated under steady state conditions. Average national efficiencies based on shipment-weighted averages are given in Table 8.12. National stock efficiencies are found by assuming that the age of an average appliance is half of its lifetime.

Table 8.12. Recent Production and National Stock Energy Efficiency[(a)]

Appliance	Energy Efficiency Measure	1987 Avg. Eff.	Lifetime (years)	National Stock Efficiency
Room air conditioner	EER	8.06	15	7.14
Central air conditioner	SEER	8.97	15	8.31
Heat pump	SEER	8.93	15	7.97

(a) LBL Residential Energy Model.

Costs

The consumer cost for a low efficiency baseline 35 kBtu/hr split system air conditioning unit with a seasonal energy efficiency ratio of 7.0 is approximately $1300. A comparable capacity heat pump costs about $200 more because it has a reversing valve and bypasses for the expansion devices so that the heating and cooling operation can be switched. Incremental design options for high efficiency models are given in Tables 8.13, 8.14, and 8.15.

The above consumer costs for room air conditioners and central air conditioners and heat pumps assume a 210% markup over manufacturing costs and include $10 for shipping. Note also that the above costs assume mass production (with low tooling costs per air conditioner) and a competitive market. The highest efficiency models, which have small market shares, will tend to cost somewhat more than the above estimates.

Development Needs

Development needs are high-efficiency compressors that do not use CFCs.

8.2.7 Refrigerator-Freezers

Refrigerator-freezers are the third largest residential energy end use. In 1985, refrigerators and freezers consumed 12%, or 1.85 quads, of the primary energy used in residences (BNL 1988). Almost 100% of all U.S. households have refrigerators (EIA 1986). The lifetime of a refrigerator-freezer is typically 19 years (DOE 1982a). Top-mount auto-defrost refrigerator-freezers account for 70% of the market, and thus we discuss efficiency options for this model. Based on a shipment weighted average, the average energy consumption of a refrigerator produced in 1987 was 974 kWh/yr (AHAM 1990).

Table 8.13. 35 kBtu/hr Split System Central Air Conditioner

Option	SEER	Consumer Purchase Cost[(a)] (1988$)
Baseline model	7.00	1320
4.8 in^3 compressor		
10.0 ft^2 frontal area		
2 parallel circuits		
1 outdoor coil tube row		
0.0052 in. fin thickness		
Increase the number of outdoor coil tube rows to 2	7.46	1420
Reduce the compressor size to 4.0 in^3		
Increase outdoor coil face area to 15 ft^2		
Reduce the number of outdoor coil tube rows to 1		
Reduce the compressor size to 3.75 in^3	9.12	1450
Reduce fin thickness to 0.0045 in.		
Increase fan/motor efficiency for outdoor coil to 15% and for indoor coil to 25%		
Increase indoor coil face area to 4.5 ft^2		
Reduce compressor size to 3.5 in^3	10.20	1700
Increase fan/motor efficiency for outdoor coil to 20% and for indoor coil to 30%		
Increase indoor coil parallel circuits to 6		
Reduce compressor size to 3.25 in^3	11.90	1730
Improve compressor EER to 10.5		
Increase outdoor coil face area to 20 ft^2		
Reduce outdoor coil tubes to 1		
Increase to 19 fins/inch on outdoor coil	12.13	1620
Louver outdoor coil design		
Reduce compressor size to 3.30 in^3		
Increase outdoor coil tubes to 2	12.42	1890
Increase compressor size to 3.33 in^3		

(a) Cost data from LBL appliance standards research project; personal communication with Isaac Turiel, LBL, March 1989.
Source: O'Neal et al. 1987.

Table 8.14. 35 kBtu/hr Split System Heat Pump

Option	SEER	Consumer Purchase Cost[(a)] (1988$)
Baseline model	6.78	1540
4.8 in^3 compressor		
10.0 ft^2 frontal area		
2 parallel circuits		
1 outdoor coil tube row		
0.0052 in. fin thickness		
Increase the number of outdoor coil tube rows to 2	8.06	1640
Reduce the compressor size to 4.0 in^3		
Increase outdoor coil face area to 15 ft^2		
Reduce the number of outdoor coil tube rows to 1		
Reduce the compressor size to 3.75 in^3	8.89	1690
Reduce fin thickness to 0.0045 in.		
Increase fan/motor efficiency for outdoor coil to 15% and for indoor coil to 25%		
Increase indoor coil face area to 4.5 ft^2		
Reduce compressor size to 3.5 in^3	10.13	2020
Increase fan/motor efficiency for outdoor coil to 20% and for indoor coil to 30%		
Increase indoor coil parallel circuits to 6		
Reduce compressor size to 3.25 in^3	11.88	2050
Improve compressor EER to 10.5		
Increase outdoor coil face area to 20 ft^2		
Reduce outdoor coil tubes to 1		
Increase to 19 fins/inch on outdoor coil	12.11	1940
Louver outdoor coil design		
Reduce compressor size to 3.30 in^3		
Increase outdoor coil tubes to 2	12.42	2200
Increase compressor size to 3.33 in^3		

(a) Cost data from LBL appliance standards research project; personal communication with Isaac Turiel, LBL, March 1989.
Source: O'Neal et al. 1987.

Technology Description

The baseline model for the energy and cost analysis is a top-mount auto-defrost refrigerator with an 18-cubic foot capacity. Energy use is 947 kWh per year. The baseline model has foam insulation in the side walls and the freezer section door of the freezer. The refrigerator section door has fiberglass insulation. Component energy use of the baseline model is shown in Figure 8.2 (DOE 1988).

Table 8.15. 8 kBtu/hr Room Air Conditioner[a]

Option	EER	Consumer Purchase Cost (1988$)[b]
Baseline	7.5	328
Increase the number of condenser tube rows to 4	8.1	344
Increase the surface area of the condenser tube rows to 1.5 ft^2	8.5	361
Use 75% efficient fan motor	8.6	374
Use 10.0 EER compressor	10.0	400
Increase evaporator frontal area to 1.0 ft^2	10.2	409

(a) From the LBL appliance standards analysis, personal communication with Isaac Turiel, LBL, March 1988.
(b) Costs do not include installation.

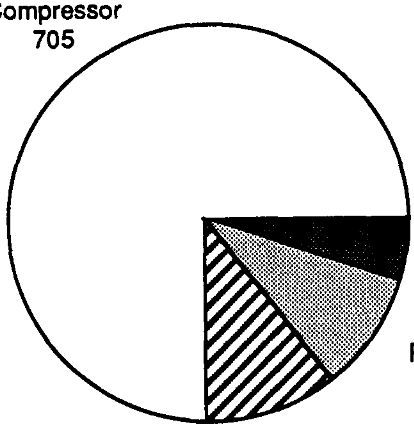

Figure 8.2. Annual Component Energy Use (kWh/yr) for Baseline Refrigerator-Freezer Model

Compressors account for approximately 75% of the energy use of a refrigerator. Compressor energy use (and thus total refrigerator energy use) can be reduced in two ways: 1) install a more efficient compressor or 2) reduce the work that the compressor must do by reducing the heat gain to the food compartment through improved insulation. Most refrigerator-freezers have compressors with energy efficiency ratios of 4.5 or greater. At least one manufacturer currently uses a compressor with an energy efficiency ratio of 5. Increasing compressor efficiency much beyond 5.0 will be difficult if chlorofluorocarbons are phased out.

Since a refrigerator-freezer needs to maximize internal space and fit into a confined kitchen space, low-conductivity insulation is essential for energy efficiency. Foam insulation has a lower conductivity than fiberglass. However, foam insulation is blown using trichlorofluoromethane (CFC 11). Chlorofluorocarbons destroy the ozone layer, and efforts are being made to phase them out rapidly.

Two alternatives to fiberglass and foam insulation are powder-filled evacuated panels and silica aerogel. Evacuated panels have less air in them to transfer heat across the gap. They can be either hard or soft vacuum. Powder-filled panels at 0.02 atmospheres have an R-value of 20-25 hr-ft^2-°F/Btu per inch (GE 1987). The Solar Energy Research Institute is working on a hard vacuum insulation panel that is only 0.1 inch thick and has an R-value of 15. Transparent silica aerogel used for high performance windows has an R-value of 20 hr-ft^2-°F/Btu at 0.1 atmospheres of pressure. Silica aerogel that does not need to be transparent should have an R-value of 25 to 30 hr-ft^2-°F/Btu per inch.[a]

Costs

The consumer prices shown in Table 8.16 assume a markup of 235% over the manufacturing cost[b] and include $10 per unit for shipping charges. Note that the energy and cost data assume unrestricted chlorofluorocarbon use. Decreases in chlorofluorocarbon production and use will increase the cost of comparably efficient models. Without chlorofluorocarbons, Options 4, 5, and 8

(a) Personal communication with Arlon Hunt, LBL, April 1989.
(b) LBL Residential Energy Model.

Table 8.16. Top-Mount Auto Defrost Refrigerator-Freezer[a]

Level	Design Option	Consumer Cost (1988$)	Energy Use (kWh/yr)
0	Baseline	548	947
2	Level 0 + 5.0 EER Compressor	556	841
3	Level 2 + Foam Door Insulation	559	787
4	Level 3 + Improved Foam Insulation (k=0.11)[b]	567	745
5	Level 4 + 5.3 EER Compressor[b]	580	714
6	Level 5 + More Efficient Fans	602	683
7	Level 6 + Door Insulation Increased to 2 in.	611	662
8	Level 7 + Improved Foam Insulation (k = 0.10)[b]	629	637
9	Level 8 + Adaptive Defrost	668	615
10	Level 9 + 2.5 in. Side Insulation	685	595
11	Level 9 + 3.0 in. Side Insulation	703	582
12	Level 9 + Evacuated Panel (k = 0.05)	734	515

(a) Volume of 18 cubic feet.
(b) Measure will be dropped if CFCs are phased out.
Source: DOE 1988.

will be dropped. Also, the above costs assume mass production (with low tooling costs per refrigerator) and a competitive market. The highest efficiency models, which have small market shares, will tend to cost somewhat more than the above estimates.

Development Needs

Development needs are

1. replacements for chlorofluorocarbon refrigerants and foam blowing agents (used in insulation)

2. compressors with higher energy efficiency ratios

3. engineering and testing of evacuated panel insulation.

Environmental Effects of Chlorofluorocarbons

Chlorine and bromine break stratospheric ozone, which protects the earth from high energy ultraviolet radiation. Most of the chlorine is from chlorofluorocarbons and most bromine is from halons used in fire extinguishers. Additionally, chlorofluorocarbons and halons also have strong heat-absorbing properties. They are projected to account for 15% to 20% of the global warming effect (Shea 1988).

International efforts are being made to reduce chlorofluorocarbon emissions and production. In September 1987, 24 countries signed the Montreal Protocol on Substances that Deplete the Ozone Layer. It calls for limiting chlorofluorocarbon production to 1986 levels by 1989, a 20% reduction in production by 1993, and another 30% cut by 1998. Halon production is to be limited to 1986 levels starting in 1992. Global chlorofluorocarbon use by category is shown in Figure 8.3 (Kohler 1987). Aerosol cans are the largest source of chlorofluorocarbons, but hydrocarbon propellants, which are currently in use, are a more economical replacement.

There are two uses for chlorofluorocarbons in refrigerators: refrigerants and foams. Chlorofluorocarbon replacements for refrigerants and foam-blowing agents are generally more expensive

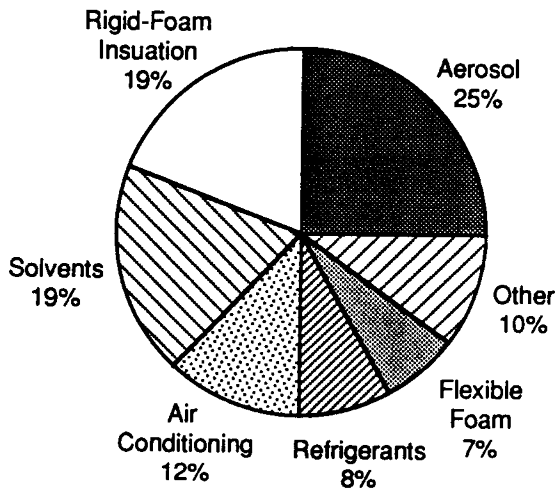

Figure 8.3. Global Chlorofluorocarbon Use by Category for 1985

and less efficient than chlorofluorocarbons. Refrigerators typically contain 2 pounds of chlorofluorocarbons in the foam insulation and approximately half a pound in the refrigerant (Shea 1988). Freon (known as CFC-12 or dichlorodifluoromethane) is the most common refrigerant for air conditioners and home refrigerators. Du Pont and Imperial Chemical Industries (the world's two largest chlorofluorocarbon producers) seem convinced that HFC-134a will replace freon in refrigerators and air conditioners. However, it will cost $2 per kilogram, which is seven times the cost of freon (Shea 1988).

Trichlorofluoromethane (CFC-11) is used in foam refrigerator insulation. Chlorofluorocarbon refrigerant foams could be replaced with evacuated panels or silica aerogel, but these technologies need further development. Foam blowing agents that do not use chlorofluorocarbons, such as methylene chloride, pentane, and carbon dioxide, are available, but each has major drawbacks.

8.2.8 Air Infiltration

Technology Description

Infiltration is the naturally induced movement of air through leaks in the building envelope. Air infiltration generally has a more significant effect on space conditioning loads for residential buildings than for commercial buildings. Large commercial buildings have a low surface-area-to-volume ratio and cooling is required to balance large internal gains from machines. Mechanical ventilation systems provide regular air exchanges that usually dwarf the infiltration rate. Residential buildings, on the other hand, have smaller gains per square foot and require heating unless the ambient temperature is high. Air infiltration, which provides relatively uncontrolled air changes in residential buildings, causes space conditioning loads. Air infiltration is significant in residences, but generally has less effect on commercial buildings.

Air infiltration causes space conditioning loads, but is also the primary mechanism for removing indoor pollutants in residential buildings (since mechanical ventilation systems are rarely used). Approximately 33% of the space conditioning energy load in residential buildings (2.5 quads) is due to infiltration (Sherman 1985). Thus, the potential for saving energy from excess air infiltration is large, but care must be taken to ensure adequate indoor air quality.

Air infiltration occurs in response to pressure differences across the shell of a building. The pressure difference can occur because of a mechanical ventilation system or wind or stack effects. Wind flowing around a building causes a pressure difference proportional to wind speed. Stack effects occur because of the temperature difference between inside and outside air. Colder infiltrating air sinks while the warmer inside air rises. The buoyancy effect causes a pressure gradient along the outside wall.

Air exchange between the inside of a building and the outside environment results in sensible and latent heat loads. The relative and absolute magnitudes of the two depend on the local temperature and humidity. In cold climates, excessive air infiltration will result in large heating loads; in humid climates, it will result in large air conditioning loads.

Drafts in buildings are undesirable for three reasons. They can increase the space conditioning load, can cause comfort problems, and can introduce radon into the structure.[a] Leaks in a building shell can be found either by occupants noting the source of drafts or by blower doors. A blower door is a large fan that pressurizes the structure to help locate leaks and also determines the effective leakage area of the house. Sealing crawlspace or attic bypass leaks results in the largest energy savings. Leaks in the neutral pressure plane (i.e., around windows) have less effect on infiltration. Thus, blower door readings of whole-house leakage area do not correlate well to energy savings.

The extremes in effective leakage areas for U.S. houses range from 0.05 to more than 3 square feet. However, most of the U.S. housing stock has a leakage area of 0.3 to 1.0 square foot (Sherman 1985). These leakage areas for typical houses correspond to 0.3 to 1.0 air changes per hour. The air changes per hour that are necessary to provide acceptable indoor air quality depend on the level and type of activity in the space. However, assuming that infiltration could be reduced by 33% (on a national average), savings from reduced air infiltration in residences are potentially 1 quad.

Energy Performance

The effect of air changes per hour on space heating and cooling loads is shown in Table 8.17. The values in the table were calculated using the Program for Energy Analysis of Residences (PEAR) developed at Lawrence Berkeley Laboratory. All houses modeled were 1,500 square feet and had double glazing, R-11 walls and R-30 ceilings. Given the above caveats, the energy savings numbers should be taken as approximate.

Costs

For minimal cost, homeowners can seal the leaks they locate. However, in a study performed by Northeast Utilities, sealing leaks identified with a

(a) The radon infiltration mechanism is discussed at the end of this section.

Table 8.17. The Effect of Air Changes per Hour (ACH) on Heating and Cooling

Location	Heating (therms)	Cooling (kWh)	ACH
San Francisco, CA	470	420	1.0
	330	420	0.5
Minneapolis, MN	1500	1500	1.0
	1200	1500	0.5
Phoenix, AZ	210	7400	1.0
	140	6700	0.5

blower door reduced infiltration by 7 to 8 times as much as sealing leaks identified by homeowners (Butterfield 1989). The cost to hire an air-sealing specialist is approximately $200 to $500.[b] Contractor labor rates and the necessary improvements will determine the actual cost. The payback period is a function of the location and size of the holes that are sealed, the climate, and the local energy prices.

Market Penetration

A very small percentage of residences (less than 1%) have been tested by blower door. Since a blower door test reduces leakage significantly more than when residents identify and plug the source of drafts, the market is essentially untapped.

Radon Infiltration

The primary source of indoor radon in the United States is the soil around the house. Radium, which is present in trace amounts in all soils, decays to form radon. Pressure differences across the shell of the building occur from wind loading and the stack effect. The pressure difference drives the radon through the soil and into the structure through cracks in the foundation or the floor (in the case of a crawl-space). Depending on the leakage distribution and the climate, reducing air infiltration can either increase or decrease radon levels.

(b) Personal communication with Max Sherman, LBL, May 1989.

Development Needs

Development needs are

1. a national study of infiltration in U.S. residences - Except in California and the Northwest, little measured data have been compiled in a systematic fashion.

2. a detailed study of the contribution of duct leakage to overall infiltration levels in homes with ducted-air central space conditioning.

8.2.9 Site Layout (Vegetation)[a]

Technology Description

Trees reduce daytime air-conditioning loads by shading and evapotranspiration. Shading reduces the cooling load through two mechanisms. First, it reduces solar gain on the structure. Additionally, as a much smaller effect, shading reduces long-wave radiative heat gain because the tree leaves are cooler than surfaces such as asphalt or bare ground. Evapotranspiration cools the air around the house and results in lower conductive and convective heat gains. In some cases, trees can increase the air conditioning load by obstructing outgoing long-wave radiative exchange, causing increased latent cooling loads (because of more moisture in the air), and blocking natural convection. However, the balance of factors generally leads to a large reduction in cooling energy use when trees are planted. If solar gain for winter heating is desirable, deciduous trees should be planted.

Energy Performance

Estimates of cooling energy savings from tree planting are based on combining results from a climate model with the DOE-2 building simulation model (Huang et al. 1987). The simulation assumes that each lot is 500 square meters and that each tree has a projected surface area of 50 square meters. Therefore, each tree gives 10% coverage. If the minimum number of trees are planted to reduce solar gain, two should be planted on the south and one on the west. The annual cooling energy savings *from shading effects alone* in Sacramento, Phoenix, and Lake Charles are 16%, 6%, and 4%, respectively. *Total* cooling energy reductions for typical houses with the optimal 3-tree configuration are shown in Table 8.18. The savings, which range from 33% to 53%, include the combined effects of shade, wind, and evapotranspiration.

(a) This section is based on Huang et al. 1987.

Table 8.18. The Effect of Tree Planting on Residential Cooling Energy Use

Location	Annual Cooling Energy Savings	Peak Power Reduction
Sacramento, CA	53%	34%
Phoenix, AZ	33%	18%
Lake Charles, LA	35%	22%

The savings listed in Table 8.18 are direct savings. Direct savings are the energy savings resulting from tree planting around one house. Additional savings will result if the entire city plants trees, thereby modifying the mesoclimate and reducing the temperature in the city. Such effects were seen in Los Angeles when it was planted in orchards. Because of extensive tree planting, Phoenix is now cooler than the surrounding desert.

Costs

To calculate the cost of conserved energy and the cost of avoided peak power attributable to tree planting, the following assumptions were made. Seedlings can be planted for about $5 per tree and will need 10 years to become an effective shading source. Five-foot-tall saplings can be purchased and planted at a cost of about $60. A 5-foot-tall tree will need about 7 years to grow large enough to shade a house. Growing trees need $2 worth of water per year (approximately 2000 gallons), and mature trees need no watering. The tree purchase and planting costs are as discussed above. A real discount rate of 7% and a 20-year lifetime have been used to compare the tree to a nominal power plant. However, the tree will live approximately 100 years. The two values for the cost of conserved energy (CCE) and cost of avoided peak power (CAPP) in Table 8.19 correspond to planting a seedling (the first number) and planting a 5-foot-tall sapling.

Table 8.19. The Economics of Tree Planting for Cooling Energy Savings

Location	CCE (cents/kWh)	CAPP ($/kW)
Sacramento, CA	0.9 - 4.3	29 - 140
Phoenix, AZ	0.3 - 1.4	45 - 217
Lake Charles, LA	0.5 - 2.4	46 - 220

The cost of tree planting can be justified for cooling energy savings alone, but there are additional reasons to plant trees. To sequester the carbon that the one tree planted around a house avoids or absorbs, 10 trees would have to be planted in an unpopulated area. Trees lower the air temperature, thus reducing the rate at which smog-causing pollutants are produced. Additionally, planting trees increases real estate values.

8.2.10 Miscellaneous Residential Energy End Uses

Appliances not specifically covered in a separate section of this report constitute the "other" category. This category uses 2.6 quads annually (17% of residential energy use) (BNL 1988). Energy use and saturation of the major home appliances in this category are listed in Table 8.20. Note that the term "Range" under oven energy use indicates that the oven energy use is included with energy use for the range.

Table 8.20. Saturation and Energy Use of Miscellaneous Appliances (1984)

Appliance	Saturation (% of Households)	Annual Energy Use per Appliance (MMBtu of Site Energy)
Range	98.6	
Electric	53.9	2.4
Gas	45.2	7.9
Television	98.1	
Color	88.0	1.1
Black/white	43.2	0.3
Oven	91.6	
Electric	49.1	Range
Gas	41.5	Range
Microwave	34.3	0.6
Clothes washer	73.1	
Automatic	70.7	0.4
Wringer	3.1	0.3
Clothes dryer	61.6	
Electric	45.8	3.4
Gas	15.9	6.0
Cooling equipment	46.9	
Window/ceiling fan	35.5	0.6
Dehumidifier	8.7	1.3
Whole-house cooling fan	7.8	0.9
Evaporative cooler	3.8	0.9
Dishwasher	37.6	1.2
Freezer	36.7	
Not frost-free	24.7	4.1
Frost-free	13.0	6.2
Electric blanket	29.4	0.5
Portable heater	16.0	
Electric	10.3	0.6
Kerosene	6.1	13.0
Outdoor gas grill	13.3	2.6
Humidifier	13.1	0.6
Waterbed heater	9.8	4.4

Source: EIA 1986.

8.3 COMMERCIAL SPACE HEATING

8.3.1 Space Heating

In 1985, space heating consumed 33%, or 3.84 quads, of the primary energy used in commercial buildings (BNL 1988). Over 95% of the commercial floor space in the United States has space heating. Almost 55% of heated commercial floor space uses natural gas as the primary space heating fuel, 23% uses electricity, and 12% uses fuel oil (EIA 1988b). Natural gas is the dominant space heating fuel in all regions of the country in terms of number of buildings and floorspace. However, in the Northeast, fuel oil is used almost as much as natural gas, and in the South, electricity is used for space heating nearly as much as natural gas (EIA 1988b).

Technology Description

Small commercial heating loads are met with furnaces. Furnace technologies are discussed in the section on residential space heating, but prices for commercial models are given below. Boilers are used to meet large commercial heating loads. Boilers produce steam or hot water and a heat exchanger is used to heat the building air. The heated air is then distributed through a central ventilation system (see Tables 8.21 and 8.22).

Energy Performance and Costs

There is little variation in the efficiencies of available commercial space heating equipment. Electric furnaces or boilers are 100% efficient because the heating coil is immersed in the conditioned air or water. However, the primary energy efficiency for space heating with electricity is 30% to 35% because of generation and transmission losses. A heat pump with a heating seasonal performance factor (HSPF) of 1.6 will have a net efficiency 60% higher than that of an electric resistance heating system. Commercial gas and oil hot air furnaces are 70% to 80% efficient. Gas- and oil-fired boilers are 75% to 85% efficient.[a]

Efficiencies of actual units will depend heavily on the installation, maintenance, and operating conditions. Flue gas condensation can increase the efficiency of nonelectric furnace and boiler units to almost 90%. A heat exchanger condenses the water vapor in the exhaust gas and recovers the heat of vaporization. A fan is needed to remove the cool, relatively nonbuoyant exhaust air. However, stack losses are reduced, and a plastic pipe can be used instead of a high-temperature chimney. Note, the efficiencies quoted in this section are steady state, not annual fuel utilization efficiency values.

Table 8.21. Commercial Hot Air Furnaces

Fuel	Capacity (kBtu/hr)	Installed Cost (1988$)
Gas	42	485
Gas	84	600
Gas	105	635
Oil	55	830
Oil	100	920
Oil	150	1,275
Electric	30	445
Electric	60	630
Electric	90	885

Source: Mahoney 1987.

Table 8.22. Commercial Boilers for Space Heating

Equipment	Fuel	Output	Capacity (kBtu/hr)	Installed Cost (1988$)
Cast iron boiler	Gas	Steam	200	3,000
Cast iron boiler	Gas	Steam	765	8,075
Cast iron boiler	Gas	Steam	1,875	15,500
Cast iron boiler	Gas	Steam	6,100	49,200
Cast iron boiler	Oil	Steam	200	3,325
Cast iron boiler	Oil	Steam	1,100	9,400
Cast iron boiler	Oil	Steam	3,000	19,700
Cast iron boiler	Oil	Steam	7,000	58,000
Cast iron boiler	Electric	Steam	200	4,800
Cast iron boiler	Electric	Steam	700	9,800
Cast iron boiler	Electric	Steam	3,700	29,500
Cast iron boiler	Electric	Steam	8,000	59,000

Source: Mahoney 1987.

(a) Personal communication with Hashem Akbari, LBL, April 1989.

8.3.2 Commercial Cooling Equipment[a]

About 80% of commercial floor space is air conditioned; 91% of cooled commercial floor space uses electricity for air conditioning and 6% uses natural gas (i.e., gas absorption chillers) (EIA 1988b). Small cooling loads (under 135 kBtu/hr) are usually met using electrically driven air conditioners. Larger buildings generally use electrically driven chilled-water systems. Some large buildings use gas absorption chilled-water systems to reduce peak demand charges and avoid expensive daytime electricity rates. Performance and costs for cooling equipment are summarized in Table 8.23. The equipment is described below.

Electrically Driven Chillers

Electrically driven chillers use a conventional refrigeration cycle to cool water. Heat from the chilled water is exchanged with the building air supply to provide space conditioning. Three different types of compressors are commonly used with electrically driven chilled-water systems : centrifugal, rotary/screw, and reciprocating. Electric chillers with coefficients of performance (COPs) of up to 5.6 are commercially available (the COP is simply the ratio of heat removed or delivered to the amount of work required).

Gas-Fired Absorption Chillers

Gas-fired absorption chillers are heat-operated refrigeration equipment. An absorbent absorbs the cold refrigerant at one point in the cycle and rejects the hot refrigerant later in the cycle. The evaporation of the refrigerant absorbs heat, providing a cooling effect. Refrigerant-absorbent pairs are either ammonia-water or lithium-bromide. The refrigerant and absorbent solutions corrode the equipment internally and degrade the performance of the heat exchanger over time. Gas-fired absorption chillers have an estimated lifetime of 20 years.

Chillers come in one- and two-stage models. In a two-stage chiller, heat from the first-stage generator is used in the second-stage generator to drive off more refrigerant vapor. Indirect-fired machines use

Table 8.23. Performance of Commercial Cooling Equipment

Type	Condensing Means	Min. COP ASHRAE 90/84 Title 24/85	Min. COP ASHRAE 90/88	1984 "Best COP"	System Cost (1988$/ft^2)
Electrically driven air conditioners	Air	2.4	2.49	3.49	0.80 - 1.95
(up to 134 kBtu/hr)	Evap/Water	2.7	2.78	3.49	
Electrically driven water chillers					0.45 - 1.60
Centrifugal (100-2000 tons)	Air	2.34	2.40	3.0	
and rotary/screw (100-750 tons)	Evap/Water	4.04	<250 tons 4.04	5.0	
		4.04	>250 tons 4.25	5.6	
Reciprocating (50-250 tons)	Air	2.46	2.55	3.0	
	Evap/Water	3.51	3.64	4.2	
Heat-driven gas absorption units					
(10-1500 tons)	Evap/Water				0.55-2.30
Indirect fired: single stage		0.68	0.68	0.71	
Indirect fired: two stage		0.68	0.68	1.14	

(a) This section is based on Usibelli et al. 1985.

a steam or hot fluid heat source. Direct-fired machines use a flame source. Currently, direct-fired chillers are manufactured only in Japan. Gas-fired absorption chillers are generally used in large buildings with chilled-water systems. The equipment is suitable for new or retrofit applications.

Comparison Between Absorption and Electrical Chillers

The ASHRAE 90/84 standards for absorption equipment specify a minimum COP of 0.48. The best absorption equipment available in 1984 had a COP of 0.67. The best electric chiller available in 1984 had a COP greater than 5. However, to compare the primary energy use of a gas absorption chiller with an electrical chiller, the conversion and transmission losses for electricity are accounted for by dividing electrical chiller COPs by 3.4. Thus, in terms of primary energy, electrical chillers use approximately half as much energy as gas absorption chillers to produce the same amount of cooling.

Evaporative Cooling

Evaporative cooling removes heat from an air stream by evaporating water. No water will be evaporated when the air is saturated. Therefore, evaporative cooling works best in warm, dry climates. Evaporative cooling systems require outside air and thus should be used with economizer systems.

There are three common types of evaporative coolers: direct, indirect, and two stage. Direct evaporative cooling brings the air stream into direct contact with the water. The dry bulb temperature decreases, but humidity increases. Indirect evaporative cooling uses a heat exchanger to cool the building air. Building air is thus cooled without increasing humidity. The cold air for the heat exchanger is provided by direct evaporative cooling. However, the temperature of the conditioned air will not be as low as with a direct system because of the inefficiency of the heat exchanger. Two-stage coolers use both indirect and direct cooling. The building air is first sensibly cooled with an indirect cooler and is then further cooled and has moisture added by a direct cooler.

Peak savings and energy savings for the three different types of evaporative cooling are shown in Table 8.24. The base system is a constant volume, variable temperature system with reheat and economizer control. Savings are calculated using the DOE-2 building simulation program. Costs of evaporative systems are $0.50 to $1.10 per cubic ft/min of capacity.

Part-Load Performance Improvement. Many cooling systems have much lower COPs at partial loads than at full loads. For systems that are often run at partial loads, cycling the system on and off so that it always operates at full load generally saves energy. Additional control systems are needed to cycle the system. Energy savings will range from 15% to 30%, depending on the equipment's partial-load efficiency curves and the cooling load profile. Peak energy use will not be reduced because the system will not be cycling off at peak demand times.

Table 8.24. Evaporative Cooling Energy Savings

System	Type of Savings	Los Angeles	San Francisco	Sacramento
Direct	Peak Savings	0%	10%	-10%
	Energy Savings	30%	55%	20%
Indirect	Peak Savings	0%	5%	0%
	Energy Savings	5%	30%	10%
Indirect/Direct	Peak Savings	-10%	10%	0%
	Energy Savings	20%	40%	20%

Control boxes are inexpensive in terms of per ton of cooling capacity when connected to a large system.

Outside-Air Economizer Cycle. Economizer cycles can be used to reduce space cooling loads, but they do not allow precise humidity control. When the outside temperature is low, economizer cycles reduce the cooling load by admitting outside air instead of mechanically cooling interior air. Economizer units consist of motorized dampers coupled to inside and outside temperature sensors. Generally, one economizer system is needed for each air distribution system.

Peak demand for a commercial building occurs on days when it is too hot to use the economizer. Therefore, there will be no peak kilowatt savings, but overall energy use will be reduced.

Economizers will not work well in hot or humid climates. They are suitable for new or retrofit applications and are required on all new commercial buildings by ASHRAE 90 and Title 24 standards. The savings in Table 8.25 compare constant volume, variable temperature systems with and without economizers. Savings will be less for variable air volume systems. Lighting loads are 2.7 watts per square foot. Cooling energy savings are based on simulations by the DOE-2 building simulation program. The cost of an economizer system per ton of cooling depends on the size of the cooling system. The installed cost per ton of cooling capacity decreases rapidly as cooling system size increases (see Table 8.26).

Table 8.25. Dry Bulb Economizer Savings

System Temperatures	Los Angeles	San Francisco	Fresno
Supply air min = 55°F Economizer lockout = 72°F	55%	77%	42%
Supply air min = 55°F Economizer lockout = 68°F	50%	74%	39%
Supply air min = 60°F	61%	77%	44%

Table 8.26. Installed Cost of an Economizer System

Peak Cooling Capacity (tons)	Cost Per Ton (1988$)
5-10	85-200
15-20	60-85
25-100	30-60

8.3.3 HVAC Systems[(a)]

The heating, ventilation, and air conditioning (HVAC) system in a building transports the conditioned air from central heating or cooling equipment to various zones within a building. There are two types of systems, those that are load-responsive and those that are not. Systems that are not load-responsive do not reduce their output when the space conditioning load decreases. Consequently, energy used to transport air is high because these systems transport more air than necessary. Such systems also have excessive cooling and heating energy use because of simultaneous heating and cooling. The first cost of a non-load-responsive system is low, but the wasted energy costs are high, unless the building has a constant load.

There are two types of load-responsive systems, variable air volume (VAV) and variable air temperature. Variable-air-volume systems have a fixed air temperature, but use dampers to control the air flow rate to each zone. The volume of air transported by the fans is the sum of the individual zone loads. However, variable-air-volume systems will not reduce flow rates below a minimum level. At this point, they will either overcool a space or provide simultaneous heating and cooling.

The other type of load-responsive system is constant volume, variable temperature. Control circuitry determines the warmest zone conditioned by the HVAC system. The system cools the air to a

(a) This section is based on Usibelli et al. 1985.

low enough temperature1 to cool the warmest zone. All other zones are overcooled or must be reheated to achieve the desired temperature.

Energy use for the most common types of HVAC systems is given in Table 8.27. Systems 1, 3, 5, and 6 in Table 8.27 are prohibited for use in new construction by 1987 Title-24 (California) office building standards. All four of the systems can use large amounts of simultaneous heating and cooling under common operating conditions.

Constant-volume, constant-temperature systems with reheat are not load-responsive systems. These systems transport the maximum volume of cooled air at all times. Reheat coils provide zonal temperature control. Heating, cooling, and transport energy uses are all high for this setup.

Constant-volume, warmest zone supply-air reset is an improvement on the constant-volume, constant-temperature system. The supply air temperature is constantly reset so that the cooling load for the warmest zone is just satisfied. Reheat is used to prevent overcooling in all the cooler zones.

The dual-duct, constant hot and cold deck system has a 95°F high temperature duct and a 55°F low temperature duct. This system is not load-responsive and, consequently, has high heating energy use because of simultaneous heating and cooling.

The dual-duct, hot and cold deck system reset according to the worst zones resets the temperature in both decks to minimize simultaneous heating and cooling.

The variable-air-volume dual-duct, constant hot and cold deck system with 30% minimum stop meets low cooling loads by reducing the flow of cool air down to 30%. Below 30% of peak cooling demand, air from the hot deck is used to prevent overcooling. Consequently, this system employs simultaneous heating and cooling.

The variable-air-volume constant temperature, 30% minimum stop system delivers air at 55°F. Air flow rates are reduced when the load lessens, but the flow rates will not drop below 30% of the peak value. Reheat is used at low loads to maintain air flow rates at the minimum of 30%.

The variable-air-volume, warmest zone supply-air reset system with 30% minimum stop does not use reheat at less than 30% of peak cooling demand. Instead, the system increases the temperature of the supply air. Energy use for these seven types of systems will vary according to loads. For variable cooling loads though, this last system will have the minimum energy use.

HVAC systems waste the most energy on simultaneous heating and cooling when loads differ

Table 8.27. Energy Consumption for HVAC Systems

System Type	Cooling	Air Transport	Simultaneous Heating/Cooling
1. Constant-volume, constant temperature with reheat	High	High	Very high
2. Constant-volume, warmest zone supply-air reset	Low	High	Low
3. Dual-duct, constant hot and cold decks	High	High	High
4. Dual-duct, hot and cold deck reset according to worst zones	Low	High	Low
5. VAV dual-duct, constant hot and cold decks, 30% minimum stop	Medium	Low	High
6. VAV constant temperature, 30% minimum stop	Medium	Low	High
7. VAV, warmest zone supply-air reset, 30% minimum stop	Medium	Low	Low

appreciably from one zone to the next. One option to reduce simultaneous heating and cooling is to divide the building into several zones, all serviced by different HVAC systems. Such a system has a high capital cost and is economical only if it results in large energy savings over more conventional systems.

Development Needs

The development need is demonstration of Swedish Thermodeck construction in U.S. commercial buildings. This technology involves thermal storage in hollow concrete floors, which allows use of inexpensive off-peak cooling but does not add significantly to construction costs.

8.3.4 Windows and Daylighting

Technology Description

Large commercial buildings have significant internal heat gains and low surface-area-to-volume ratios. Therefore, they primarily require cooling, not heating. Lighting a space not only supplies illumination, but adds a heat load. Thus, lighting in commercial buildings, whether from daylight or artificial sources, should minimize the heat gain to minimize cooling costs.

Daylighting can reduce both lighting and cooling bills if the solar gain is controlled. Direct beam sunlight has an efficacy of 92 lumens per watt (Aresteh et al. 1985). Selected wavelengths of light transmitted through glazings that block the solar infrared will have even higher efficacies. Visible sunlight has an efficacy of 240 lumens/watt (AIP 1975). For comparison, standard incandescent and fluorescent lights with core/coil ballasts have respective efficacies of 15 to 17 and 60 to 65 lumens/watt, respectively. (High efficacy values indicate a large ratio between visible light and admitted heat.)

Time and spatial variations are two disadvantages of daylighting compared with artificial light sources. Daylighting levels increase from none to a maximum each day. Daylighting levels also fall off rapidly away from a window. Excess daylighting is necessary near a window to provide acceptable light levels at the back of the room. Spatial variations within a room can be reduced by light distribution mechanisms, such as light shelves and reflective surfaces. Daylighting can be used in building cores as well as perimeter zones. Skylights, light pipes, and reflective wall surfaces can provide daylighting to the core of a building. Thus, daylighting can reduce both lighting and cooling loads for core and perimeter zones of a building.

The shading coefficient of a fenestration system is defined as the ratio of solar gain through the window system to the solar gain through 1/8-inch glass. The visible transmittance, T_v, is the fraction of visible light in the solar spectrum transmitted through the glass. The glazing luminous efficacy constant, K_e, is the ratio of the visible transmittance to the shading coefficient. An ideal commercial window has a high K_e value in order to reduce both lighting and cooling costs.

Low emissivity coatings and optical switching films control solar gain. Sunlight has a high efficacy (lumens/watt), but if the incoming flux is not controlled, removing the solar heat gain may consume more energy than is saved by not using electrical light sources. Low emissivity coatings are transparent over the visible wavelengths (0.30 to 0.77 microns) and reflective in the infrared (2.0 to 100 microns). In order to simultaneously minimize cooling loads and maximize visible transmittance, the film should be reflective in the entire infrared (including the near infrared). Optical switching materials change their reflectance (and transmittance) over part or all of the spectrum in response to an electric field or a change in light intensity. Optical switching materials are not currently available for windows in commercial buildings. Until the fabrication technology improves, the cost to coat a large area is prohibitive.

The lifetime of a multiple-pane window is limited by the integrity of the seal. Typically, seals on multiple-pane windows are assumed to last 20 years. Single-glazed windows have essentially infinite lifetimes if properly installed and maintained.

Energy Performance and Costs

Glazing properties and costs for different types of commercial glazings are shown below in Table 8.28 (Sweitzer et al. 1986). The window types are ordered by K_e values, which should be as large as possible for commercial windows. The theoretical limit for K_e values is approximately 2 (Johnson et al. 1986) and assumes that only visible light is transmitted and that all near infrared is rejected. The R-values are calculated for ASHRAE winter conditions. Glazing unit costs assume 1-inch-thick units with 0.25-inch-thick glass and a 0.5-inch air gap.

Window coating technologies are advancing rapidly, and costs are falling. The physical characteristics of these materials are more akin to those found in the semiconductor industry than to those in the more traditional "heavy industries," so this progress should continue.

Development Needs

The development needs are

1. higher K_e coatings

2. low cost optical switching films, with long lifetimes.

8.3.5 Lighting[(a)]

Lighting consumed 25%, or 2.95 quads, of the primary energy used in commercial buildings in 1985 (BNL 1988). This section will discuss artificial lighting. For a discussion of daylighting, see the section on commercial windows. The breakdown of commercial lighting by lamp type and billions of kilowatt hour use is shown in Figure 8.4.

(a) This section is based largely on Usibelli et al. 1985.

Table 8.28. Glazing Properties

Generic Glazing Products	R-Value (hr-ft^2-°F/Btu)	Emittance	SC	T_v	K_e	Installed Cost[(a)] (1988$/ft^2)
Reflective IG (bronze)	2.5	0.40	0.20	0.10	0.5	17.50
Tinted IG (bronze)	2.0		0.57	0.47	0.8	16.60
Clear IG	2.0		0.82	0.80	1.0	15.10
Low E IG (bronze)	3.0	0.15	0.42	0.41	1.0	18.80
Low E IG (clear)	3.0	0.15	0.66	0.72	1.1	18.20
Tinted IG (green)	2.0		0.56	0.67	1.2	16.60
Triple glazing IG (green) with low E coated polyester film suspended in airspace	3.6	0.15	0.47	0.58	1.2	22.80
Low E IG (green)	3.0	0.15	0.41	0.61	1.5	18.80

(a) Cost data from Mahoney 1987.

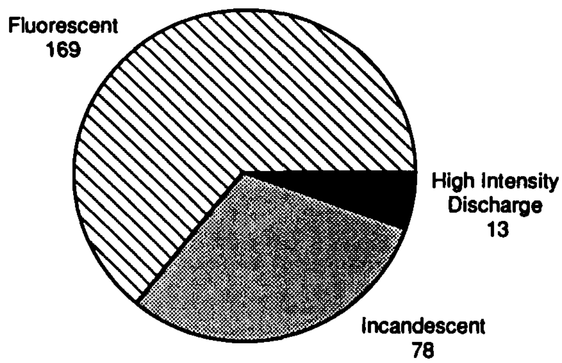

Figure 8.4. 1985 Commercial Lighting

In most buildings, reducing commercial lighting also results in reduced cooling load at the time of many utility systems' peak demand. Thus, the combined cooling and lighting load reductions result in a lowering of electric demand at the time when it is most expensive for the utility to generate electricity.

Technology Description

Energy-Efficient Core/Coil Ballasts. Energy efficient core/coil ballasts have larger iron cores than conventional core/coil fluorescent ballasts and use copper (instead of aluminum) windings. These ballasts are required by California Title-24 regulations. As of January 1990, conventional core/coil ballasts were outlawed by the new federal appliance standards.

Electronic (Solid-State) Ballasts. Standard fluorescent core and coil ballasts operate at 60 Hz. Electronic ballasts convert the 60-Hz wall current into a 10,000- to 30,000-Hz current. Lamps operating at these frequencies have a higher efficacy and often have no detectable flicker. Dimming is more efficacious with solid-state ballasts than with core/coil ballasts. Additionally, earlier reliability problems with solid-state ballasts have largely been eliminated.

Fluorescent Delamping. Delamping is used when existing light levels are excessive or specific task lighting replaces overall uniform lighting levels. Dummy tubes are necessary when both bulbs in a fixture are wired to the one ballast. Reactive impedance lamps may be necessary to get the power factor back up to 0.9 after delamping. Savings depend on lights removed and whether impedance correction is needed.

Compact Fluorescents. See residential lighting section for more details. Compact fluorescents are typically more cost-effective when replacing incandescents in commercial applications than in residential. The savings result from higher duty cycles and the monetary value of avoiding the labor of constantly replacing short-lived incandescents.

Ellipsoidal Bulb Replacements for A/R Type Incandescents. Recessed incandescent light fixtures with conventional bulbs have large interior absorption losses. Ellipsoidal bulbs have a focal point below the fixture aperture so that less light is absorbed in the fixture. This design results in a higher system efficacy for the same efficacy bulb. Ellipsoidal bulbs replace conventional bulbs with 2 to 4 times the wattage.

Lower Wattage Fluorescent Lamps. Lower wattage fluorescent lamps use improved phosphors for savings of about 7% and are a widely used conservation measure. Lamp wattage and lumens are both decreased but efficacy may improve. In some situations, the consequent reduction in lighting levels (despite higher efficacy) may reduce lighting to unacceptably low levels.

Coated Filament Incandescent Lamps. Coated filament incandescent lamps have an infrared reflective coating that reflects heat back to the filament and reduces energy needed to heat the filament. Prototype models have efficacies of 29 lumens/watt compared with 15 to 17 for a standard incandescent.

Electrodeless Fluorescent Lamps. The electrodeless fluorescent lamp is a compact fluorescent lamp without electrodes. It fits into standard incandescent (Edison-type) sockets. These lamps are not commercially available at this point. Prototypes have a high efficacy (55 lumens/watt) but a poor color rendering index (CRI = 57). For comparison, a standard incandescent has a color rendering index of 90.

High Pressure Sodium Lamps. High pressure sodium lamps are a type of high intensity discharge lamp. They have high efficacies (60 to 127 lumens/watt) but poor color rendering. Additionally, the warmup time is three to four minutes and the restrike time is between 30 and 90 seconds. Thus, high intensity discharge lamps are commonly used for street lighting and not for indoor lighting.

8.3.6 Lighting Controls[a]

Lighting controls reduce energy consumption by providing the optimum amount of artificial light necessary to perform a given task. Lighting systems can dim artificial lights in response to daylight, turn off lights when occupants are not there, and allow occupants to fine tune lighting for individual areas. Four energy saving lighting control measures are discussed below.

Occupancy Scheduling

Occupancy scheduling involves turning off or dimming lights during periods when occupants are not present or do not need a high light level. The four control mechanisms are 1) manual wall switches, 2) mechanical or electrical timeclocks, 3) microprocessor-based systems, and 4) personnel sensors.

Lumen Maintenance

The light output of lamps decreases approximately 30% between installation and replacement. Thus, the light levels provided by newly installed fixtures are typically 30% higher than optimal design conditions. Using a photocell to measure actual light levels, lumen maintenance systems dim the lights to the optimal level. The savings range from 30% initially to no savings shortly before replacement.

(a) This section is based on Usibelli et al. 1985.

Fine Tuning

Most buildings are designed with worst case lighting which often far exceeds actual needs in the space. Additionally, changes in occupancy or tasks performed in the space will change the necessary lighting levels. Local dimming control on individual or small groups of fixtures allows the occupants to choose optimal light levels.

Load Shedding

Commercial buildings pay peak demand charges, as well as rates that are influenced by the time of day. To reduce peak charges, unnecessary electricity-consuming devices can be shut off as the peak load is approached. Lighting loads typically account for 30% to 60% of the electric load. To reduce commercial building peak loads, which occur during daylight hours, lights should be dimmed or shut off as the peak load is approached.

8.3.7 Building Insulation

For a discussion of insulating materials, see the section on residential insulation. Costs and energy performance of different insulating materials are given in Table 8.29.

8.3.8 Miscellaneous Commercial Energy End Uses

Almost 2 quads of commercial energy use is lumped into the "other" category. (Information processing equipment is not included in this estimate, though we consider it an important "miscellaneous" end use here.) As shown in Table 8.30, the largest commercial end uses in the "other" category include refrigeration, waterheating, and cooking. The significance of each end use depends on the building type. Computer equipment and other information processing devices can, in some building types (e.g., offices), be an important end use, though its future importance is difficult to predict. Information processing devices are changing rapidly in both form and function: integrated printers, copiers, and fax machines are now available, and laptop computers (which typically use 1/10 the

Table 8.29. National Average Contractor-Installed Cost of Insulation in New Commercial Construction

Insulation Type	Thickness (inches)	R-Value (hr-ft^2-°F/Btu)	Installation Method	Cost (1988$/ft^2)
Fiberglass	3.5	11	Batts	0.40
Fiberglass	5.5	19	Batts	0.54
Polystyrene	1.0	5	Rigid sheets	0.55
Polystyrene	2.0	8	Rigid sheets	0.90
Urethane	1.5	10	Rigid sheets	0.86
Urethane	2.0	14	Rigid sheets	1.00
Isocyanurate	0.5	4	Rigid sheets	0.48
Isocyanurate	1.5	8	Rigid sheets	0.74

Note: Fiberglass data assume that studs are 16 in. on center.
Source: Kiley (1988).

Table 8.30. Miscellaneous Energy End Uses

End Use	Building Type	Energy Use (kWh/ft^2-yr)
Refrigeration	Food stores	14 - 26
	Restaurants	5 - 22
Cooking	Restaurants	6.5 - 18.5
Waterheating	Restaurants	1.5 - 14
	Schools, hospitals, offices	1.0 - 4.0
Computer Equipment	Offices	3

Source: Turiel and Lebot 1988.

electricity of their desktop counterparts) are by far the fastest growing segment in the personal computer industry (Harris et al. 1988).

8.4 DISTRICT HEATING FOR RESIDENTIAL AND COMMERCIAL BUILDINGS

Waste heat from electric power generation can be used in residential and commercial space and water heating. This use of waste heat is called district heating or combined heat and power cogeneration. Iceland, Denmark, and other European countries derive major fractions of their space heating needs from district heating, but in the United States, use of this technology has been confined to small-scale installations in a few large cities.

Traditionally, district heating schemes have relied on large, central station power plants, but this preference may be changing. Recent advances in small-scale, mass-producible, gas-fired, cogeneration systems make such district heating extremely attractive in many applications. Large reductions in pollutant emissions are possible using gas-fired systems because they will often replace space heating boilers that use oil (or coal). Even if the displaced boiler fuel is gas, emissions reductions can be significant because of the higher thermal efficiency overall. Further research is needed to pinpoint the most cost-effective applications, and policies may be needed to encourage rapid adoption of such technologies in specific applications.

8.5 SUMMARY

Estimates of the potential for cost-effective, electricity-saving retrofits in the building sector range from the Electric Power Research Institute projection of 30% to the 75% estimate from the Rocky Mountain Institute. New technologies are constantly being developed and further savings will then be possible. The Rocky Mountain Institute has found that most of the best energy-efficiency technologies are less than one year old (Ficket et al. 1990).

Higher standards of cost-effective energy efficiency are possible in new construction than in retrofitted buildings. Retrofits involve discarding existing equipment and are thus more expensive than building the structure right in the first place. There are significant "lost opportunities" when energy-efficient new technologies are not installed in new construction. Buildings last for approximately 100 years, thus such "lost opportunities" are long-term liabilities.

Many of the technologies that provide cost-effective electricity savings have existed for years, but have not even come close to saturating the market. Energy-efficient windows, lighting, and HVAC technologies, as well as landscaping, offer some of the largest potentials for cost-effective savings. Stricter standards and enforcement, coupled with financial incentives for customers and utilities to adopt these technologies, are necessary to achieve large market penetrations.

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9.0 GREENHOUSE GAS REMOVAL TECHNOLOGY

Published technical and economic data on the control and disposal of greenhouse gases are summarized in this chapter. The principal focus is on technologies that could be used to control emissions of carbon dioxide; nitrogen oxides, including nitrous oxide; and carbon monoxide from fossil-fuel-fired industrial and utility boilers and cement plants. In addition, methane control technologies for coal mines, natural gas pipelines, and landfills are characterized.

This chapter is limited to a review of information previously published. The review of published references for greenhouse gas removal revealed numerous inconsistencies among data published in different reports, even reports published by the same author. In addition, there was a general shortage of designs, cost estimates, and economic analyses using a consistent, well-defined basis. To the extent possible, the data from different sources have been adjusted to a consistent basis using professional judgment. However, no independent analysis or process optimization was performed. Thus, the results reported in this chapter should be considered preliminary order-of-magnitude estimates that should be evaluated more closely in the near future.

The results in this summary chapter provide a useful comparison of the various greenhouse gas control technologies by identifying typical processes and expected performance and cost data. It is important to remember that the data are based upon readily available information. A rigorous and thorough analysis of the subject area was beyond the scope of this study.

The technology descriptions and economic data for control technology for emissions of carbon dioxide, carbon monoxide, nitrogen oxides, and methane are presented in Sections 9.1.1 through 9.1.4, respectively. Section 9.2 describes various carbon dioxide transport and disposal technologies. Finally, Section 9.3 summarizes the performance and cost data for the greenhouse gas control technologies. Section 9.4 lists and defines the terms and assumptions used in the performance and cost calculations presented in the tables throughout this chapter.

9.1 EMISSIONS CAPTURE AND CONTROL TECHNOLOGIES

As shown in Table 9.1, several types of components/compounds are present in the exhaust gases of boilers, cement plants, landfills, natural gas pipelines, and coal mines. Some of these compounds (e.g., nitrogen oxides and particulates) are currently controlled; others, such as carbon dioxide are not mitigated. In addition, not all compounds released by the various sources have been classified as greenhouse gases. Table 9.1 also lists the gases for which technical and economic data have been collected and reviewed in this report. The assumptions and other technical details associated with controlling greenhouse gases are discussed below.

9.1.1 Carbon Dioxide Control

Carbon dioxide can be removed from the energy cycle either before fuel combustion or after. Pre-combustion removal generally involves using chemical processes to break the hydrocarbon bonds in the fossil fuel; these measures then allow selective combustion of hydrogen without the formation of carbon dioxide. Pre-combustion processing may also include measures designed to concentrate carbon dioxide levels in the flue gas for post-combustion removal. Post-combustion removal involves eliminating carbon dioxide from the power plant flue gas through use of a scrubber or similar filtering technology.

A number of physical and chemical separation processes are available to effect carbon capture in

Table 9.1. Exhaust Gas Emissions by Source

Source	Primary Pollutants	Example Control Technology	Status/Use	Comments	Greenhouse Gas	Summarized in Current Study[a]	Cost Data in Study
Industrial and Utility Boilers	Carbon monoxide	NA[b]	None required	None required	Yes	Yes	No
	Carbon monoxide	Monoethanol amine, molecular sieves, potassium carbonate	Not practiced	Not considered a pollutant	Yes	Yes	Yes
	Nitrogen oxides	Low No_x burners, selective catalytic reduction, staged fuel/air injection	Commercial	---	Yes	Yes	Yes
	Nitrous oxide	None	---	Very small amounts in exhaust gas; no data available	Yes	Yes	No
	Sulfur oxides	Fuel sulfur control, dry sorbent injection, wet scrubbers	Commercial	---	No	No	No
	Particulates	Baghouses, electrostatic precipitation, wet scrubbers	Commercial	---	No	No	No
	Non-methane volatile organic compounds	NA	NA	Precursor to ozone destruction	No	No	No
	Methane	NA	NA	Not considered a pollutant	Yes	No	No
Cement Plants	Nitrogen oxides	Process control (e.g., fuel firing rate, excess air level)	Commercial	Very small amounts in exhaust gas	Yes	No	No
	Carbon dioxide	Monoethanol amine, potassium carbonate	Not practiced	Not considered a pollutant	Yes	Yes	Yes[c]
	Carbon monoxide	---	---	Very small amounts in exhaust gas	Yes	No	No
	Methane	---	---	Very small amounts in exhaust gas	Yes	No	No
Landfills	Carbon dioxide	Molecular sieves, membranes	Not practiced	Not considered a pollutant	Yes	Yes	Yes[c]
	Methane	Molecular sieves, membranes	Commercial	Not considered a pollutant	Yes	Yes	Yes
Natural Gas Pipelines	Methane	---	Not practiced	Emissions small and very dispersed	Yes	Yes	No
Coal Mines	Methane	Membranes	Commercial	---	Yes	Yes	Yes

(a) Limited by scope of study.
(b) Not applicable.
(c) Similar to boilers.

either pre- or post-combustion modes. The most important of these processes can be grouped into four categories.

- chemical separation
- physical separation
- membrane processes
- cryogenic processes.

These categories are briefly described below (Parekh 1982; Marland 1986; Baes et al. 1980a; Steinberg et al. 1984; Kaplan 1982; Steinberg 1983a,b; Fraser et al. 1983).

Chemical Separation

Figure 9.1 is a simplified flow diagram showing a typical pre-combustion chemical separation process. The incoming acid gas (hydrogen sulfide and carbon dioxide) in the diagram reacts chemically with the solvent in the absorber to form intermediate compounds. The purified gas exits the top of the absorber, while the rich solvent exits the bottom and flows to the regenerator. In the regenerator, the solvent is heated to reverse the chemical reaction, driving off the acid gases. The regenerated solvent is then returned to the absorber.

Two common chemical separation processes are the alkanol amine processes (e.g., monoethanol amine, diethanol amine, and methyl diethanol amine) and the carbonate processes (e.g., Benfield), both of which have been in use for many years in the natural gas processing industry and which are described in some detail below.

Physical Separation

The process configuration of a physical separation process is similar to that of the chemical separation process shown in Figure 9.1. In physical separation processes, however, the acid gases do not react chemically with the solvent, but instead are physically absorbed (dissolved) into the solvent. The rich solvent is then heated in the regeneration column to drive off the acid gases. Examples of physical separation processes are Rectisol and Selexol.

Physical separation processes are generally favored for higher pressure applications (>200 psig).

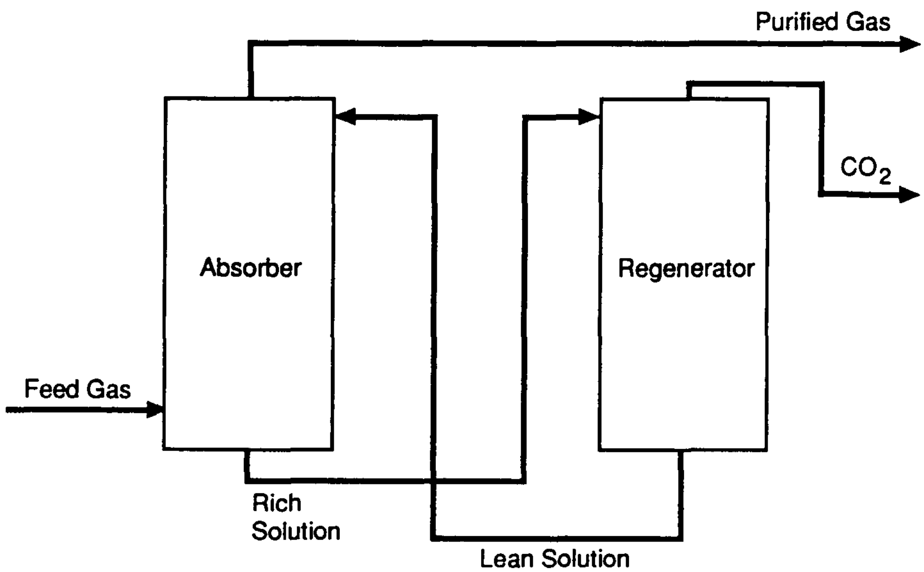

Figure 9.1. Chemical Separation Process Flow Schematic

For low pressure applications, the equipment required for physical separation is much larger for the same gas throughput, and the economics favor the chemical separation processes.

Membrane Processes

The basic concept of membrane separation processes is illustrated in Figure 9.2. To effect mass transport through the membrane, a driving force (e.g., pressure, concentration, electromagnetic field, etc.) must be applied across the membrane. Under the influence of the driving force, the membrane permits specific components (solutes, solvents, or gases) to pass through (permeate) it. The membrane also inhibits transport of some components. This selective transport forms the basis of the membrane separation process, which generally involves the separation of solutes from a fluid or the separation of two fluids.

In general, membrane processes are economical for purifying gases at high pressure (e.g., 500 psig). To date, their major commercial application has been to purify hydrogen. Because the gases are driven through the membrane by pressure, membrane processes usually are not used for low-pressure separation.

Cryogenic Processes

Cryogenic processes refrigerate and distill the feed gas at high pressures (600 psig) and low temperatures (-120°F) to separate the constituents according to their different boiling points. Cryogenic processes are not commonly used to separate carbon dioxide from hydrogen streams unless liquefied natural gas is the desired product. If the product is a gas (instead of a refrigerated liquid), a chemical, physical, or membrane process is more economical.

Examples of carbon dioxide removal technologies are discussed below. Some of these are still under development and have not been proved commercially.

Pre-Combustion Technologies

Air Separation. Separating the constituents of the flue gas allows the carbon dioxide to be isolated and subsequently removed. Typically, only about 15% of the flue gas by volume is carbon dioxide; thus, the energy required in the separation is significant. One approach to reducing this energy requirement involves a pre-combustion separation process on the incoming air to enhance its oxygen

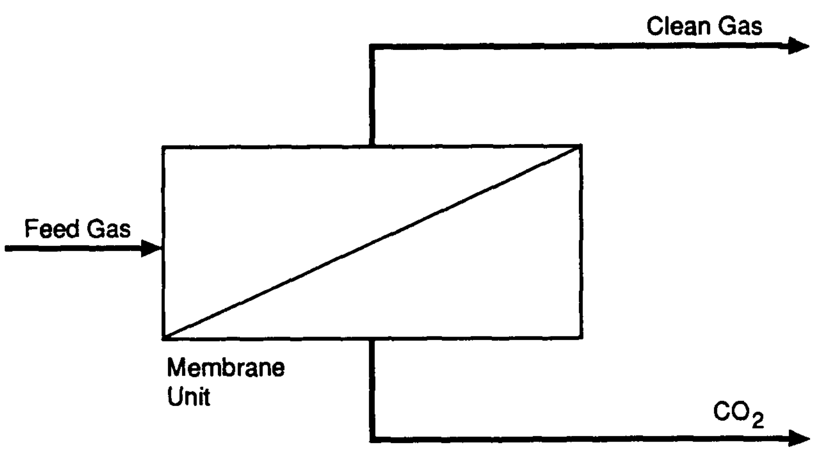

Figure 9.2. Membrane Process Flow Schematic

content and reduce other would-be components of the flue gas. Processes available for air separation include membranes, pressure swing absorption, and cryogenic distillation, although cryogenic distillation is currently the only practical choice for large-scale applications (Golomb et al. 1989). Enhanced oxygen levels increase the combustion efficiency of the fuel so that a greater portion of the carbon within the fuel is converted to carbon dioxide (versus carbon monoxide or unburned hydrocarbons). The carbon dioxide is not removed until after combustion.

Gasification. In the case of coal, gasification produces a hydrogen-rich gas from which the carbon can be removed before combustion in the power plant. The hydrogen-rich gas is produced through "water shift" reactions. A gasification plant incorporates three basic steps:[a]

Coal (c) + H_2O = CO + H_2 (water gas reaction)

Coal (c) + O_2 = CO_2 (to provide endothermic energy for water gas reaction)

CO + H_2O = CO_2 + H_2 (water gas reaction).

The carbon dioxide can then be removed through one of the advanced recovery technologies and the hydrogen directed to the power plant for combustion. Some of the advanced electricity technologies discussed in Chapter 2 incorporate gasification processes (e.g., IGCC, fuel cells). Blok et al. (1989) estimate the efficiency penalty of an IGCC plant incorporating carbon dioxide recovery (Selexol process assumed) to be about 5% (dropping the efficiency from 43.6% to 38.7% in their estimate). The same study also estimates an increased busboard electricity price of 24%.

The HYDROCARB Process. Coal is hydrogenated in an exothermic reaction at about 800°C (1500°F) and about 50 atm, forming methane in high yields and leaving coal ash behind. After the oxygen has been removed from the process gas as either carbon dioxide or water by adsorption or condensation, the methane-rich gas is heated with excess hydrogen to about 1100°C (2000°F). At this temperature, methane thermally decomposes in an endothermic reaction to carbon black and hydrogen. Several types of reactors can be used to carry out the hydrogasification and thermal decomposition reactions, including fluidized beds and packed moving beds.

The HYDROCARB process essentially removes the carbon from coal as carbon black and places it in "monitored retrievable storage" for future use, rather than removing the carbon dioxide from the flue gas after coal combustion. The major product from the HYDROCARB process is hydrogen, which can then be burned as fuel in a power plant. Steinberg (1987) claims that, under the best conditions, the efficiency to produce hydrogen from coal is 24%. This is comparable to the use of nuclear reactors for generating electricity to electrolyze water for producing hydrogen, which also has a thermal-to-hydrogen energy conversion efficiency of 24%.

The HYDROCARB process was conceptually developed at the Brookhaven National Laboratory. It has not been commercialized or even demonstrated in the laboratory. Brookhaven researchers are advocating the construction of coal refineries based on this process technology.

Post-Combustion Technologies

Flue Gas Recycling. Recycling a portion of the flue gas increases the carbon dioxide content of the final exhaust stream. Recycling would typically be used in conjunction with a pre-combustion air separation process. The combination of air separation/flue gas recycling is a relatively inexpensive means of concentrating the carbon dioxide for subsequent removal (Golomb et al. 1989). Approximately 75% of the flue gas is recycled to the combustor under this approach. The remainder is

(a) Steinberg, M., J. Lee, and S. Morris. March 1991. *An Assessment of CO_2 Greenhouse Gas Mitigation Technologies.* BNL-46045 Informal Report (Limited Distribution), Brookhaven National Laboratory, Upton, Long Island, New York.

directed through the chosen carbon dioxide capture process, dehydrated, compressed, and disposed of.

Many technologies could potentially be used to remove carbon dioxide from the flue gas stream. The preferred absorption system (physical, chemical, or a combination) will depend on the operating pressure chosen. Chemical solvents are generally preferred for their high absorptive capacity at low pressure. In contrast, physical separation processes require high pressures. Low-pressure flue gases must therefore be compressed, introducing associated energy losses and costs. However, chemicals can introduce solvent degradation and other problems. A partial listing of these technologies includes[a]

Fluor Solvent	Fluor Econamine
Purisol	SNPA-DEA
Rectisol	Alkacid M
Selexol	Ammonia-based processes
Amisol	Benfield
Sulfinol	Giammarco-Vetrocoke
ADIP	Vacuum carbonate
Dow MEA	

Two of these technologies (Dow MEA and Benfield) are discussed in further detail below.

Monoethanol Amine. The monoethanol amine process has been used in the natural gas processing and petroleum refining industries to remove hydrogen sulfide and carbon dioxide from hydrocarbon gases for many years. The technology is well developed and understood, and can be readily adapted to remove carbon dioxide from boiler flue gas.

Monoethanol amine is a strong base that removes the acidic carbon dioxide by two reactions:

$$C_2H_4OHNH_2 + CO_2 + H_2O \rightarrow C_2H_4OHNH_3 \cdot HCO_3$$

$$2\,C_2H_4OHNH_2 + CO_2 \rightarrow C_2H_4OHNHCO_2 \cdot NH_3C_2H_4OH$$

The conventional monoethanol amine process has several disadvantages that limit its application in the refining and natural gas industries. Because monoethanol amine does not remove mercaptans efficiently and because it is degraded by reduced sulfur compounds, such as carbonyl sulfide, diethanol amine is more commonly used when these compounds are present. Another disadvantage of the monoethanol amine process in refinery applications is that it does not preferentially remove hydrogen sulfide. These disadvantages in natural gas purification, however, should not be significant for removal of carbon dioxide from flue gas. For flue gas purification, the oxygen and sulfur dioxide contents of the flue gas are of greatest concern.

Figure 9.3 is a flow diagram of the monoethanol amine process. A solution of 20% monoethanol amine in water is fed to the top of the absorber where it flows countercurrent to the flue gas. As the flue gas rises in the absorber, the carbon dioxide reacts with the monoethanol amine at approximately 140°F. The cleaned gas exits the top of the absorber while the rich solvent flows to the regenerator, operating at approximately 260°F. At this temperature, the chemical reaction is reversed, driving off the carbon dioxide. The regenerated solvent is returned to the absorber. If sulfur compounds other than hydrogen sulfide are present, monoethanol amine can be degraded by nonreversible reactions. In the monoethanol amine process, a small purge is taken from the regenerator to reclaim the degraded solvent.

The carbon dioxide gas from the regenerator must be subsequently disposed of. Some carbon dioxide could also be used in enhanced oil recovery. The enhanced oil recovery market has been estimated at 1 to 3 trillion cubic feet of carbon dioxide per year. However, this market is very sensitive to oil prices. In the early 1980s, many different organizations, including DOE and EPRI, investigated the recovery of carbon dioxide from flue gas for use in enhanced oil recovery. Several amine units were

(a) Smith, I., K. Thambimuthu, and L. Clarke. January 1991. *Greenhouse Gases, Abatement and Control: The Role of Coal*. Draft Report. International Energy Agency Coal Research, London.

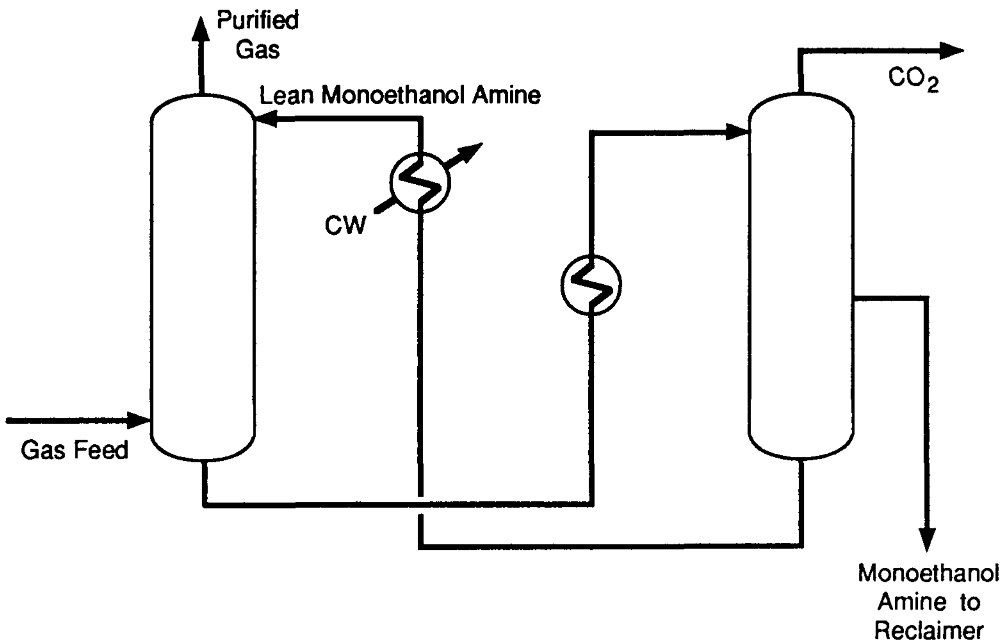

Figure 9.3. Monoethanol Amine Process Flow Schematic

installed on plants fired with methanol gas. Because of the decline in oil prices, however, these projects are no longer operating. The enhanced oil recovery application was based on the economics of carbon dioxide recovery, rather than on global warming considerations. The use of carbon dioxide for enhanced oil recovery may only be partially effective as a global warming mitigation technology because a significant portion of the carbon dioxide used in enhanced oil recovery is later released into the atmosphere.

Potential for Carbon Dioxide Reduction. Monoethanol amine can remove carbon dioxide to less than 1,000 ppm in the purified gas. Studies of 90% carbon dioxide removal from boiler flue gas have been published based on the demonstrated commercial experience in gas processing.

Approximately 5.6 million Btu of energy is required to remove one ton of carbon dioxide via the monoethanol amine process.

Development Needs. Monoethanol amine is a commercial process widely installed in the natural gas processing and petroleum refining industries throughout the United States. The amine processes have been fully commercialized for the removal of hydrogen sulfide and carbon dioxide from natural gas. However, for large-scale removal of carbon dioxide from flue gas, it may be possible to develop more efficient and more economical processes than monoethanol amine. In addition, the flue gas from coal-fired boilers is likely to have a higher particulate loading than the natural gas and refinery gas feedstocks normally processed in monoethanol amine. Furthermore, these processes recycle the chemicals and are thus subject to influence by the small amount of impurities usually present in the flue gas (which are concentrated in the chemicals as the chemicals are recycled). There is no experience in using these processes on flue gas from coal-fired boilers, where particulates, sulfur, and other chemicals are expected in the flue gas. A second potential issue is the ability of the monoethanol amine unit to load-follow. However, neither of these issues should be a significant barrier to applying the technology to carbon dioxide removal from flue gas.

Commercialization Issues. Except in very few instances, such as enhanced oil recovery, there is no economic incentive for a utility or any industrial process to install a system to recover and dispose of carbon dioxide. Thus, policy intervention in terms of regulation or economic incentive would be required to promote adoption of this technology. With policy intervention mandating the use of carbon dioxide control, 3 to 5 years would be required to pilot test and demonstrate the technologies using actual boiler flue gas. Thereafter, the selected mature technologies could be installed with a construction time of about 1 year.

There are many potential problems in applying this technology universally. For example, existing power plants located in congested areas, such as New York City, might not be able to install a carbon dioxide scrubbing system economically because of lack of space. Some other plants might not be located close enough to the ocean or to underground caverns to dispose of the carbon dioxide economically.

Quantitative Performance and Cost Data. Table 9.2 summarizes the performance and cost data for a monoethanol amine plant. (The terms and assumptions used to develop the data in Table 9.2 are more fully defined in Section 9.5.)

Potassium Carbonate. Figure 9.4 shows a schematic of the potassium carbonate process, also known as the Benfield process. In this process, the carbon dioxide in the gas reacts with potassium carbonate to form potassium bicarbonate in the first column (the absorber). In most gas processing applications, the absorber operates at 100 to 2,000 psig and at temperatures as high as 250°F. Next, the potassium bicarbonate solution flows to the regenerator where it is reconverted to potassium carbonate. The regenerator operates at atmospheric pressure and at a temperature of about 230°F.

The chemical reaction that takes place in the absorber to recover carbon dioxide is

Table 9.2. Performance and Cost Data for Carbon Dioxide Removal Through a Monoethanol Amine Plant

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	5.6
Heat Rate, Btu/kWh	4300
Capacity Factor	90%
Percent Removal	90%
Operating Lifetime	20 years
Operating Characteristics Uncertainty	Low
COSTS	
Capital Costs, annual $/million Btu	0.71
O&M Costs, $/million Btu fired	2.10
Cost of Capital	Low
MARKET POTENTIAL	
Maximum Potential Penetration	95%
Expected Date of First Entry	
Without Policy Intervention	None
With Policy Intervention	2000
Construction Time, Years	1

$$K_2CO_3 + CO_2 + H_2O \rightarrow 2\,KHCO_3$$

The reverse reaction takes place in the regenerator.

Potential for Carbon Dioxide Reduction. The Benfield Hi Pure process is reportedly able to reduce carbon dioxide concentration to 10 ppm in the purified gas. No economic data for this extreme treatment were found during this study, but this degree of scrubbing is likely to be very expensive. Studies of 90% carbon dioxide removal from boiler flue gas have been published based on the demonstrated commercial experience in gas processing.

Approximately 6.6 million Btu of energy is required to remove 1 ton of carbon dioxide.

Development Needs. Over 500 Benfield-activated potassium carbonate plants have been reported in commercial operation, mostly for selective removal of hydrogen sulfide from hydrocarbon gases. The potassium carbonate process is capable of scrubbing low pressure gas, but it has mostly been

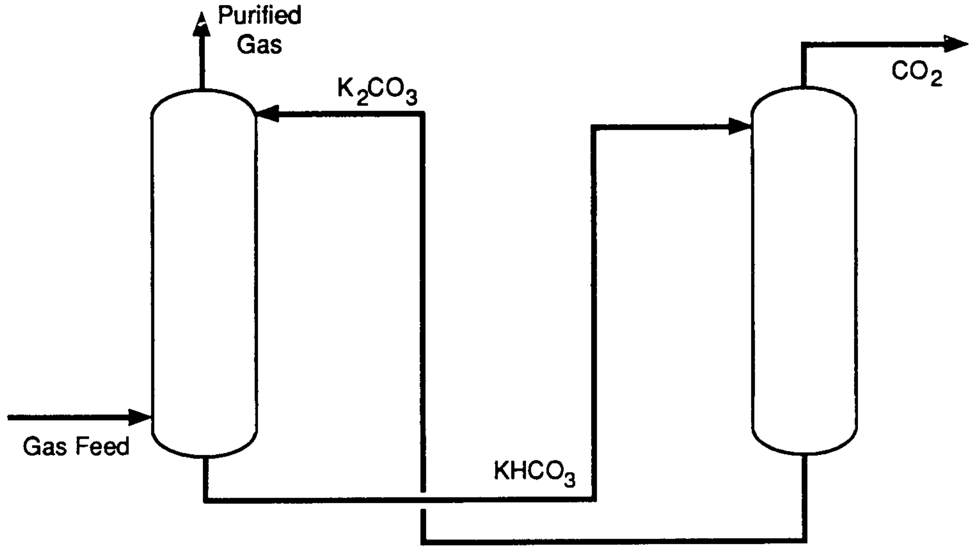

Figure 9.4. Benfield Potassium Carbonate Process Schematic

applied for gas pressures over 100 psig. Application to low pressure gas is more an economic issue than a technical one.

As stated previously, the flue gas from coal-fired boilers is likely to have a higher particulate loading than the natural gas and refinery gas feedstocks normally processed in potassium carbonate units. In addition, these processes recycle the chemicals and are thus subject to influence by a small amount of impurities usually present in the flue gas. (The impurities are concentrated in the chemicals as the chemicals are recycled.) There is no experience in using these processes on flue gas from coal-fired boilers, where particulates, sulfur, and other chemicals are expected in the gas. A second potential issue is the ability of the potassium carbonate unit to load-follow. Once a decision has been made to use a potassium carbonate system to remove carbon dioxide from flue gas, technical solutions to these two issues can be developed, probably without any additional government support.

Commercialization Issues. Currently, a utility or an industrial firm has no economic incentive to install a potassium carbonate system to recover and dispose of carbon dioxide. Thus, policy intervention in terms of regulation or economic incentive will be required to promote adoption of this technology. With policy intervention mandating the application, 3 to 5 years would be required to pilot test and demonstrate the technologies using actual boiler flue gas. Thereafter, the selected mature technologies could be installed with a construction time of about 1 year.

Once carbon dioxide scrubbing is required, the potassium carbonate process may be more economical than monoethanol amine in a few applications. Among its advantages is the ability to process feed gas up to 280°F. However, as in the case of the monoethanol amine process, some utilities will find space or location constraints to be significant barriers to installation of a carbon dioxide recovery and disposal system.

Quantitative Performance and Cost Data. Table 9.3 summarizes the performance and cost data for a potassium carbonate facility. (See Section 9.5 for definition of terms.)

Table 9.3. Performance and Cost Data for Carbon Dioxide Removal Through a Potassium Carbonate Facility

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	6.6
Heat Rate, Btu/kWh	5100
Capacity Factor	90%
Percent Removal	90%
Operating Lifetime	20 years
Operating Characteristics Uncertainty	Low
COSTS	
Capital Costs, annual $/million Btu	0.75
O&M Costs, $/million Btu fired	1.80
Cost of Capital	Low
MARKET POTENTIAL	
Maximum Potential Penetration	95%
Expected Date of First Entry	
Without Policy Intervention	None
With Policy Intervention	1995
Construction Time, Years	1

Carbon Dioxide Control Technology Selection

Preliminary assessment of the process categories described above shows that chemical separation is expected to be the most economical and technically feasible process for removing carbon dioxide from the low pressure flue gas generated by boilers. Both amine and potassium carbonate processes would be suitable. Among the amines, however, only monoethanol amine appears promising for the selective removal of carbon dioxide. The other amine processes (e.g., diethanol amine or methyl diethanol amine) are not suitable because of their ability to remove hydrogen sulfide in preference to carbon dioxide and because they can remove other sulfur compounds, such as carbonyl sulfide. In other words, diethanol amine and methyl diethanol amine processes are used to remove carbon dioxide in the presence of sulfur-containing compounds. These considerations, however, are not important for carbon dioxide removal in many utility and industrial boilers.

In addition, monoethanol amine processes are less expensive to apply because they require less initial capital investment for installation than do other chemical absorption control methods. These processes, however, have higher operating costs than the potassium carbonate chemical absorption systems. They are also sensitive to sulfur and oxygen contamination and experience a loss in absorption efficiency because of the contamination. In comparison, carbonate-based processes are more sulfur tolerant, and at the sulfur dioxide levels expected in the flue gas after desulfurization, the carbonates could be less expensive to operate. The carbonates will still have higher initial capital costs than the amine-based processes.

Removing carbon dioxide from the atmosphere through chemical absorption processes is estimated to require 1.5 to 2 times the energy required to remove it from power plant flue gases; the cost range depends upon the percent of carbon dioxide removed from the flue gas. The subsequent disposal of the carbon dioxide into the ocean as either a gas or a liquid requires about the same amount of energy, while disposal as a solid requires about twice the energy. The estimates further indicate that removing 50% of the carbon dioxide in flue gases would reduce power plant efficiency to less than 27%, while removing 90% of the carbon dioxide would reduce power plant efficiency to less than 14%.

In general, physical separation and membrane processes are not technically or economically feasible for existing utility and industrial boilers. Such plants currently emit their exhaust at about atmospheric pressure, which does not offer sufficient pressure differential to allow diffusion membranes or molecular sieves to be used to separate the carbon dioxide from the flue gas. However, if pressurized fluidized-bed combustion becomes an important power plant technology, there would be sufficient pressure head, making it worthwhile to evaluate mechanical or physical separation technologies.

The cryogenic process is not summarized in this report primarily because no published information on the application of the process for removing carbon dioxide from boiler flue gas could be found. In general, cryogenic processes are likely to be very expensive, although they might be competitive in some instances (e.g., large-scale applications). In addition, the energy required to remove carbon dioxide by cryogenic technologies is 20 times greater than the energy required by chemical processes.

Besides the four process categories (chemical separation, physical separation, membrane processes, and cryogenic processes) described above, other "acid gas removal" processes are used in the natural gas industry. These processes have not been considered in this study because they are primarily applicable to removal of hydrogen sulfide and are not used to separate carbon dioxide. These processes include

- solid bed adsorption (zinc oxide)
- direct conversion (Stretford, Unisulf, Takahax, etc.)
- dry oxidation (Selectox).

In addition, lime scrubbing was not considered because it is not promising for carbon dioxide removal from flue gas.

Thus, at present, chemical separation processes appear to be the most feasible (technically and economically) near-term option for removing carbon dioxide from boiler flue gas. This selection is consistent with the work of other investigators (Steinberg 1983a,b; Fraser et al. 1983). The information presented in this report is based on published studies of carbon dioxide removal from boiler flue gas which contains 8% to 16% oxygen.

The chemical separation processes could also be applied to remove carbon dioxide from cement kiln flue gas. The exhaust gases from cement kilns contain a mixture of combustion products and carbon dioxide from calcination. This stream is normally cleaned of particulates and vented into the atmosphere. The primary components of cement kiln stack gas are carbon dioxide, water vapor, and nitrogen, with small amounts of carbon monoxide, methane, and nitrogen oxides. In general, nitrogen oxides emissions are mitigated by process control such as by controlling flame temperature, fuel firing rate, or level of excess air. To date, no nitrous oxide emissions have been identified in cement plant exhaust gases. Since cement kiln flue gas contains more carbon dioxide (20% to 25%) than boiler flue gas (8% to 16%), the removal costs should be slightly lower per ton of carbon dioxide removed.

9.1.2 Carbon Monoxide Control

Carbon monoxide is controlled by tuning the boiler to reduce carbon monoxide emissions or by employing oxidizing catalysts to convert the carbon monoxide in the flue gas to carbon dioxide. In general, tuning the boiler involves making simple mechanical changes to the burner/boiler system. By far, the most economical and common methods used are to adjust burner controls and/or tilt the burners and/or adjust the location and amount of combustion air.

The carbon monoxide catalysts are highly oxidizing, noble metal catalysts that tend to oxidize sulfur dioxide to sulfur trioxide and nitrogen compounds to nitrogen oxides. As a result, they are usually applied to the exhaust stream after sulfur dioxide controls and before any flue gas nitrogen oxide treatment is applied. Carbon monoxide catalysts are rarely applied to boiler operations; to date, they have been applied only to gas turbine systems that use wet combustion controls to control nitrogen oxides.

9.1.3 Nitrogen Oxides Control

The principal nitrogen oxides generated in boiler operations are nitric oxide, which is 80% to 95% of nitrogen oxides, and nitrogen dioxide. Although nitrous oxide is generated, recent measurements on boiler systems indicate it is in the less than 20 ppm range (and probably less than 5 ppm), which indicates that boilers are not the principal source of nitrous oxide emissions to the atmosphere.

Nitrogen oxides emissions from utility boilers are controlled either by treating the flue gas chemically to convert nitrogen oxides to nitrogen or by modifying the combustion process to minimize the amount of nitrogen oxides produced. In-situ or in-boiler controls (such as low nitrogen oxides burners, gas recirculation, reburning, and air or fuel staging) can eliminate up to 50% of the uncontrolled nitrogen oxides emissions from boilers. These controls have been applied to fossil-fuel-fired boiler applications, though mostly to low sulfur fuels, since the 1970s. In general, flue gas treatment is applied in addition to in-boiler combustion controls to achieve the lower nitrogen oxides emissions required to meet local regulatory requirements. The combination of the combustion modifications and the flue gas treatment is generally designed to reduce emissions of nitrogen oxides by 80% to 90% from uncontrolled levels (EPRI 1985; Damon et al. 1987; Robie et al. 1989).

Flue Gas Treatment Processes

Of the various chemical processes available to reduce nitrogen oxides in flue gas, selective catalytic reduction (SCR), selective noncatalytic reduction, and Exxon Thermal DeNO$_x$ are the most common. Among these processes, the selective catalytic reduction process is the most widely used because it can remove more nitrogen oxides than the other two processes. Figure 9.5 illustrates the selective catalytic reduction process.

The selective catalytic reduction process is based on using ammonia to reduce nitrogen oxides to nitrogen and water. The process has been demonstrated for up to 80% nitrogen oxides reduction from large commercial systems such as those used at electric utilities. Japan has applied the technology widely on low sulfur fuels, and West Germany is now installing it on low and medium sulfur coal-fired boilers. The technology has not yet been widely used in the United States, although it has been applied on some natural gas-fired utility equipment. Some performance and cost data for the selective catalytic reduction process are shown

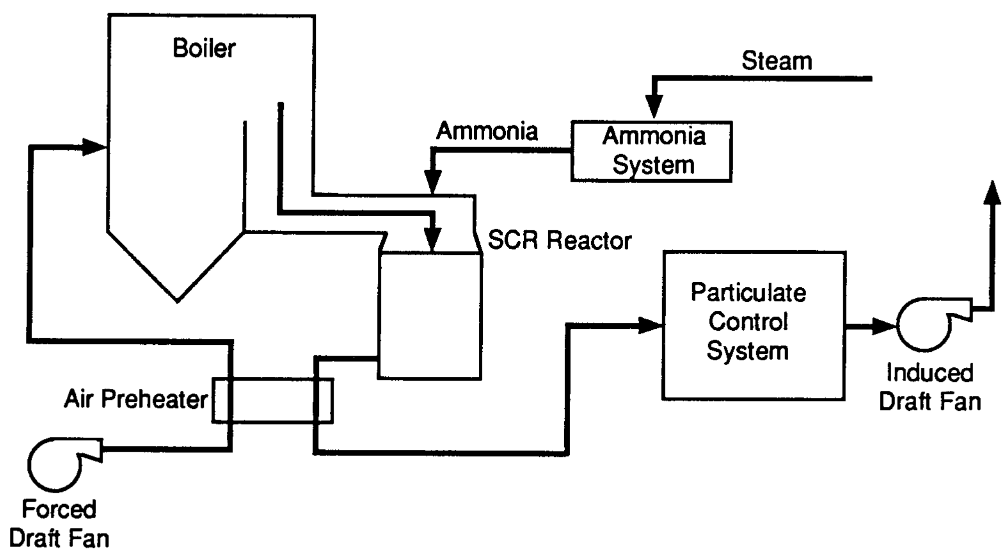

Figure 9.5. Selective Catalytic Reduction Process

in Table 9.4. (See Section 9.5 for definition of terms used in the table.)

Table 9.4. Performance and Cost Data for Selected Catalytic Reduction Nitrogen Oxides Control Technology

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	1.3
Heat Rate, Btu/kWh	400
Capacity Factor	90%
Percent Removal	80%
Operating Lifetime	20 years
Catalyst life (80% of capital cost)	5 years
Operating Characteristics Uncertainty	Low to medium
COSTS	
Capital Costs, annual $/million Btu	0.2623
O&M Costs, $/million Btu fired	0.7448
Cost of Capital	Low
MARKET POTENTIAL	
Maximum Potential Penetration	85%
Expected Date of First Entry	
Without Policy Intervention	1996
With Policy Intervention	1994
Construction Time, Years	0.6

Other post-combustion processes that have the potential to be more economical than selective catalytic reduction are also under development. Most of these processes combine sulfur oxides and nitrogen oxides removal in a single unit. These processes can be grouped into several categories:

- solid adsorption/regeneration processes - copper oxide process, NOXSO process, Mitsui/Bergbau Forschung Activated Coke process, Electric Power Development Company Activated Charcoal process, etc.

- irradiation processes - Ebara E-Beam Process, Combustion Engineering Corona Process

- wet SOxNOx processes - Saarberg-Holter Iron Chelate

- gas/solid catalytic processes - WSA-SNOx, SOxNOxROxBOx.

Many of these processes have been developed under U.S government sponsorship, and two have been selected for demonstration projects in the Innovative Clean Coal Technology (ICCT) solicitation (i.e., WSA-SNOx and SOxNOxROxBOx).

When more economical processes for post-combustion control of nitrogen oxides are commercialized, they will likely compete with selective catalytic reduction. However, the net effect on nitrogen oxides emissions is likely to be small because the new processes will also be operated to achieve the nitrogen oxides emissions limits prescribed by regulators.

Low Nitrogen Oxides Burners

The rate at which nitrogen oxides emissions are generated in the combustion zone of a boiler or furnace can be decreased by new burners being developed for coal, oil, and natural-gas-fired combustors. These burners employ methods that distribute the fuel and the combustion air such that local reducing and separate oxidizing regions are formed. The initial combustion takes place in an oxygen lean zone (a reducing zone), while the final burnout of the fuel takes place in an oxidizing zone. This process can obtain up to about 50% nitrogen oxides reduction, but not all furnace and boiler designs can accommodate the new burners. Requirements to allow the boiler to load-follow by controlling the combustion process impose further restrictions on such nitrogen oxides control technologies. However, for base load plants, it is a preferred solution because the initial capital costs are relatively small and the system is passive in that it does not require an active control system beyond that needed to control the combustion process. However, control points and settings are limiting factors of this technology because, as nitrogen oxides decrease, the unburned hydrocarbons and the generation of carbon monoxide increase. At some point these emissions become more troublesome than nitrogen oxides. Some cost and performance data for low nitrogen oxides burners are shown in Table 9.5. (See Section 9.5 for definition of terms used in the table.)

Table 9.5. Performance and Cost Data for Low Nitrogen Oxides Burner Technology

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	0
Heat Rate, Btu/kWh	0
Capacity Factor	99%
Percent Removal	50%
Operating Lifetime	15 years
Operating Characteristics Uncertainty	Low
COSTS	
Capital Costs, annual $/million Btu	0.0262
O&M Costs, $/million Btu fired	0.0017
Cost of Capital	Low
MARKET POTENTIAL	
Maximum Potential Penetration	95%
Expected Date of First Entry	
Without Policy Intervention	Currently in use
With Policy Intervention	Currently in use
Construction Time, Years	0.2

Other In-Boiler Controls

The concept of staging the fuel and air or adding reducing gases such as ammonia to the boiler can be applied within the boiler at locations other than at the burners. Examples of such controls are

- low excess combustion air
- over-fire air
- flue gas recirculation
- coburning of natural gas and the primary fuel
- reburning by adding natural gas and air into the upper regions of the boiler
- ammonia addition in the hot upper regions of the boiler where the flue gas temperature is high enough to cause nitrogen oxides reduction without the need for a catalyst.

Typically, nitrogen oxides reductions of up to 40% are possible through use of such procedures, although higher reductions are possible if greater ammonia, carbon monoxide, or unburned hydrocarbon emissions can be accepted.

A number of processes under development reduce both sulfur oxides and nitrogen oxides from boiler flue gases. Their development is based upon the belief that controlling both acid gas precursors in a single process should be less expensive than applying separate processes. When compared with the costs for removing nitrogen oxides only, all of the combined processes will be more expensive. Thus, the combined processes are not expected to be commercialized based upon a greenhouse gas policy initiative, but upon an acid rain policy initiative.

9.1.4 Methane Control

Leakage from gas pipelines and methane discharges from landfills and coal seams are significant sources of methane in the atmosphere. Several investigators have suggested that methane leakage from the natural gas distribution system might be as high as 2%. These estimates, however, have been strongly disputed by the gas industry. Nonetheless, they are an indication of both the potential magnitude of methane releases into the atmosphere and the small amount of data currently available.

The methods available to decrease the amount of methane released to the atmosphere from these sources are briefly discussed below.

Coal Mines

Coal mines are degassed both before a new coal seam is opened and continuously during mining operations. Degassing is usually accomplished by exposing the coal seam, then pumping fresh air into the mine and continuously withdrawing the air/methane mixture. The collected methane is then vented to the atmosphere.

Over the years, the DOE has sponsored the development of various methods to collect coal mine methane in situ before the coal is mined. These methods have been applied to commercial mines, and the collected gas has been added to the natural gas transmission system (Layne et al. 1988; Byrer et al. 1987; Boyer 1986). In one technology, holes are bored into the coal seam and a partial vacuum is applied. The vacuum helps draw the methane into the open holes to a header system, where it is compressed and then added to the natural gas supply system. To apply this technology, a gas transmission line or user of natural gas must be located near the coal mine; otherwise, the compression and transportation costs can make the delivered cost of methane from the coal mine noncompetitive with natural gas extracted from wells. Table 9.6 summarizes the performance and cost data for recovering methane from coal beds. (See Section 9.5 for definition of terms used in the table.)

Table 9.6. Performance and Cost Data for Recovering Methane from Coal Beds

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	Process uses recovered gas as fuel. No external fuel is required.
Heat Rate, Btu/Kwh	NA
Capacity Factor	90%
Percent Removal	50-80%
Operating Lifetime	20 years
Operating Characteristics Uncertainty	Low
COSTS	
Capital Costs, Annual $/million Btu	0.9644
O&M Costs, $/million Btu fired	0.6960 (Royalty payments are approximately 50% of the annual O&M costs.)
Cost of Capital	Low
MARKET POTENTIAL	
Maximum Potential Penetration	80%
Expected Date of First Entry	
Without Policy Intervention	Currently in use.
With Policy Intervention	Required for uneconomical applications.
Construction Time, Years	0.2-0.5 years

Gas Pipelines

The extent of methane leaks from natural gas transmission and distribution systems is not clear. A potential exists for methane leakage at the gas compression stations within the transmission infrastructure and at ruptures or cracks in the distribution piping system. In addition, there are construction projects that have accidentally ruptured distribution lines and pipe joints, valves that have experienced leaks, and other accidents that cause methane leakage. However, the natural gas transmission industry claims that much of the difference between the measured amount of natural gas in the pipelines and the measured amount of natural gas sold to customers represents metering errors, not leakage problems. At present, the controls for methane leakage are to repair/replace the leaking component or fixture or vent the leak to the atmosphere if the source of the leak cannot be found. Venting is done to ensure that explosive quantities of natural gas do not collect and subsequently explode, as concentrations of 5% to 15% by volume in air are explosive.

Encased pipelines, in which the natural gas pipeline is enclosed within a second pipeline to collect the leaking methane, are a technical option to reduce methane releases in the future. The cost of an encased pipeline will be significantly higher. During this study, no published reports analyzing this option could be found.

Landfill Gas

Current EPA regulations require methane concentrations to be less than 1.25% by volume in an enclosed structure and less than 5% (10% for landfill gas) at the property boundaries of a landfill. Landfill gas is approximately half methane; the rest is carbon dioxide, water, air, and other impurities.

Landfill gas controls have been classified as passive or active. In passive controls, the landfill volume is penetrated with pipes or structures open to the atmosphere, and the collected gas is allowed to vent freely to the atmosphere. In addition, vertical barrier trenches are placed around the landfill and backfilled with gravel. These trenches intercept any laterally migrating landfill gas and provide a path to vent freely to the atmosphere, thus ensuring that the EPA concentration requirements are met at the property boundaries. The active control system consists of perforated pipes installed in a series of vertical and horizontal holes in the landfill. The piping is connected to a header, and a partial vacuum is applied to enhance the collection of the gas, which is then either flared or further processed for use as an energy source. The energy application is normally as pipeline gas (after suitable cleaning and pressurizing) or to drive an engine to produce heat or mechanical work. The fuel gas in this case has a heating value of 450 to 550 Btu/scf. Only in special circumstances are electric generation plants economically fueled by landfill gas (ANL 1988; Borgardus 1987).

In the last 10 years, about 40 landfill gas collection and use plants have been installed in the United States. In general, the application of the vacuum technology to landfills is highly dependent upon local economics. The technology is well understood. The age, quantity, and depth of waste generally determine the quantity of gas available. Table 9.7 summarizes the performance and cost data for methane gas recovery from landfills. (See Section 9.5 for definition of terms used in the table.)

Table 9.7. Performance and Cost Data for Gas Recovery Methane from Landfill

ENERGY CHARACTERISTICS	High Btu Gas	Electricity
Fuel Use Requirements, million Btu/ton	Process uses recovered gas as fuel. No external fuel is required.	
Heat Rate, Btu/Kwh	NA	NA
Capacity Factor	90%	90%
Percent Removal	85%	85%
Operating Lifetime	20 years	20 years
Operating Characteristics Uncertainty	Low	Low
COSTS		
Capital Costs, annual $/million Btu	0.85	1.0
O&M Costs, $/million Btu fired	0.09	0.1
Cost of Capital	Low	Low
MARKET POTENTIAL		
Maximum Potential Penetration	6%	6%
Expected Date of First Entry		
Without Policy Intervention	Currently in use	Currently in use
With Policy Intervention	Required for uneconomical applications	
Construction Time, Years	0.2-0.5	0.2-0.5

9.2 CARBON DIOXIDE TRANSPORT AND DISPOSAL TECHNOLOGIES

As mentioned previously, the two principal carbon dioxide disposal options are as a liquid and as a gas. Of these two options, liquid carbon dioxide is more expensive because of high compression and liquefaction costs. On the positive side, liquid carbon dioxide does not require large storage space; in other words, large amounts of carbon dioxide recovered in liquefied form from boiler flue gas can be stored in small volumes. This is in contrast to the large storage volumes required to store gaseous carbon dioxide. In addition, gaseous disposal may result in a significant portion of the recovered carbon dioxide being lost to the atmosphere.

At least four methods exist for carbon dioxide disposal: storage in depleted gas wells, ocean disposal, use in enhanced oil recovery (EOR), and storage in excavated salt domes. Site availability will obviously be a key issue for each of these options, since the distance of a power plant from a disposal site would have a significant impact on the cost of transporting the carbon dioxide. There are an estimated 12,000 abandoned oil and gas reservoirs in the United States (Horn and Steinberg 1982) that could provide several decades of carbon dioxide storage at current emission rates from the U.S. utility system. EOR has a potential market for 1 to 3 trillion cubic feet/year of carbon dioxide

(NPC 1984). On an annual basis, this could accommodate approximately 5% to 10% of the current U.S. utility capacity. Ocean disposal is essentially unlimited in capacity (the capacity would exceed fossil fuel reserves). Storage capacity in salt domes apparently is sufficient for several centuries of output from the U.S. utility system (Horn and Steinberg 1982).

9.2.1 Transport

A fundamental constituent of any scheme to dispose of captured carbon dioxide emissions is transport of the resulting substance from the location of capture to the site of disposal. Transport can be a major barrier as the necessary transport distances increase. This section includes brief descriptions of seven different carbon dioxide transport technologies.

The carbon dioxide collection and disposal system involves an extensive network of pipelines. Construction of this large system is likely to generate public opposition similar to that encountered by any large-scale project in the current political climate. Individuals in the vicinity of the proposed pipelines are likely to form groups to oppose the pipeline. In addition, carbon dioxide is not generated uniformly. A relatively small number of coal-burning states may account for a disproportionate share of the emissions. Thus, the entire program could be politically sensitive. Table 9.8 summarizes the cost and performance data for liquefied carbon dioxide disposal technology. (See Section 9.5 for definition of terms used in the table.)

Table 9.8. Performance and Cost Data for Liquefied Carbon Dioxide Disposal Technology

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	1.8
Heat Rate, Btu/Kwh	1420
Capacity Factor	90%
Percent Removal	90%
Operating Lifetime	20 years
Operating Characteristics Uncertainty	Medium
COSTS	
Capital Costs, annual $/million Btu	0.71
O&M Costs, $/million Btu fired	0.10
Cost of Capital	Medium
MARKET POTENTIAL	
Maximum Potential Penetration	95%
Expected Date of First Entry	
Without Policy Intervention	None
With Policy Intervention	2000
Construction Time, Years	2-3

Pipeline Transport of Carbon Dioxide Dissolved in Sea Water

Gaseous carbon dioxide is dissolved in sea water at the power plant and transported via pipeline to the deep ocean for disposal. Albanese and Steinberg (1980) evaluated the collection and disposal of carbon dioxide in sea water for a 200-MWe plant located at the coast, with 10-mile transport of the carbon-dioxide-rich sea water to the deep ocean. This study concluded that the sea water pumping energy alone would exceed the energy produced by the plant, even at a carbon dioxide removal efficiency of only 60%.

Pipeline Transport of Liquid Carbon Dioxide

Near-atmospheric pressure carbon dioxide is compressed in a series of inter-cooled compressors to a supercritical pressure (above 1200 psi). An aftercooler would typically be used to reduce the temperature of the carbon dioxide leaving the last compressor to near ambient conditions. The liquid carbon dioxide is transported via a high-pressure steel pipeline.

Pipeline transport of liquid carbon dioxide is the most commonly proposed transport mechanism for centrally collected carbon dioxide. The concept is not only technically feasible, but currently employed on a large scale in the Western United States where carbon dioxide is transported several hundred miles from naturally occurring sources to EOR operations.

Pipeline Transport of Gaseous Stack Gas

Power plant stack gas at near-atmospheric pressure is compressed in a series of inter-cooled compressors and transported via a high-pressure steel pipeline. The potential advantage of this concept is that carbon dioxide removal and disposal could be accomplished simultaneously after transporting the stack gas to a deep ocean location. The primary disadvantage of this concept is the voluminous quantity of stack gas that would have to be transported compared with a concentrated carbon dioxide stream coming from the same power plant.

Pipeline Transport of Gaseous Carbon Dioxide

Near-atmospheric pressure carbon dioxide is compressed in a series of inter-cooled compressors to a temperature and pressure well within the gaseous phase of carbon dioxide. The pressure would generally be less than supercritical, and the temperature must be high enough to avoid the two-phase region. Transport is via a high-pressure steel pipeline.

The component technology for pipeline transport of gaseous carbon dioxide is available and mature. Although no gaseous carbon dioxide pipelines of 100 or more miles in length are known to exist, liquid carbon dioxide pipelines are currently employed on a large scale in the Western United States, where carbon dioxide is transported several hundred miles from naturally occurring source points to EOR operations. Extensive worldwide natural gas pipelines provide a wealth of experience with similar technology.

Mobile Container Transport of Solid Carbon Dioxide Hydrate

Near-atmospheric pressure carbon dioxide is compressed and cooled in the presence of water to form a solid hydrate ($CO_2 \cdot 6H_2O$) with a clathrate structure and a specific gravity of 1.12. Like "dry ice," the carbon dioxide hydrate can be transported in a refrigerated mobile container by truck, rail, barge, or ocean freighter.

The energy requirements for creating carbon dioxide hydrate are about 1/3 higher than for solidifying carbon dioxide (Baes et al. 1980a). Transportation costs per unit of carbon dioxide are expected to be greater than three times that for dry ice because the hydrate is 71% (by mass) water and the hydrate density is lower than solid carbon dioxide.

Mobile Container Transport of Solid Carbon Dioxide

Near-atmospheric pressure carbon dioxide is compressed and cooled to a liquid state, solidified to "dry ice" via expansion through a nozzle and compressed into blocks for transport. As a solid, carbon dioxide can be transported in a refrigerated mobile container by truck, rail, barge, or ocean freighter.

Not only is the component technology largely mature for this concept, the basic transportation infrastructure already exists. Although pipeline transport is likely the least expensive long-run overland transport option, dry ice transport via truck, rail, or barge could be immediately implemented. In the long term, ocean barge transport of solid carbon dioxide might even be superior to undersea pipelines.

Mobile Container Transport of Liquid Carbon Dioxide

Near-atmospheric pressure carbon dioxide is compressed and condensed to a liquid at a state similar to that for liquid transport in a pipeline. As a liquid, carbon dioxide can be transported in a pressurized mobile container by truck, rail, barge, or ocean freighter. Transporting carbon dioxide in its liquid phase eliminates the extra energy that must be expended to solidify carbon dioxide, but would require higher-pressure containers, which could be prohibitively expensive. If the high-pressure containers were not too expensive, this concept could be quite attractive. Conceivably, gaseous carbon dioxide could be transported via a mobile container as well. However, the advantages of having lower-pressure containment would more than likely be overwhelmed by the disadvantages of having a much lower density.

9.2.2 Disposal

This section includes brief technical descriptions of twelve different carbon dioxide disposal technologies. The environmental impacts of the different carbon dioxide disposal schemes have not been resolved. The effect of large-scale ocean disposal of liquid carbon dioxide on marine life, for example, has not been suitably addressed and would likely be the focus of much public concern. This issue will require significant scientific research before any form of ocean disposal could be undertaken. The descriptions included here primarily focus on the methodology for implementing the schemes.

Ocean Disposal of Solid Carbon Dioxide by Surface Injection

Solid carbon dioxide (dry ice) is dropped directly into the ocean. Solid carbon dioxide or dry ice has a specific gravity of about 1.5 and sinks quickly when dropped into ocean waters. As a cube of dry ice sinks to the ocean floor, it gradually warms while the pressure increases. Initially, some carbon dioxide is released to the surface as part of the cube sublimates. At a depth of about 500 meters, the pressure is great enough to cause sublimation to cease. The remainder of the cube will continue to melt and sink to the bottom. This concept must be linked with the production and refrigerated transportation of solid carbon dioxide. In addition, the dissolution and dispersion of the injected carbon dioxide and its subsequent interaction with the upper ocean layer is not currently well understood and is an area for future study.

Ocean Disposal of Solid Carbon Dioxide Hydrate by Surface Injection

Solid carbon dioxide hydrate ($CO_2 \cdot 6H_2O$) is dropped directly into the ocean. Solid carbon dioxide hydrate has a specific gravity of about 1.1 and sinks when dropped into ocean waters, although not as quickly as solid carbon dioxide. As a cube of carbon dioxide hydrate sinks to the ocean floor, it gradually warms while the pressure increases. Initially, some carbon dioxide is released to the surface as part of the cube sublimates. At a depth of about 500 meters, the pressure is great enough to cause sublimation to cease. Because the hydrate's lower density causes it to descend at a slower rate, the percent of carbon dioxide lost during descent is probably greater than for dry ice. The remainder of the cube will continue to melt and sink to the bottom. This concept must be linked with the production and refrigerated transportation of solid carbon dioxide hydrate.

Antarctica Disposal of Solid Carbon Dioxide or Carbon Dioxide Hydrate

Solid carbon dioxide (dry ice) or carbon dioxide hydrate would be shipped by ocean freighter to permanent repositories in Antarctica. The mean annual temperature at the South Pole is about -50°C. Some regions within Antarctica experience temperatures of -20°C or below year round. The cold Antarctic weather offers an environment that would be conducive to the long-term storage of solid carbon dioxide or carbon dioxide hydrate. Of course, even at these temperatures, solid carbon dioxide or carbon dioxide hydrate would decompose if left exposed. A well-insulated repository with minimal refrigeration capacity could eliminate essentially all sublimation losses.

Space Disposal of Gaseous, Liquid, or Solid Carbon Dioxide

Carbon dioxide in gaseous, liquid, or solid form would be launched from the Earth for disposal in space. Although several sources cite this proposed disposal process, the concept is almost certainly impractical because of the energy consumed and cost associated with launching vehicles into space, as well as the quantity of carbon dioxide requiring disposal and the availability of launch vehicles.

Ocean Disposal by Sinking Current Injection of Carbon Dioxide

Liquid or gaseous carbon dioxide is injected directly into a near-surface sinking current that transports the carbon dioxide into the deep ocean. Several locations in the world have naturally sinking currents that originate relatively close to shore and at relatively shallow depth. Injecting carbon dioxide into these currents could greatly simplify the equipment needed for deep ocean disposal. One example of this is the thermohaline current that exits to the Atlantic from the Mediterranean Sea. Surface evaporation of Mediterranean waters exceeds the inflow of water from rivers, causing the Sea to be saltier than the ocean. This creates two different currents crossing the entrance to the Mediterranean at the Straits of Gibraltar. Near the floor of the Sea, the denser salt water flows out to the Atlantic and sinks below the lighter ocean water. At the surface, a larger current flows into the Mediterranean, making up for the net water lost via evaporation and the subsurface outflow.

Calculations by Marchetti (1976, 1979) indicate that the Mediterranean undercurrent entering the Atlantic has sufficient capacity to dispose of all the carbon dioxide produced in Europe. According to Marchetti, disposal could be accomplished at carbon dioxide concentrations (less than 1%) thought tolerable to shell-forming mollusks and other sea life precipitating $CaCO_3$.

Underground Disposal of Biomass

Biomass is stored in an underground repository that prevents or minimizes its decay or conversion to carbon dioxide. Biomass could be explicitly cultivated to collect carbon dioxide, then harvested and stored to permanently remove the carbon dioxide from the atmosphere. This concept has not yet received any detailed evaluation. Transportation would be expensive and energy-intensive if the biomass were not buried near the plantation.

Ocean Disposal by Deep-Water Injection/ Sinking of Carbon Dioxide

Carbon dioxide is injected into the ocean as a dense liquid that sinks to the bottom. An alternative to dissolution is to inject carbon dioxide at a density that would allow it to sink and settle into a pool on the ocean floor. Liquid carbon dioxide at 0-10°C and 150-300 atm has a density greater than sea water. For example, liquid carbon dioxide at 3°C and 300 atm has a specific gravity of 1.05 compared with 1.04 for sea water at the same temperature and pressure. Presumably, this disposal approach might result in an even longer retention period than direct dissolution in the deep ocean. However, an injection depth of approximately 3000 meters would be needed, which would typically be much further from the shore than the 500-meter depth required for dissolution to be effective. While the 3000-meter requirement would significantly increase the pipeline transport costs, Steinberg et al. (1984) estimated that only a 2% increase in compressor energy would be required, because most of the compressor energy is associated with liquefaction rather than overcoming piping frictional losses. Other aspects of this concept are similar to carbon dioxide dissolution.

Ocean Disposal by Deep-Water Injection of Carbon-Dioxide-Rich Sea Water

Carbon dioxide is dissolved in a stream of sea water which is then transported to the deep ocean for injection. This concept provides an alternative to pumping carbon dioxide to the final ocean disposal point. A pipeline of carbon-dioxide-rich sea water would presumably operate at a much lower pressure than a carbon dioxide pipeline; however, the volume of fluid involved would be much greater. Albanese and Steinberg (1980) evaluated the collection and disposal of carbon dioxide in sea water for a 200-MWe plant located at the coast, with 10-mile transport of the carbon-dioxide-rich sea water to the deep ocean. This study concluded that the sea water pumping energy alone would exceed the energy produced by the plant, even at a carbon dioxide removal efficiency of only 60%.

Another application of this concept would be to site a fossil-fired power plant out on an ocean platform or barge. Cool ocean water could be used as the condenser coolant as well as carbon dioxide solvent. This would add considerably to the cost of building the power plant, of course, but would eliminate most of the cost associated with carbon dioxide transport.

Ocean Disposal by Deep-Water Carbon Dioxide Injection/Dissolution

Liquid or gaseous carbon dioxide is injected directly into the ocean at a depth of approximately 500 meters and dissolved into the surrounding water. This is perhaps the most commonly proposed approach to ocean disposal; yet, detailed design, cost, performance, or environmental analyses are not publicly available. Carbon dioxide is injected directly into the deep ocean via a pipeline extending from the nearest shore or a platform on the ocean's surface. The required injection depth is subject to some debate. Essentially all sources agree the upper layer of the ocean in relatively intimate contact with the atmosphere is about 75 to 100 meters deep. Below this depth, or below the thermocline, is commonly referred to as the "deep" ocean. Most references presume an injection depth of 500 meters to ensure the injected carbon dioxide dissolves and remains in the deep ocean below the thermocline. At least one study had indicated that an injection depth of 300 meters would be adequate (Baes et al. 1980b). Baes et al. also provide a good thermal and hydraulic analysis of the dissolution and dispersion of carbon dioxide in sea water. In general, dissolving carbon dioxide is more advantageous than sinking it in the ocean because dissolution can take place in shallower waters that are closer to the shore.

Compared with the costs of collection and transportation, ocean disposal costs are predicted to be negligible (Marchetti 1979). Most, if not all, literature sources agree that the deep waters of the ocean have adequate capacity to absorb all of the carbon dioxide emissions currently being produced and projected to be produced in the coming decades. Retention time is expected to be centuries long. Potential environmental impacts are unknown, but a concern. One variation of this concept is to inject stack gas directly rather than carbon dioxide, thus combining stack gas scrubbing and carbon dioxide disposal.

The fundamental technology required for injecting liquid or gaseous carbon dioxide into the deep ocean exists. Nevertheless, the associated transmission pipeline is a development issue because no lengthy (e.g., 100 miles or so) undersea transmission lines are currently in use.[a] In addition, the dissolution and dispersion of the injected carbon dioxide and its subsequent interaction with the upper ocean layer is not well understood, and this will require significant scientific research.

Underground Disposal of Carbon Dioxide Adsorbed on Solid Material

Gaseous carbon dioxide would be adsorbed on a solid material and transported to an underground burial site for disposal. Fixation on natural clays is probably impractical, even if enough clay exists, because of the volume of clay that would have to be handled. A general problem with this concept is the availability of adequate quantities of low cost adsorbing solid materials. The available capacity in abandoned mine shafts or wells is also unknown, as is the long-term rate of carbon dioxide release from this form of storage. No specific figures on the amount of solid required, energy consumption, or costs were provided in the information sources noted below. A variation of this concept is to dissolve carbon dioxide in potassium hydroxide or sodium hydroxide, evaporate the water, and bury the residual carbonate.

(a) Mueller, E. A., and INTECH, Inc. May 1989. *A Summary of Selected Greenhouse Gas Control Technologies* (draft). Prepared for the U.S. Department of Energy, Washington, D.C.

Carbon Dioxide Disposal in Excavated Salt Domes

Disposal of carbon dioxide in excavated salt domes is technically feasible and could be pursued either as a long-term disposal option or as a storage option where the carbon dioxide is retrieved for later use. Salt domes have been used for a number of years to store natural gas and recently have been used for liquid storage in the strategic petroleum reserve. Salt domes are solution-mined by injecting water (either fresh or sea) and extracting the brine. The salt is plastic and self-sealing; thus any cracks that form in the dome should fuse together without outside aid. Ideally the carbon dioxide would be stored at high pressures as a liquid.

Currently, there is no "market" for carbon dioxide disposal in salt domes. However, in the future, carbon dioxide could be needed in a hydrogen economy based on nuclear or solar energy. These energy sources would be used to hydrogenate carbon dioxide to form hydrocarbon fuels such as methane or gasoline. The required carbon could come from carbon dioxide stored in salt domes.

Salt domes are plentiful in the Gulf Coast region of the United States and exist in other areas as well, although many parts of the country (for instance, the West Coast) have few salt deposits. One drawback of this method is the large quantities of water needed to excavate the dome. In many regions of the country (such as the dry Southwest) water availability and disposal of brine may eliminate solution-mining as a viable alternative. Therefore, geography is definitely a factor in the overall feasibility of this method.

The overall salt dome volume available for carbon dioxide disposal is on the order of $1.6x10^{15}$ cubic feet (Horn and Steinberg 1982). However, this does not take into account the geographical constraint with respect to the necessary water required for excavation. Gulf Coast salt dome capacity is approximately $1x10^{14}$ cubic feet, which is estimated to be sufficient capacity to store all the carbon dioxide emissions from total U.S. coal reserves (Horn and Steinberg 1982). Even if only a fraction of the capacity of Gulf Coast salt domes is technically feasible, they appear capable of storing centuries of carbon dioxide output from U.S. industrial and utility sources at current rates.

As far as capacity is concerned, this disposal option is very attractive. The drawbacks are the costs for salt dome excavation and the geographic constraints. An interesting aspect of this disposal option is the prospect of easily retrieving the carbon dioxide in the future if carbon recycling becomes viable.

Carbon Dioxide Disposal in Depleted Gas/Oil Reservoirs

Natural gas and crude oils are found in porous sedimentary rock materials, generally sandstones or limestones. Suitable reservoir rocks are also permeable, that is, pores interconnect so that fluids can migrate through the rock. As the gas or oil is removed, the reservoir rock becomes somewhat analogous to an emptied sponge (except that a pressure generally remains within the reservoir).

Empty reservoirs offer a significant potential capacity for disposal of carbon dioxide that has been captured in either liquid or gaseous forms. Carbon dioxide has a higher density than natural gas, so that a depleted natural gas reservoir could actually store more carbon dioxide than the natural gas it originally contained. The storage capacity of any particular reservoir depends on the permeability of the constituent rock.

Carbon dioxide injection technology exists already and is commercially used to an extent in enhanced oil recovery (EOR--discussed below). Further study of this option is required in the areas of transportation costs, safety issues, and in comparison with other options. Early analyses of these areas indicate that this option may compare favorably to alternatives like ocean disposal.

Disposal in Geological Formations

Natural underground formations or voids provide potential disposal opportunities that are similar to depleted oil and gas wells. It has been estimated that there are widespread areas of underground formations with permeabilities to accept CO_2 at pressures of 2000 psig (Horn and Steinberg 1981), which is the pressure of current EOR technology. While some technical questions and concerns (e.g., effects on water tables) remain to be investigated, this option appears to be attractive from an economic standpoint.

Carbon Dioxide Disposal by Enhanced Oil Recovery Injection

Enhanced oil recovery is a general category of techniques used to improve the amount of crude oil that can be economically extracted from a reservoir. EOR can be accomplished by several techniques including chemical methods such as polymer flooding, thermal methods such as steam flooding, and miscible flooding using miscible solvents. The technique that is attractive for carbon dioxide disposal is flooding via carbon dioxide injection.

The technology for miscible flooding for EOR has been around since the 1950s. As of December 1983 (NPC 1984), at least 11 large commercial carbon dioxide EOR projects were in operation. In carbon dioxide flooding, the carbon dioxide is injected to increase the reservoir pressure. This has generally been done in a miscible mode, wherein the carbon dioxide partially dissolves in the oil. In this case, the crude ore contains significant carbon dioxide, and a carbon dioxide recovery unit is used to remove the carbon dioxide and reinject it in the reservoir.

By the year 2000, over 500,000 barrels of crude oil per day may be produced by carbon dioxide injection (Taber 1985, NPC 1984). Field experience indicates that 6,000 to 10,000 cubic feet of carbon dioxide per barrel of oil produced is required (DOE 1981). If the average is taken, then 8 Mscfd of carbon dioxide is needed to produce one barrel of oil and 4000 MMscfd is required for the overall yield. However, roughly 50% of the carbon dioxide used in EOR is recycled at the well (Steinberg 1983b, NPC 1984). Thus the demand would be for only approximately 2000 MMscfd carbon dioxide. This represents 3.5% of today's actual carbon dioxide emissions from fossil fuel power plants (NPC 1984). It is unlikely that all EOR projects could be switched to carbon dioxide flooding; however, if this were possible, the required carbon dioxide would be 1 million to 3 million MMscf/year (Kane and South 1989), which is 4.8% to 14.4% of current fossil fuel plant carbon dioxide emissions.

This disposal option is very promising but is limited in the total capacity available. The demand for carbon dioxide use in EOR may increase in the future, but this appears to be most dependent on oil prices and, to a lesser extent, on carbon dioxide prices. However, even under the most promising scenario, the demand for carbon dioxide is not likely to be a major percentage of the carbon dioxide emissions from fossil-fueled power plants. The fact that only half of the carbon dioxide stays "downwell" limits the effectiveness of using EOR for storage. Overall effectiveness of EOR as a sink for carbon dioxide is by itself not sufficient to meet U.S. disposal needs.

9.2.3 Other Disposal Methods

Besides liquid and gaseous disposal, other potential carbon dioxide disposal methods have been identified in the literature. Two of the more commonly identified schemes are briefly described below.

High Energy Radiation Decomposition

Carbon dioxide could be irradiated with high energy gamma, electron, and particle radiation to decompose it to carbon monoxide and oxygen via the following reaction

$$2\,CO_2 \rightarrow 2\,CO + O_2$$

The carbon monoxide could then be used to make methanol, or it could be irradiated further to decompose it to carbon suboxide via the following reaction

$$6\,CO \rightarrow 2\,C_3O_2 + O_2$$

The carbon suboxide is a reddish polymer, which could be disposed of as a solid or used to produce a useful product.

Development of this process would require extensive federal support because there is little economic incentive to motivate private industry to develop the process.

Photochemical Decomposition

The chemical reactions described above can also be promoted by ultraviolet radiation. Photochemical decomposition of carbon dioxide to carbon monoxide has been studied in the region of 1,295 to 1,470 angstroms, and formation of the carbon suboxide has been studied at 1,800 angstroms. However, extensive research and development (R&D) will be required to develop a useful process.

Greenhouse Vegetation

A potential use for the carbon dioxide recovered from boiler flue gas is in greenhouses. A greenhouse is a structure made primarily of glass and light-admitting plastic designed for the cultivation of vegetation. Plants, vegetables, fruits, and flowers can be grown in greenhouses. Groundcover, shrubs, evergreens, and trees can also be propagated in greenhouses. The major advantage of greenhouses is that they make it possible to grow vegetation throughout the year. In other words, the maintenance of an environment that is favorable to vegetation throughout the year even when conditions on the outside are very hostile is critical to the performance of greenhouses.

Among the major control variables for a typical greenhouse are heating and cooling, temperature, ventilation, humidity, water consumption, carbon dioxide, misting, and light. Modern automatic devices (especially thermostatically controlled heating plants and ventilators, mist systems, watering systems, and methods of controlling shading and supplying additional light) have relieved greenhouse operations of the necessity of hour-by-hour attention and made it entirely feasible to operate a greenhouse unattended throughout the day, over a weekend, or even for longer periods.

Heating is necessary to provide warmth during the cold season without drying out the greenhouse or depriving the vegetation of necessary moisture. The heat must be evenly distributed throughout the structure. A greenhouse also needs to be shaded and cooled in the summer. All forms of vegetation in active growth need moisture in the air around them, but this is especially true of tropical plants, seedlings, and cuttings. Moisture absorbed by their roots and distributed throughout the tissues is exhaled (transpired) through the pores in the leaves. The rate of this moisture transpiration depends upon the relative humidity of the surrounding air. When the air is too dry, the transpiration rate surpasses the roots' ability to replace tissue moisture. If the dryness goes on for some time, the leaves dry up and growth is stunted. To achieve a correct balance between the amount of moisture taken up by the roots and the amount transpired by the leaves, a humidity level of at least 65% is usually recommended.

In some specialized applications, it is advantageous to add to the natural supply of carbon dioxide, especially when the vents are closed and the heater is on. The more carbon dioxide, the faster some plants will grow. However, carbon dioxide should only be added to the greenhouse atmosphere during daylight hours because it aids in the photosynthesis necessary for plant growth. The level of carbon dioxide that is best for plants but does not endanger humans is 2,000 ppm. Greenhouse output has been shown to increase by 20% with increased carbon dioxide in the atmosphere. A typical greenhouse will require approximately 3 to

5 million Btu/hour/acre during the heating season. Electricity consumption is about 276,000 kW/year/acre. Six acres of land is sufficient for a 5-acre greenhouse.

Currently, less than 5% of the U.S. production of salad-type vegetables come from greenhouses. In contrast, almost all of Europe's salad-type vegetation is produced in greenhouses. Any expansion of U.S. greenhouse capacity is limited by supply (i.e., lack of growers). In other words, commercial organizations are simply not interested in greenhouses. However, their enthusiasm could be increased by better education and improved financing mechanisms.

9.3 CARBON SEQUESTRATION

Carbon sequestration stands apart from other strategies for avoiding or mitigating possible greenhouse effects because sequestration options rely on removal of carbon from the atmosphere after it has been emitted. This strategy is in contrast to the pre- or post-combustion technologies described earlier that attempt to restrict the amount of carbon *emitted* from combustion and other processes. The two primary sequestration options currently receiving attention are the use of trees and vegetation or aquatic organisms to absorb and store carbon from the atmosphere. Although these options are finite in their capacity for carbon storage and many uncertainties remain concerning their overall effectiveness, even conservative estimates of their potential indicate that further investigation is warranted.

9.3.1 Reforestation and Afforestation

Large tracts of land in the United States and elsewhere were originally covered in forest before they were cleared and developed for agricultural or urban uses. While some amount of crop and pasture land is necessary to sustain a society's food requirements, advances in agricultural yields continue to reduce the amount of land needed per citizen. Much of the land previously cleared, particularly that which is only marginal for agricultural purposes, could be returned to forest and be effectively used for carbon sequestration. Returning land to its original state of forest cover is termed reforestation.

Afforestation differs from reforestation in that it involves the introduction of forest to lands that previously contained grasslands, deserts, or other nonforest environments. Afforestation implies the existence of additional natural barriers that must be overcome (e.g., through irrigation) because the land did not originally support forest growth.

Technology in either of these approaches involves breeding and selecting suitable tree species that will grow in the given environment while sequestering the maximum amount of carbon. In addition, changes to the growing environment to overcome natural barriers involve technology to a large extent, e.g., irrigation and drainage systems, possible land treatment and cultivation, disease and pest eradication, etc. Once designed, the forest system that requires a minimum of additional human input is most favorable.

Designating land for forestation raises land-use issues in that such land is at least temporarily unavailable for food or biomass production, urbanization, or other uses. Various cost/benefit issues need to be addressed in evaluating the most suitable use of individual lands before the decision to designate them for forestation is made. The potential sequestration impacts of designating lands for forestation programs are the subject of significant discussion in Volume II of this study.

9.3.2 Ocean Sequestration

Phytoplankton are free-floating marine organisms containing chlorophyll. Through photosynthesis, phytoplankton convert carbon dioxide and water into organic compounds. Recent studies by the National Research Council suggest that currently the most limiting factor for the potential uptake of carbon by phytoplankton is the level of iron available in seawater (Martin et al. 1990). A large-scale program of fertilizing areas of the Antarctic

Ocean with a timed-release infusion of iron could possibly stimulate growth of phytoplankton to the extent that carbon emissions from human activities were entirely offset (Moun 1990). The feasibility of this approach is being studied further.

9.4 CONCLUSIONS

Several commercial processes currently exist to remove carbon dioxide and nitrogen oxides from flue gas. However, at present, there is no regulatory or economic incentive for utilities or private industry to remove carbon dioxide, and large-scale carbon dioxide removal and disposal processes are likely to be very expensive. Thus, policy intervention will be required to promote adoption of carbon dioxide removal technologies.

In general, low nitrogen oxides burners, boiler in situ technologies (such as staged fuel and air injection, flue gas recirculation, and burner orientation), and flue gas treatments (such as the selective catalytic reduction process and the addition of reducing gases at high temperatures) have been commercially applied to boiler facilities. They have been implemented because policy intervention to control acid rain has mandated their use for both new and retrofit applications. Currently, the low nitrogen oxides burners are the commercially favored treatment technologies; however, the continued application of other control methods is dependent upon continued policy intervention. If government policy does not require nitrogen oxides controls, they will not be implemented, as these controls reduce the efficiency of boilers.

Several commercial processes are currently being used to recover methane from landfills and coal seams. These processes are being installed when the value of the energy recovered provides sufficient economic justification. Policy intervention will be required if greater application of this technology is desired. Price supports might be the most effective method of promoting additional methane recovery.

Table 9.9 summarizes the cost and performance characteristics of selected greenhouse gas control technologies.

Table 9.9. Performance and Cost Data for Greenhouse Gas Control Technologies

	Carbon Dioxide[a]	
	Monoethanol amine and Liquid Disposal	Potassium Carbonate and Liquid Disposal
ENERGY CHARACTERISTICS		
Fuel Use Requirements, million Btu/ton of collected gas[b]	7.4	8.4
Energy Efficiency, %	NA	NA
Heat Rate, Btu/kWh	5720	6520
Capacity Factor, %	90	90
Percent Removal	90	90
Operating Lifetime, Years	20	20
Operating Characteristics Uncertainty	Low-Medium	Low-Medium
DIRECT EMISSION COEFFICIENTS	NA[c]	NA
COSTS		
Capital Costs, $/million Btu fired	1.42	1.46
O&M Costs, $/million Btu fired	2.2	1.9
Cost of Capital	Low-Medium	Low-Medium
MARKET POTENTIAL		
Maximum Potential Penetration, %	95[d]	95[d]
Expected Date of First Entry		
Without Policy Intervention	None	None
With Policy Intervention	2000	2000
Construction Time, Year	2-3	2-3
COMMENTS	Sulfur Intolerant	Sulfur Tolerant

	Nitrogen Oxides (NO_x)		
	Selective Catalytic Reduction	Low NO_x Burners	Boiler In situ
ENERGY CHARACTERISTICS			
Fuel Use Requirements, million Btu/ton of collected gas	1.3	0	0
Energy Efficiency	NA	NA	NA
Heat Rate, Btu/kWh	400	0	0
Capacity Factor, %	90	90	95
Percent Removal	80	50	40
Operating Lifetime, Years	5[e]	15	40
Operating Characteristics Uncertainty	Low-Medium	Low	Low
DIRECT EMISSION COEFFICIENTS	NA	NA	NA
COSTS			
Capital Costs, $/million Btu fired	0.2623	0.0262	0.0210
O&M Costs, $/million Btu fired	0.7448	0.0017	0.0005
Cost of Capital	Low	Low	Low-Medium
MARKET POTENTIAL			
Maximum Potential Penetration, %	85	95	50-100[f]
Expected Date of First Entry			
Without Policy Intervention	1996	Currently in Use	Currently in Use
With Policy Intervention	1994	Currently in Use	1992[g]
Construction Time, Year	0.6	0.2	0.2-0.5

Table 9.9. (contd)

	Nitrogen Oxides (NO_x)		
	Selective Catalytic Reduction	Low NO_x Burners	Boiler In situ
ENERGY CHARACTERISTICS			
Fuel Use Requirements	0[h]	0[h]	0[h]
Energy Efficiency, %	NA	NA	NA
Heat Rate, Btu/Kwh	NA	3400	NA
Capacity Factor, %	90	90	90
Percent Removal	85	85	50-80
Operating Lifetime, Years	20	20	20
Operating Characteristics Uncertainty	Low	Low	Low
DIRECT EMISSION COEFFICIENTS	NA	NA	NA
COSTS			
Capital Costs, $/million Btu fired	0.85	1.0	0.9664
O&M Costs, $/million Btu fired	0.09	0.1	0.6960[i]
Cost of Capital	Low	Low	Low
MARKET POTENTIAL			
Maximum Potential Penetration, %	6[j]	6[j]	80
Expected Date of First Entry			
Without Policy Intervention	Currently in Use	Currently in Use	Currently in Use
With Policy Intervention	1991[k]	1991[k]	1995[k]
Construction Time, Year	0.5-1.0	1	0.2-0.5

(a) For boilers, cement plants, and landfills
(b) Basis: coal as fuel
(c) Not applicable
(d) Potentially applicable to all boilers
(e) Catalyst lifetime, which represents 80% of capital cost; equipment lifetime: 20 years
(f) 100% for new facilities and 50% for retrofit applications
(g) Required for retrofit applications
(h) No external fuel source required; process uses landfill gas as fuel
(i) Royalty payments account for about 50% of annual O&M costs
(j) Basis: Only 970 out of 15,570 landfills can be used for commercial landfill gas recovery
(k) Required for uneconomical applications

9.5 DEFINITIONS OF TERMS USED IN PERFORMANCE AND COST CALCULATIONS

The following list explains the terms and assumptions used in the performance and costs data presented in Tables 9.2 through 9.9.

ENERGY CHARACTERISTICS	
Fuel Use Requirements, million Btu/ton	The estimated energy used per ton of greenhouse gas pollutant removed.
Heat Rate, Btu/Kwh	The estimated energy use per Kwh of electricity generated before the controls are applied.
Capacity Factor	The estimated capability of the process, which may be higher than the actual capacity factor of the boiler plant.
Percent Removal	Approximate percent of the greenhouse gas pollutant that is removed by the process.
Operating Lifetime	Design operating lifetime.
Operating Characteristics Uncertainty	Judgment factor to account for the current developmental status. Commercial technologies received a rating of "Low."
COSTS	
Capital Costs, annual $/million Btu	The annual capital charge at 15% capital charge rate and 65% operating rate, divided by the unit capacity (MMBtu/hr).
O&M Costs, $/million Btu fired	Annual operating and maintenance costs divided by the unit capacity (MMBtu/hr).
Cost of Capital	A judgment factor to account for the level of project risk. Regulatory-driven utility projects received a rating of "Low."
MARKET POTENTIAL	
Maximum Potential Penetration	An estimate of the maximum percent of the utility population that could install the technology, given that installation is required by regulation.
Expected Date of First Entry	
Without Policy Intervention	Assumes no federal or state regulations.
With Policy Intervention	Assuming final rules are published on January 2, 1990.
Construction Time, Years	An estimate of the construction time, assuming normal design and construction backlogs. If a large number of U.S. utilities order systems at approximately the same time, the actual time between order and startup could be much longer.

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10.0 APPROACHES TO RESTRUCTURING THE DEMAND FOR ENERGY

Abundant and inexpensive energy forms have played a prominent role in the development and evolution of modern-day, industrialized societies. However, it has only been during the last two decades of this era of economic growth that the *demand* for energy has risen to a level of importance that is comparable to capital and labor as vital inputs into consumption activities and industrial processes. The abrupt structural shifts in fossil fuel supplies and prices in the 1970s have given energy--fossil and nonfossil forms alike--a status as important as the more traditional factors of production and consumption. Moreover, concerns about the increasing costs of addressing environmental problems that result from burning fossil fuels have also emphasized the importance of the demand for energy.

As a result, understanding the nature and determinants of the demand for energy and its services has emerged as a key link for developing policies to influence our energy and economic future.

10.1 INTRODUCTION

This chapter presents a general discussion of the concept of "modifications" to final product (goods and services) demand as a means of reducing greenhouse gas emissions, with emphasis on the role of structural change. The changes in preferences, technologies, and populations that lie at the heart of the restructuring concept are typically eschewed in treatments that reduce energy use through efficiency measures or fuel switching (see, for example, Carlsmith et al. 1990, p. 3; OTA 1991, p. 6). However, final demand shifts, in both the household and business sectors, are among the most fundamental determinants of energy use. Final product demand is met with energy services as one input factor, and the corresponding use of fossil fuels to provide needed energy services will, of course, result in greenhouse gas emissions.

Unfortunately, the relationships between changes in final product demand, energy use and greenhouse gas emissions are complex and not well understood. What is clear, however, is that both the *scale* and *mix* of final product demand are basic drivers for the level and type of energy use and related emissions. This means that some types of modification to final demand have the potential to serve as an emission reduction strategy because they ultimately help to restructure the demand for energy services.

The role for final demand modification as an emission reduction strategy is difficult to determine, especially when contrasted with the three other emission reduction strategies--energy efficiency improvement, fuel switching and direct carbon removal. The difficulty is due, in part, to the fact that structural shifts in final demand occur over long periods of time for reasons that may not relate to energy use or emissions. Moreover, the other three reduction strategies, which are intended to directly affect either fuel use or emissions, can also have their own impact on final demand. This impact on final demand can, in turn, affect fuel use and emissions, although the direction of the changes in greenhouse gas emissions cannot be determined until adjustments in the use of specific fuels are known.

The purpose of the chapter is to discuss the key issues regarding restructuring of energy demand, to describe the role of technology in structural change, and to identify research needs which must be addressed to better understand the potential that energy demand restructuring may have for reducing greenhouse gas emissions. The remainder of the chapter is divided into four sections. In Section 10.2, basic concepts and terms related to the demand for energy are presented. Working definitions of energy demand restructuring are offered in Section 10.3. In Section 10.4, examples of past, present, and potential future energy demand restrucuring are given. Finally, in Section 10.5, research and development needs for energy demand restructuring are listed.

10.2 BACKGROUND ON ENERGY DEMAND

As commonly used, the term "demand" may refer to a number of related phenomena that are important to distinguish from one another. One purpose of this section is to make these necessary distinctions. Similarly, the phrase "energy demand" also may have different meanings depending on the context. Another purpose of this section, therefore, is to define the various aspects of energy demand that might be targets for restructuring.

10.2.1 Basic Demand Concepts

The term "demand" is commonly used to refer to either 1) the *quantity* of a good demanded, or 2) the *relationship* (or schedule) between various prices of a good and the corresponding quantities of the good demanded. Both of these concepts are illustrated in Figure 10.1 where the line labeled D_1 portrays the demand for an item, such as passenger

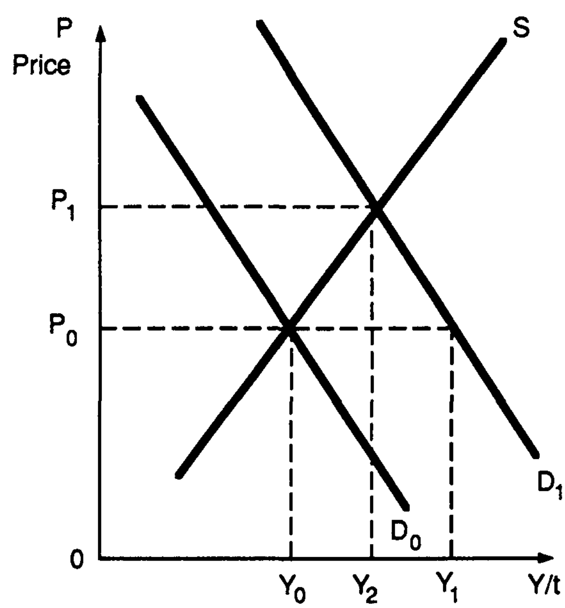

Figure 10.1. Basic Demand Concepts

vehicle miles. At price P_1 the quantity of the vehicle miles demanded is Y_2, while at price P_0 the quantity demanded is Y_1. The line D_1, which represents a schedule of the price of a good versus the quantity of the good demanded, is called the demand for good Y (passenger vehicle miles). An analogous situation holds for the terms "supply" and "quantity supplied" as illustrated by line S in Figure 10.1.

The phrase "change in demand" refers to a shift in the demand schedule (e.g., from D_0 to D_1) brought about by factors other than the price of the good. The phrase "change in quantity demanded" refers to movements along a demand schedule (e.g., movement along D_0). A change in quantity demanded usually occurs in response to a change in supply. The phrase "change in *equilibrium* quantity" (demanded and supplied) refers to the movement of one equilibrium demand-supply quantity (where the demand for the good equals the supply of the good) to another. Policies for reducing greenhouse gas emissions should be evaluated on how well they reduce equilibrium quantities.

The graph in Figure 10.1 depicts a change in the demand for a good within an equilibrium framework. The change in demand is indicated by the shift from the initial demand schedule, D_0, to the final demand schedule, D_1. The change in demand is equal to the distance between Y_0 and Y_1. The change in the equilibrium quantity demanded, however, is only the distance between Y_0 and Y_2. The distance Y_0 to Y_2 can also be referred to as a change in equilibrium quantity supplied.

The basic supply-demand linkages illustrated in this figure are crucial to understanding how changes in either the demand or the supply for a production factor input like energy can affect energy use and associated emissions.

10.2.2 The Demand for Energy

To understand and explain the demand for energy, analysts have observed that energy is not a final product which produces consumption benefits, but is rather an intermediate commodity used in combination with other commodities to produce benefits. The seminal survey article by Taylor captures this view of energy demand for the case of electricity:

> Electricity does not yield utility in and of itself, but rather is desired as an input into other processes (or activities) that do yield utility. The processes all utilize a capital stock of some durability (lamps, stoves, water heaters, etc.), and electricity provides the energy input. The demand for electricity is thus a *derived demand*, derived from the demand for the output of the processes in question. [Taylor (1975), p. 80, emphasis added.]

This portrayal can be extended to other energy forms, including natural gas, oil/gasoline, wood, solar, wind, or hydro energy. Moreover, while the quotation is obviously focused on household energy behavior, the derived demand for energy in business and industry is similarly apparent, just like the demand for labor as a productive input is derived from the need to produce output to meet market demand.

Conditional on this derived demand aspect of energy usage, changes in the *structure* of end-use demand for energy may very likely change the nature of energy production and consumption. Coupled with the strong linkage between fossil energy use and greenhouse gas emissions, changes in the demand for goods and services may have considerable potential for also changing associated greenhouse gas emissions. If demand restructuring occurs in appropriate ways, it is possible to reduce emission levels, although the reverse can also occur. Simply reducing energy demand levels, substituting less "carbon-intensive" goods and services, or changing the type of service demand sought can reduce energy needs and associated greenhouse gas emissions.

To show this relationship, Figure 10.2 illustrates the role of energy resources in the economy's production of goods and services for final consumption. As shown at the top, basic consumer preferences drive the demand for final products, energy services, and energy resources. Energy resources, at the far left, are combined with physical capital, labor, and raw materials in primary and secondary energy conversion to produce a flow of energy services to firms and consumers. Firms and consumers, in turn, use energy service inputs in conjunction with capital, other materials, and labor/time to engage in productive activities which result in final goods and services to society. These final products provide benefits to meet consumer preferences through final consumption activities.

Past consideration and analysis of energy resources have customarily addressed physical quantities of energy sold and consumed. This conventional perspective has in the past aligned very closely with the sources of supply or the producers and distributors of energy resources. However, this slightly narrow view has been recently widened somewhat with measures and efforts to use energy more efficiently. Attention has been directed to the demand side of the energy balance relationship with the important result that energy *service* requirements can be satisfied by more than just production and generation from the supply side. This development is depicted in Figure 10.2 by the shaded column labeled "Energy Services Demand." For a treatment based on this distinction in the context of utility resource planning and electricity generation, see Jaske (1989). Contemporary econometric modeling of residential end-use behavior has also embraced this broader interpretation, as reflected, for example, in Hamblin et al. (1985). The term energy service demand is used here to reflect this more comprehensive way of viewing energy demand.

Along with the demand for the many other goods and services that are used in productive processes, the demand for energy is derived from its usefulness in producing other goods and services. The sources of all this derived demand are the goods and services that are directly consumed by final consumers, represented in Figure 10.2 as the block of "Final Consumption Activity." Many of these goods are produced by the consumers themselves within their own households using inputs

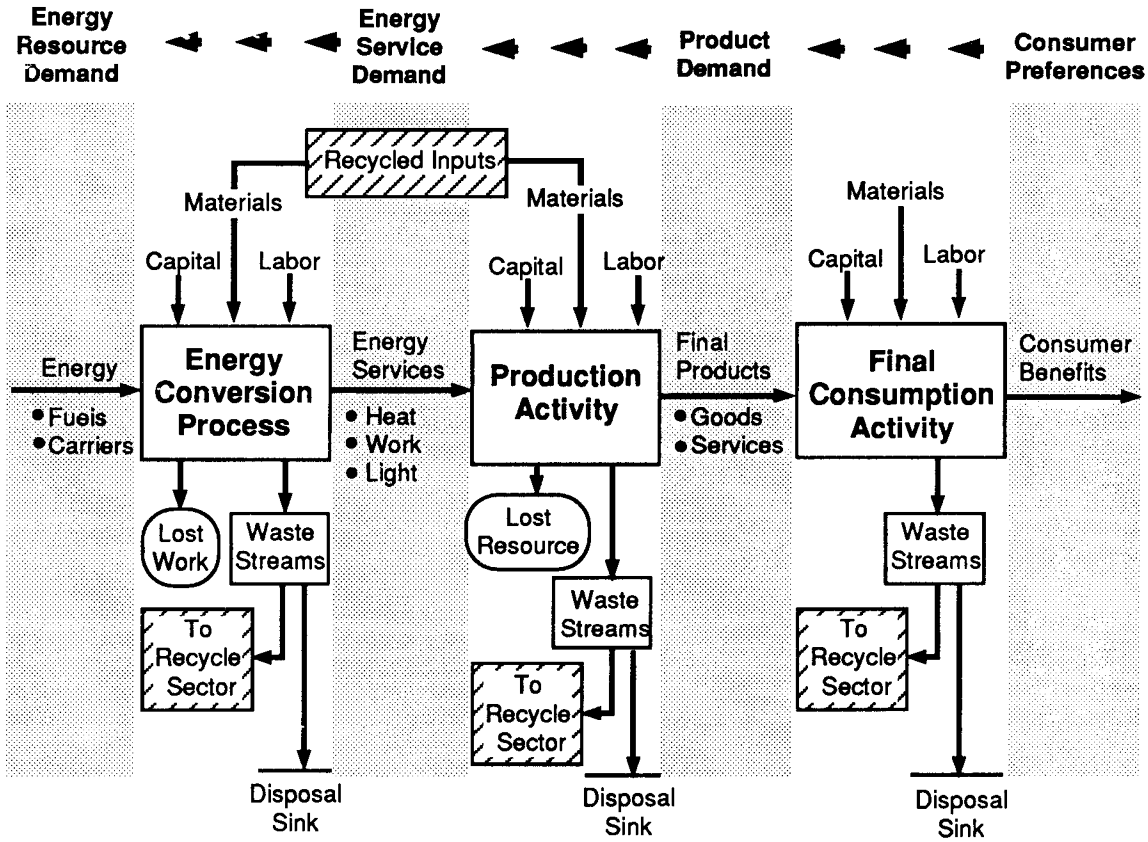

Figure 10.2. Determinants of Energy Demand

supplied by business enterprises (e.g., food preparation or personal transportation). Some of these goods are produced by firms using inputs supplied by other firms (e.g., professional medical care). Other goods may be produced either in households or in firms (e.g., meals). For the most part, however, business enterprises produce intermediate goods and services (including energy services) used by households or other firms. All these activities are represented in the block labeled "Production Activity."

The fact that the demand for many production inputs is derived means that changes in the demand for a particular good or service will also affect the demand for the inputs used in the production of the product or service. For example, when the price of a particular output increases (because, say, of an increase in demand), the quantity of the product supplied will increase in response. To increase the quantities supplied will require more inputs, so the demand for inputs also increases. These derived demand linkages represent another type of demand-supply relationship that needs to be taken into account when considering energy demand restructuring activities.

Finally, mechanisms for reducing greenhouse gas emissions should be evaluated on the basis of how well they reduce the equilibrium quantities of emissions. If only a few households or firms undertake demand restructuring activities involving technological change, there will be little if any effect on prices. If, however, a large number of households and firms undertake demand restructuring (or other kinds of emission reduction activities), one would expect to see some price reactions. For example, if drivers cut their driving mileage in half by using mass transit systems, the price of gasoline would fall and its price advantage in other uses would increase. These types of macroeconomic effects need to be factored into analyses of demand restructuring to determine the net effect on emissions.

A collateral interpretation of energy service demand can also rest on the recognition that energy services are demanded to meet certain *functional needs* inherent in consumption activities and production processes. Some of these functional needs are shown in Table 10.1.

Recognizing that some of these functional needs can be met through different means, or simply through better system designs, energy service demand can be changed in two basic ways:

1. **directly reducing the demand for a given function** - changing preferences or hardwiring energy conservation measures into household and firm technologies so that functional needs are met without lowering one's standard of living (e.g., supplanting a portion of building thermal energy demand through use of passive solar heating techniques)
2. **serving a particular function with "lower-intensity" type of service demand** - shifting the composition of service demand, for a fixed demand level, in a way that leads to less consumption of high-emission fuels (e.g., recycled aluminum scrap can be substituted for primary alumina, thereby reducing energy requirements, because scrap is less energy-intensive to process; or low-intensity materials, such as composites, can be used in place of high-intensity ones, such as steel).

10.3 WHAT IS ENERGY DEMAND RESTRUCTURING?

In this section, a working definition of the restructuring of energy demand is presented, beginning with a brief discussion on what is meant by a structural change. The long-run aspects of structural change are then detailed. Finally, the relationship of energy demand restructuring strategies to the other emission-reducing strategies presented in this report is outlined.

Table 10.1. Relationships between Functional Needs and Energy Service Demands in the Buildings, Industrial, and Transportation Sectors

Sector	Energy Service Demand	Functional Need
Building	• Space conditioning (thermal energy)	• Physical comfort
	• Lighting (radiant)	• Illumination
	• Appliance drive (mechanical, thermal)	• Convenience, heat
Industrial	• Equipment drive (mechanical)	• Reduced manpower work
	• Electrolytic power (electrical)	• Material processing
	• Steam (thermal)	• Equipment drive, heat
	• Direct heat (thermal)	• Heated materials
	• Equipment control (electrical)	• Human control
	• Feedstocks (chemical)	• Raw materials
Transportation	• Vehicle motion (mechanical)	• Transporting people and materials
		• Person-to-person communication

10.3.1 Structural Change

Structural change usually refers to a shift or alteration of an economic relationship in a long-run context. It can manifest itself by a change in the value of a parameter, a change in the functional form of the relationship, or a change in the set of economic influences that determine an economic variable. A primary implication of structural change is that the previously stable relationship that was useful for prediction purposes no longer holds, and a new one needs to be formulated and empirically tested.

The kinds of structural changes that are pertinent to energy demand restructuring are

1. changes in individual preference
2. changes in technology
3. changes in demographic factors that affect either preferences or technologies in the aggregate, as distinct from the individual unit level.

Any of these types of change can result in a fundamental reorganization of how energy resources, energy services, or final products are supplied and demanded. Preference changes, or how people value the goods and services they consume, for example, directly affect the demand for final products. Changes in technology, or the adoption of new ways of combining capital, labor, materials, and energy in production, affect both the supply of final products as well as the demand for inputs, including the demand for energy services and energy resources. Demographic changes affect preferences and technology in the aggregate because different groups within a given society consume and want to be supplied with different sets of final products. As the demographic composition of society changes, so does the aggregate supply and demand of various final products.

It is important to note, however, that this classification of structural changes is relatively arbitrary. Most energy demand restructuring activities, even those grounded in changing preferences, are generally accompanied by technological change. At the same time, changes in technology are usually accompanied by changes in preference. For example, changes in preferences, or, more precisely, changes in the way people value the impacts of burning of fossil fuels, are primary reasons why the U.S. Congress solicited this report on emission-reducing technologies. Federal funding of some of the R&D initiatives included in this report would also be a signal that changes in preferences will have occurred with regard to fossil-fuel use.

10.3.2 Short-Run and Long-Run Change

As stated above, structural change generally occurs within a long-run context. The importance of short-run and long-run changes in the demand for electricity also was discussed by Taylor:

> However, since durable goods are involved [in the demand for electricity], we must from the outset distinguish between a short-run demand for electricity and a long-run demand. The short run is defined by the condition that the electricity-consuming capital stock is fixed, while the long run takes capital stock as variable. In essence, therefore, the short-run demand for electricity can be seen as arising from the choice of a short-run utilization rate of the existing capital stock, while the long-run demand is tantamount to the demand for the capital stock itself. [Taylor (1975), p. 80.]

In the short run, energy demands reflect the influence of elements which govern the utilization of a given stock of durable or capital goods. In this context, it is important to note that short-run changes in quantities demanded may not be permanent. Short-run changes in demand are easily reversed when the capital stock has remained fixed. In the long run, however, both the rate at which the stock is used and the amount and type of the stock is itself variable. When the capital stock can change, changes in quantities demanded may exhibit more limited reversibility. In other words, short-run changes are not structural change; whereas, long-run changes, i.e., changes in the capital stock, are.

This means that energy demand restructuring does not generally pertain to reductions in the quantity of energy demanded that are generated directly by short-run disruptions in the supply of fossil fuels. When oil prices increased dramatically during the 1970s, for example, people quickly reduced the amount of energy they demanded by conserving energy. This straightforward reduction was achieved, for instance, by turning down the thermostat (reducing the thermal comfort level sought in a building) or by changing travel plans to reduce miles driven. Such strategies rely on foregoing something (thermal comfort, trip amenity, etc.) in exchange for energy savings. As noted in a recent study for Congress by the Office of Technology Assessment, not only is the implicit sacrifice incongruent with maintaining one's standard of living, such demand reductions have the drawback from a policy perspective of being too transitory (OTA 1991). Once prices returned to their previous levels, these types of demand reductions were easily reversed.[a]

If energy prices remain relatively high long enough, however, people will tend to evaluate the energy efficiency of their capital equipment stocks. In some instances, inefficient capital equipment will be replaced sooner or the replacement equipment will be more energy efficient than would have been the case had prices remained low. In other instances, new technologies like automatic timers used for thermostat setback, or motion indicators used to control lighting, may be added. Higher fossil fuel prices, therefore, may affect the demand for the kinds of energy efficient capital discussed in previous chapters. These changes represent structural changes.

(a) If the implementation of energy conservation is induced because of a change in preferences, however, then one can say that the demand for energy has been restructured (see Section 10.4.1).

10.3.3 Energy Demand Restructuring as a Strategy

Clearly delineating the energy demand restructuring strategy from the fuel substitution, energy efficiency improvement, and carbon removal strategies is difficult because implementing any of these emission-reduction strategies typically requires new capital, and, therefore, as implied immediately above, represents a structural change. In addition, implementation of any of these strategies will result in a restructuring of the demand for energy.

What sets energy demand restructuring apart from the other strategies is its indirectness. The carbon removal strategy, for example, focuses on the direct removal of carbon or carbon compounds from fuels before they are burned or from the emissions that their combustion generates. Both the fuel switching and energy efficiency improvement strategies focus directly on the reduction of those productive inputs that are most responsible for carbon emissions. The primary focus of the energy demand restructuring strategy, however, is on changes that may result in lower levels of emissions, but only indirectly, either through changes in the demand for final products or through the adoption of new technologies which reduce emissions only incidentally. This indirect impact of energy demand restructuring on energy requirements and, ultimately, on greenhouse gas emissions, is reflected in Figure 10.2 by the arrowheads representing feedback to the Energy Service and Energy Resource Demand blocks from the objectives and activities selected and accounted for in the block "Final Consumption Activity."

A number of candidate strategies for reducing greenhouse gas emissions result, it should be recognized, from distortions to perfectly functioning markets for energy. Because the costs borne by society at large from global warming are not reflected in the prices which consumers and firms pay for energy in their private consumption and production activities, the mix of energy forms is very unlikely to be socially optimal. Too much use of a high-intensity greenhouse gas energy form is undertaken when price is less than social cost.

Prices which reflect the higher cost to society would re-direct energy demands away from these higher-cost energy forms. In the absence of markets to perform these allocations in a decentralized fashion, these basic strategies are viewed as necessary, surrogate mechanisms for achieving socially desirable levels of global air quality.

10.4 EXAMPLES OF RESTRUCTURING ENERGY DEMAND

The purpose of this section is to discuss some concrete examples of energy demand restructuring activities in more detail. The section is organized by the three major types of structural changes that affect energy demand--changes in preferences, technological changes, and demographic changes.

10.4.1 Changes in Preferences

The simplest energy demand restructuring strategy would be a straightforward, preference-change-induced reduction in the demand for final products that embody high levels of emissions. As the environmental problems associated with the use of fossil fuels become more well known, some people will voluntarily begin to implement various conservation measures, i.e., car pooling, combining trips, washing clothes in cold water, turning down the thermostat at night, and turning off the lights in empty rooms. Other reductions could be obtained by changing the mix of outputs consumed, e.g., eating meals that require less cooking or refrigeration, or reading books instead of watching television.

The fact that some consumers now place a higher value on the environment and are becoming more aware of how the environment might be threatened has not been lost on businesses. The recognition of this phenomenon is reflected in the environmental claims that firms make with regard to their products or policies. Firms that are seen to have "bad" environmental records are likely to lose sales. Thus, firms have some incentive to reduce negative impacts that might result from their products or policies, even if it entails a smaller profit per unit of output.

The preference-induced adoption of conservation activities is generally referred to as "changing one's lifestyle or way of doing business." This mechanism is sometimes disparaged because it is sometimes confused with price-induced reductions in energy consumption (see Section 10.3.2 above) or a "change in one's standard of living." A change in lifestyle or business style does not necessarily mean that one's standard of living or business profits are reduced. Indeed, changing one's lifestyle or business style could cause one's standard of living or business profits to increase. In the context of consumer standard of living, Durning (1991) is a good source for a multidimensional view beyond pure consumption as an indicator of quality of life in a market-based economy.

For some changes in lifestyle or business style, the emissions impacts, though significant, are secondary. For example, during the past two decades, consumers have decreased their consumption of beef and increased their consumption of chicken and fish. The reason for this shift may have been their increasing awareness of the health hazards of cholesterol and saturated fat intake (see Moschini 1991). Most people do not know that it takes 5 kilograms of grain and the energy of 2 liters of gasoline to produce 1 kilogram of steak in the U.S. or that cattle produce methane emissions.

Another trend that has had and probably will continue to have an effect on energy consumption is the increased preference for urban living since the end of WWII. Urbanization can mean smaller houses and more multifamily dwellings. This trend in preferences probably has helped to reduce space conditioning requirements because the amount of space available per person has decreased. Also, multifamily dwellings use less energy than single-family homes; a single-family townhouse uses about 25% less energy for heating than a detached house of the same size (Keyes 1980).[a] Increasing urbanization may also result in significantly reduced number of miles traveled.

In addition, some small firms have recently entered into the practice of sharing production facilities with other firms as a way to reduce facility costs. This practice also saves energy because a single production resource can be used on a continuous basis versus separate facilities which are sometimes idle.

Finally, another manifestation of changing preferences is the *marketization* of traditional household activities. Marketization refers to the process of substituting commercially produced goods and services for those produced by the household, with a concomitant change in the scale and, perhaps, nature of the technological process. A commonly mentioned item is the use of mass transit systems instead of household-owned automobiles (see Chapter 6). A number of other "marketization" processes have occurred in the past and have involved basic goods and services such as raw agricultural products, the education of children aged 5 to 18, and specialized medical care. At present, marketization of meal preparation, entertainment, and the care of infants and pre-school children is occurring at a rapid rate.

Energy efficiency has not been a driving force for most marketization activities. The primary causes for these changes have been structural in nature. Leading sources of contemporary changes reside largely with the increase in both urbanization and the number of woman participating in the workforce. Such activities might reduce emissions, however, because one would expect that goods and services produced commercially would be less energy-intensive because of economies of scale.

(a) On the other hand, suburbanization with its reliance on the automobile has probably helped to increase emissions since the end of WWII. The focus of community design and mass transit technologies is, to a large extent, on the problems arising from suburbanization (see Chapter 6).

The competitive nature of some of these markets also serves as a stimulus for the generation and adoption of cost-reducing technologies.

This shift of production out of the household sector and into the commercial sector is a major factor in the growth of the service sector in the United States. While manufacturing has maintained a relatively steady 20% to 23% of output, the service sector has risen from 39% to 47% of GNP over the period 1965 - 1985. This shift in the structure of the U.S. economy has not only changed the mix of goods and services produced commercially, but has also affected energy use patterns. As the service sector of the economy expands, the mix of energy sources required to meet national demand also shifts.

10.4.2 Technological Change

A large number of technologies are available to those consumers or business firms seeking lifestyles or business styles that are less emissions-intensive. Chapters 2 through 8 discuss technology options that focus directly on energy resources or energy services. Demand restructuring is typically also allowed through technological advancement, but the technologies which enable restructuring are not necessarily energy technologies, nor are energy savings necessarily the leading drivers of restructuring activities. Three examples of such drivers that could have a significant impact on emissions by restructuring energy demand are

1. increased use of *low-emission materials*

2. *waste reduction* and *recycling*

3. the *electronic revolution*.

Recent studies of primary materials use in the United States and other industrialized countries indicate an important shift in the materials demand mix, away from basic materials like steel or aluminum toward increasingly refined and complex goods such as plastics and composites (see, for example, Williams et al. 1987). These shifts to *lower-emission materials*[(a)] can occur as a result of many factors, but two important demand-side mechanisms of change are

- redesigning products and manufacturing processes to require less material or less energy to manufacture

- substituting low-emission materials in products or processes for high-emission materials.

For instance, the rise in substitution of lighter materials for steel; production of steels with greater durability or strength-weight ratios; and growing preferences for high-value, low steel-intensity products have all contributed to a decline in aggregate U.S. steel demand in the last two decades. Recent changes in the automobile material composition, vehicle downsizing, and longer vehicle ownership patterns illustrate this trend.

These phenomena point to the prospect of an important structural change from an era of materials-intensive production to one where economic growth is driven by highly engineered products with lower material content. If the rapid growth of low-intensity industrial sectors relative to their high-intensity counterparts represents a structural change, then the outlook for industrial greenhouse gas emissions could be improved through shifts in product material demand alone. The substitution of gas-fired plastics or composites for coal-fired steel in autos, construction, and other durable goods could significantly reduce greenhouse gas emissions on both a unit and a total output basis. Similar illustrations exist in the chemical industry, where the production of certain organic chemicals using ambient temperature biological processes instead of high-temperature thermal reactors can have the same reduction effect on emissions.

(a) Lower-emission materials are defined as those materials that can be produced with reduced emissions because of a relatively low energy/ton-output requirement or those that can be processed using low-emission fuels. The former are called low-energy intensity materials; the latter are called low-emission intensity materials.

All industrial processes produce material *wastes*, from raw material-input through product distribution and servicing. Moreover, use of goods and services by consumers also results in large amounts of waste. Many of these solid, liquid, and gaseous waste streams impose serious disposal costs and environmental problems for industry and local governments. If a feasible technology existed, some waste materials could be economically recycled or converted into useful fuels or feedstocks. Many wastes are now reused, but a significant additional portion of the approximately 5 quads of energy embodied annually in discarded wastes could be recovered.

In general, costs and environmental concerns make the combustion of wastes the least desirable use of their energy content. Emerging new technologies such as biotechnology, membrane separation systems, and new pyrolysis techniques point to attractive prospects for converting these wastes to more valuable products or feedstocks, provided the technologies can be made practical, economical, and reliable. Innovative mechanical, biochemical, and thermochemical conversion processes are needed to recover and reuse these resources.

Many examples are now available to indicate the possibility of converting selected wastes into higher value chemicals. In the area of solid waste processing, four interesting cases are 1) pyrolytic conversion of mixed plastics wastes to their chemical precursors, 2) a process to convert waste tires into high-performance polymer composites, 3) a single-step system to recover zinc from galvanized auto scrap, and 4) a process to obtain adhesives and high-value chemicals from wood wastes. For liquid wastes, examples are 1) use of freeze crystallization to recover process water from complex wastewater, 2) a process which converts lactic acid in liquid waste streams to a specialized lactide copolymer for plastics production, and 3) recovery of hydrocarbons from abandoned refinery disposal sites. Application of biotechnology-based processes, now being developed with liquid feedstocks, to high-carbon gaseous waste feeds such as carbon monoxide, carbon dioxide, and volatile organic compounds has also been discussed.

In some applications, minimizing waste before it is generated through careful product and process design is possible and can be very attractive economically. Development of products and manufacturing processes to require less material or less energy to manufacture is now being investigated by many companies and research laboratories.

A number of household and business activities are also candidates for *waste recycling*. Newspapers and aluminum cans are examples of recent successes, and further advances in plastics recycling are currently under way. Some difficulty may still be encountered in recycling certain materials, however, because of the cost of separating or collecting enough material to justify the effort. In some instances, markets for the recycled product have to be developed. New technology developments in materials applications, production processes or production control would be required to implement these approaches.

Finally, in the third example, increased use of *electronically based processes* is likely to have a major impact on energy consumption. Emission reductions are likely to arise from electronic communications because of its ability to substitute for the physical transport of people or materials. In firms, for example, sophisticated telecommunications will reduce the need for traveling long distances for meetings or even the relatively short distance between home and office. The advent of increased "telecommuting" is almost certain to occur in densely populated areas like California, for example, where traffic congestion already costs $17 billion annually in wasted fuel and lost productivity, a figure which is expected to triple in the 1990s (Ayres 1991). In households, cable link-ups for local shopping and televised selling and demonstration will replace some trips to the store and mail order catalogs. And, even though products that are ordered by phone will still need to be transported to final customers, centralized batch delivery systems can be used rather than individual pickup. Finally, electronic storage mediums promise to significantly alter the way households and businesses access and retain information and records, with a major impact on the demand for printed matter.

10.4.3 Demographic Changes

Demographic trends can also change preferences in the aggregate. For example, as the average age of the U.S. population has increased, more people have moved from colder to warmer climates. If this southerly migration continues, it could mean abandoning older homes in the North in favor of constructing new homes, perhaps multi-family dwellings, in the South. In the commercial sector, hospitals might be built instead of schools, and perhaps more leisure-related buildings such as hotels instead of commercial office buildings. In terms of operations, homes might be occupied more of the day (no one leaving for work) and kept relatively more comfortable (warmer in winter and cooler in summer). All of these changes are likely to affect energy consumption and emissions patterns, though exactly what the overall impacts will be remains highly speculative.

10.5 CONCLUSION - RESEARCH NEEDS FOR SERVICE DEMAND RESTRUCTURING

For the energy demand restructuring strategy to be successful, policy makers need to know 1) what energy demand restructuring activities will be successful in reducing emissions and 2) what mechanisms will ensure implementation. Energy demand restructuring, however, is a relatively new concept. Many of the basic theoretical aspects of using energy demand restructuring to reduce emissions are still being formulated, and empirical research on the effects of preference and technological change on the demand for goods and services is scarce. Moreover, the interactions of the other strategies (fuel substitution, energy efficiency, and carbon removal) with energy demand restructuring have not been investigated.

Although some applicable technologies already exist, many new technologies would also be required to implement many energy demand restructuring activities. Better taxonomies and descriptions of the new technologies required for implementing emission-reducing energy demand restructuring activities are needed to better understand, among other things, the role of technological change in household production activities. Analysis of underpinnings and estimates of technological advance for a range of demand changes like marketization, waste reduction/recycling, and electronically based processes is also needed to identify other technology improvement pathways. First-cut estimates of the emissions content of various goods and services is essential to assessing the potential energy and emission savings resulting from a change in their demand. Finally, the mechanisms for implementing energy demand restructuring activities, especially the effects of federal policies or market actions, are not yet well understood.

Energy demand restructuring promises considerable gains toward the goal of reducing greenhouse gas emissions. Further research is required, however, to determine the extent of the potential and the extent to which it can be realized.

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APPENDIX A

CONSERVATION COST CURVES FOR END-USE TECHNOLOGIES

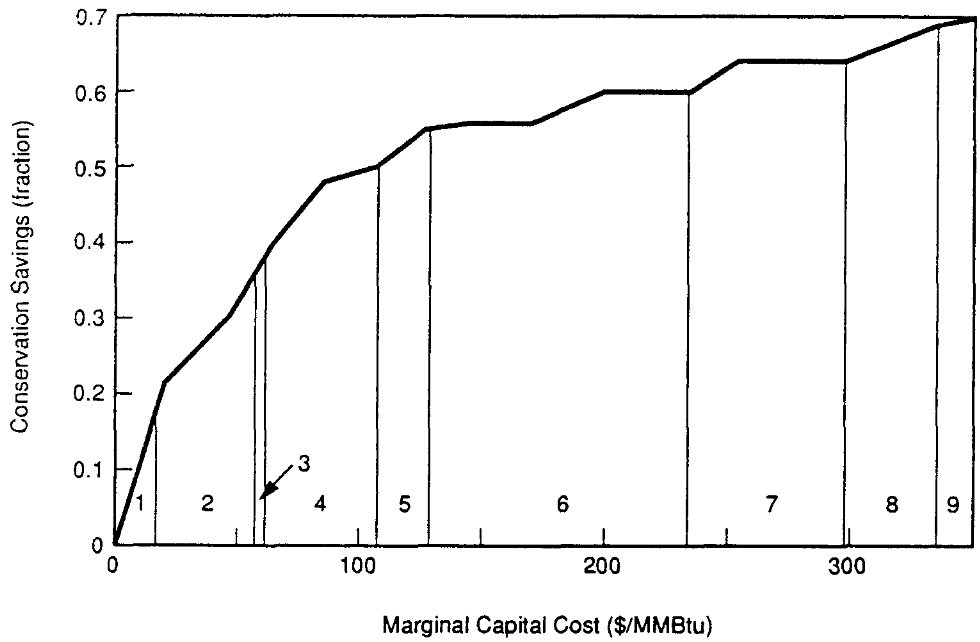
APPENDIX A

CONSERVATION COST CURVES FOR END-USE TECHNOLOGIES

The data depicted in Figures A.1 through A.14 incorporate technology characteristics used for the National Energy Strategy (NES) analysis and for the analysis in Volume II of this study.

In some cases, data used to prepare the curves differ slightly from corresponding data reported in this volume (Volume I). The NES data were developed after much of the work for this volume had been completed.

Typically attempts to determine relevant technical information such as cost and performance data will return a range of values, particularly for emerging or future technologies. The differences mentioned here would in all cases fall into what would normally be considered an acceptable range of uncertainty.



Representative Conservation Measures:*

1. High efficiency furnace: all building types, all regions
2. Shell conservation level I: all building types, all regions
3. Shell conservation level II: MF - all regions
4. Pulse combustion furnace: SF, LD, MH - NE, NC
5. Shell conservation level II: SF - all regions
6. Pulse combustion furnace: SF, LD, MH - SO, WE; MF - NE, NC
   Shell conservation level III: MF - NC, SO; MH - SO, WE
7. Shell conservation level II: LD, MH - all regions
   Shell conservation level III: SF - NC; MF - NE, WE
8. Shell conservation level III: SF - NE, SO, WE; MH - NC
9. Shell conservation level 3: LD - all regions; MH - NE
   Pulse combustion furnace: MF - SO, WE

SF - single family houses	NE - northeast region
LD - low density housing units	NC - north central region
MF - high density housing units	SO - south region
MH - mobile homes	WE - west region

Example Shell Conservation Improvements:

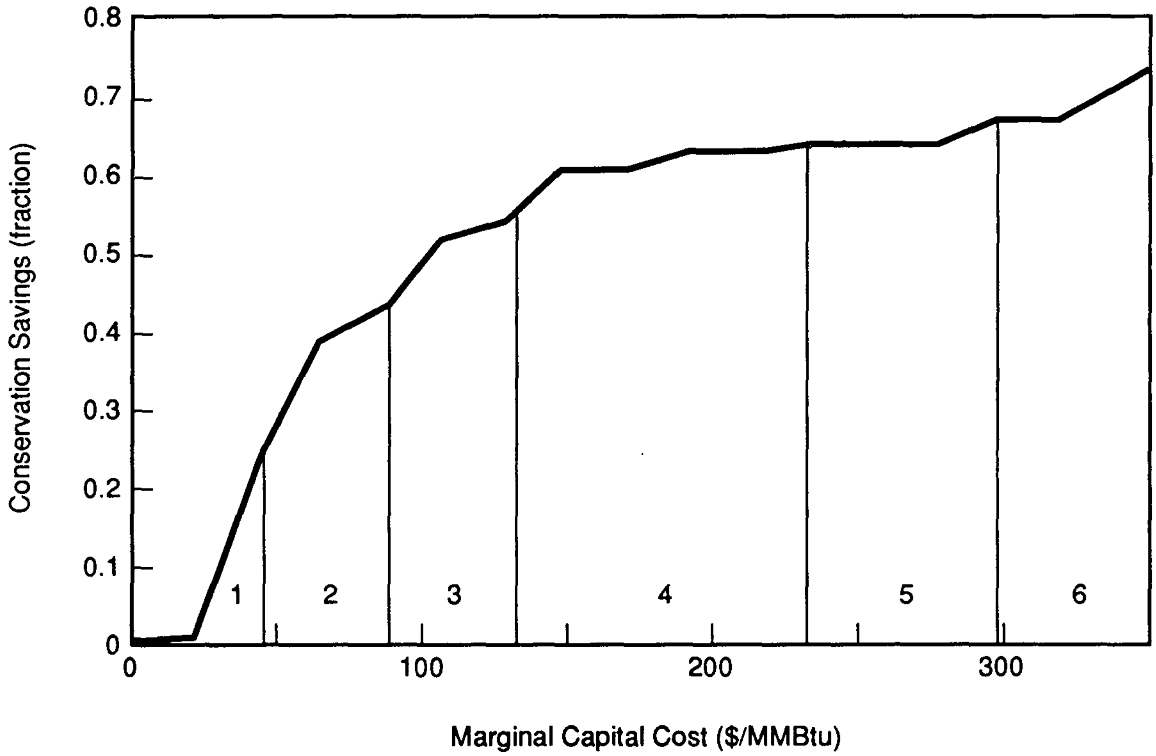
SF shell conservation level I: R-22 ceiling and R-19 wall insulation, improved caulking, 24" O.C. and few thermal bridges in framing, tighter sheathing, infiltration barriers, ductless fans, insulated pipes, etc.

SF shell conservation level II: level I plus additional ceiling, wall, ceiling insulation, thicker walls, minimal north face glass, south side thermal mass, waste heat recycling, landscaping, clock thermostats, etc.

SF shell conservation level III: level II plus south face summer shading, additional glazing, additional insulation, thicker walls, etc.

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.1. New Residential Space Heat Conservation Savings Curve - Natural Gas



Representative Conservation Measures:*

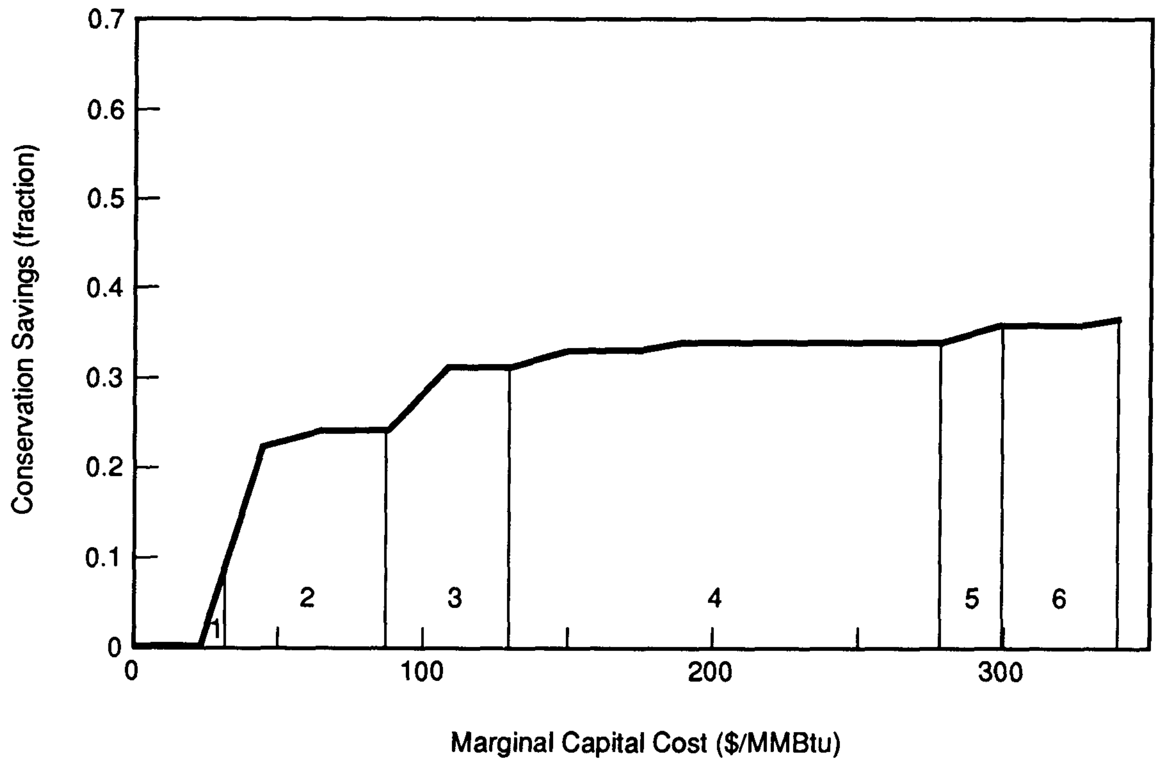
1. Shell conservation level I: all building types, all regions
   Shell conservation level II: MF - all regions
2. Heat pump: SF, LD, MH - NE, NC
3. Shell conservation level II: SF - all regions
   Heat pump: SF - WE; MH - SO, WE
4. Shell conservation level III: MF - NC, SO; MH - SO, WE
   Heat pump: SF - SO; LD - SO, WE; MF - NE, NC
5. Shell conservation level II: LD, MH - all regions
   Shell conservation level III: SF - NC; MF - NE, WE
6. Shell conservation level III: SF - NE, SO, WE; LD - all; MH - NE, NC
   Heat pump: MF - SO, WE

SF - single family houses
LD - low density housing units
MF - high density housing units
MH - mobile homes

NE - northeast region
NC - north central region
SO - south region
WE - west region

* Conservation measures are assumed to penetrate in least-cost order.
Example shell conservation improvements are given in Figure A.1.

Figure A.2. New Residential Space Heat Conservation Savings Curve - Electricity



Representative Conservation Measures:*

1. Shell conservation level I: SF - NE, NC, WE; LD - NC, NE; MF, MH - all regions
2. Shell conservation level II: MF - all regions
   Shell conservation level I: SF - SO; LD - SO, WE
3. Shell conservation level II: SF - all regions
   Shell conservation level III: MF - NC
4. Shell conservation level III: MF - SO; MH - SO, WE
5. Shell conservation level II: LD, MH - all regions
   Shell conservation level III: SF - NC; MF - NE, WE
6. Shell conservation level III: SF - NE, SO, WE; LD - all; MH - NE, NC

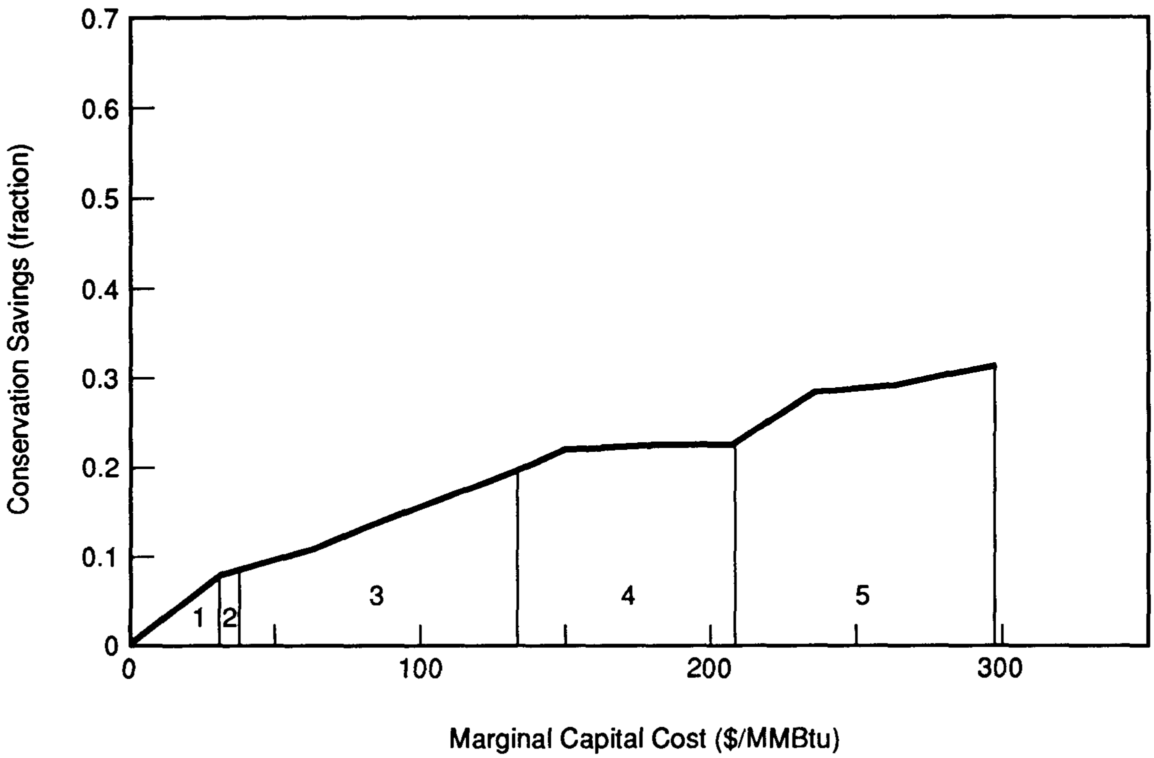
SF - single family houses
LD - low density housing units
MF - high density housing units
MH - mobile homes

NE - northeast region
NC - north central region
SO - south region
WE - west region

Note: Investments in shell conservation result in both space cooling and heating conservation savings; investments up to $20 above result in space heating savings only.

* Conservation measures are assumed to penetrate in least-cost order. Example shell conservation improvements are given in Figure A.1.

Figure A.3. New Residential Space Cooling Conservation Savings Curve - Electricity

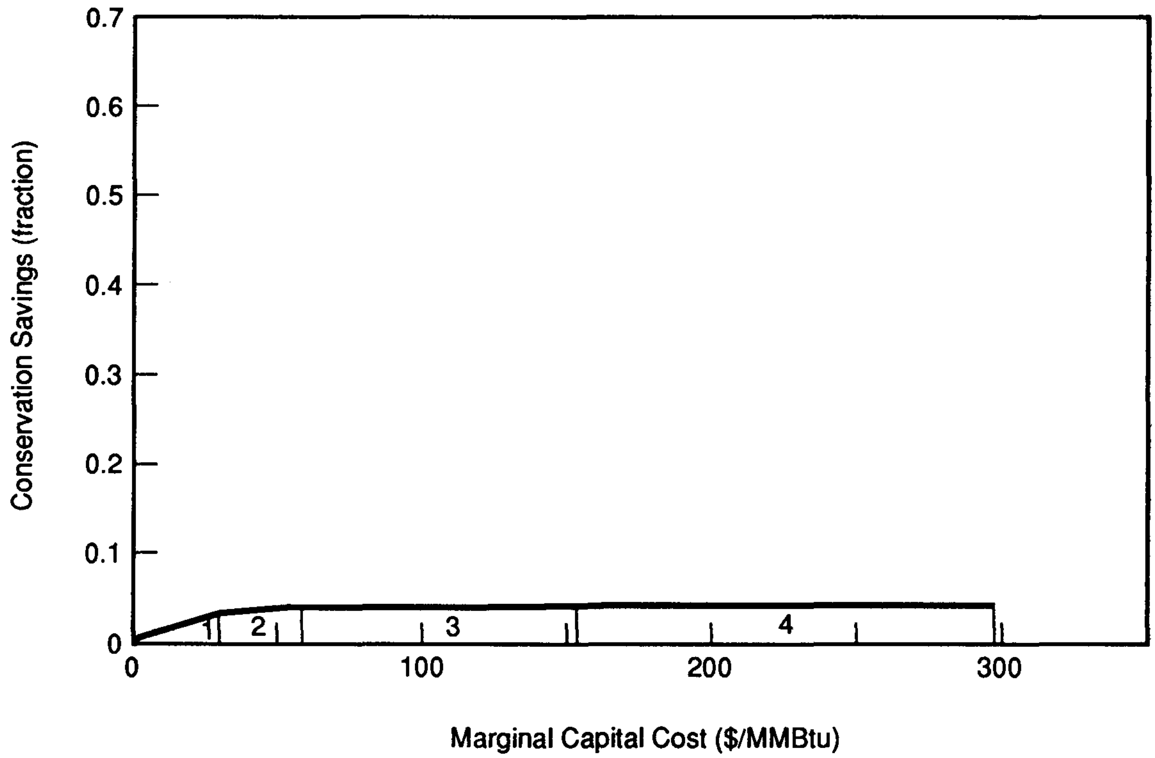


Representative Conservation Measures:*

1. Water heating: 2" insulation and heat trap
2. Clothes drying: temperature and moisture termination
3. Water heating: measure 1 + IID and flue damper
4. Water heating: measure - 3 + multiple flues
5. Water heating: measure 4 + pulse condensing

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.4. New Residential Thermal Conservation Savings Curve - Natural Gas

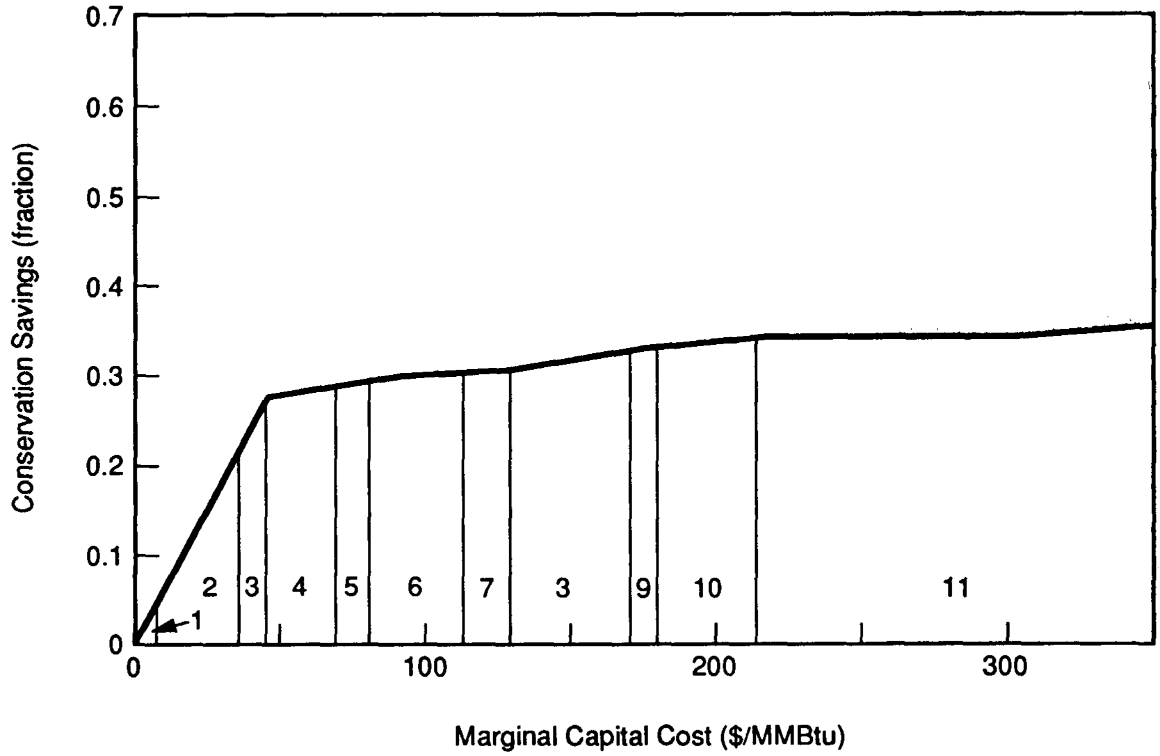


Representative Conservation Measures:*

1. Water heating: 2" insulation and heat trap
2. Clothes drying: temperature and moisture termination
3. Clothes drying: insulation
4. Clothes drying: recycle exhaust

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.5. New Residential Thermal Conservation Savings Curve - Electricity

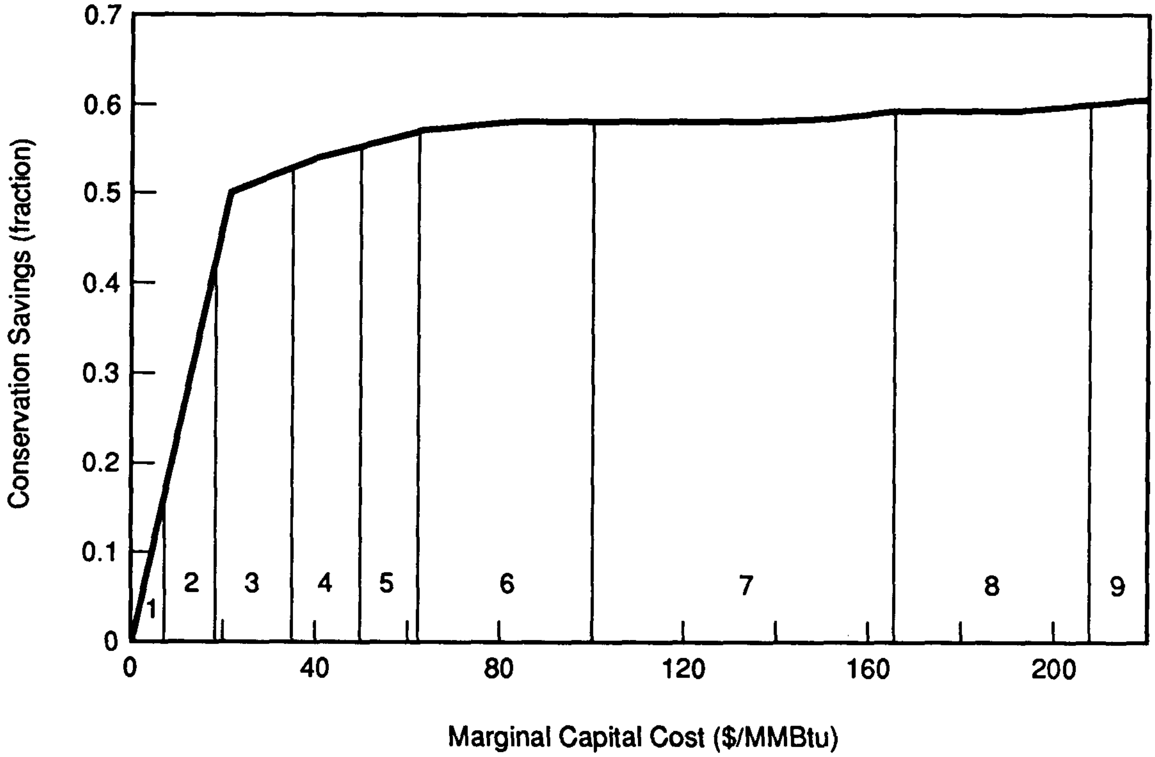


Representative Conservation Measures:*

1. Lighting: high efficiency incandescent
2. Lighting: compact fluorescent
3. Refrigeration: 5.0 EER compressor and foam door
4. Refrigeration: K = 0.11 insulation
5. Freezers: 5.0 EER compressor and K = 0.11 insulation
6. Refrigeration: 5.3 EER compressor
7. Freezers: 5.3 EER compressor and 2" door insulation
8. Refrigerators: high efficiency fan and 2" door insulation
9. Freezers: K = 1.0 insulation and 2" door insulation
10. Refrigerators: K = 1.0 insulation
11. Refrigerators: adaptive defrost and 2.5" side insulation

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.6. New Residential Appliances/Lighting Conservation Savings Curve



Representative Conservation Measures:*

1. High efficiency furnace: all building types, all regions
2. Shell conservation level I: all building types, all regions
   Shell conservation level II: RET - NE, NC
3. Shell conservation level II: OFF - NE, NC, SO, WE; RET - SO, WE; HOS - NE, NC, SO
4. Shell conservation level II: HOS - WE; SCH - NE, SO; MIS - NE, NC
   Shell conservation level III: RET - all regions
5. Shell conservation level II: SCH - NC, WE
   Shell conservation level III: OFF - NC; HOS - NE, NC SO, WE
6. Shell conservation level II: MIS - SO, WE
   Shell conservation level III: OFF - SO, WE
7. Shell conservation level III: SCH - NE, NC
8. Shell conservation level III: MIS - NE, NC

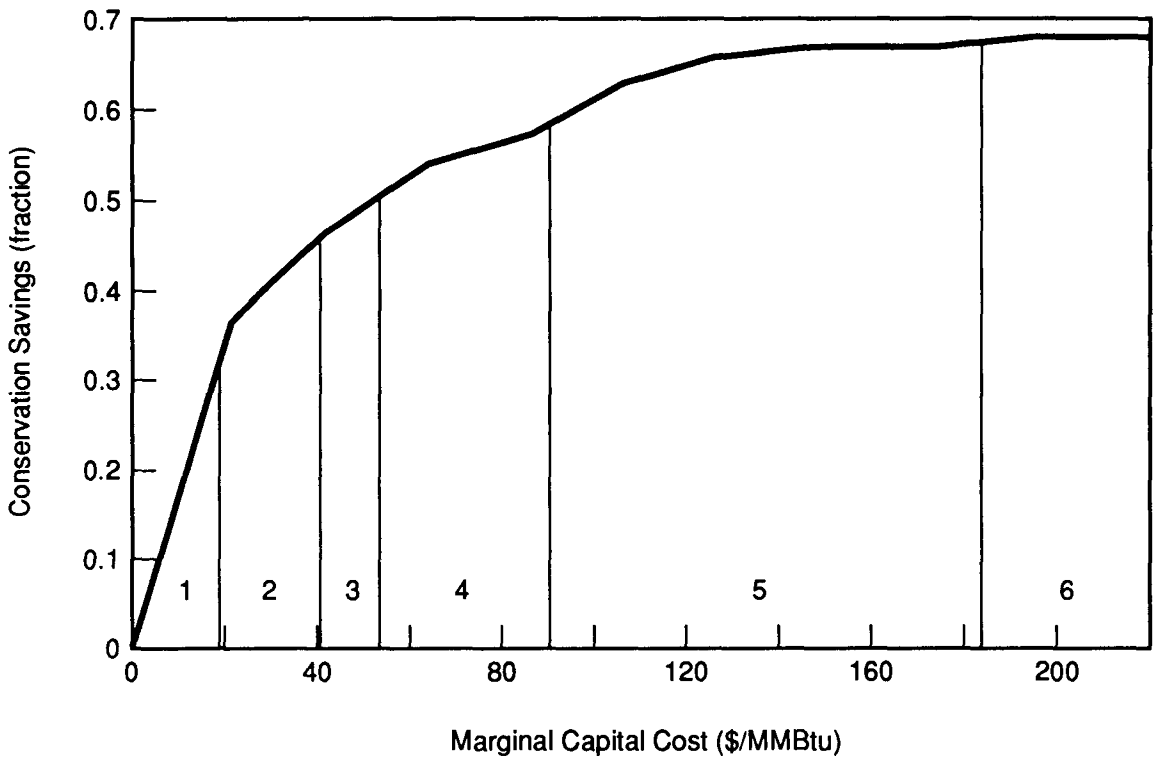
HOS - hospitals
SCH - schools
OFF - office buildings

RET - retail buildings
MIS - other buildings

NE - northeast region
NC - north central region
SO - south region
WE - west region

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.7. New Commercial Space Heat Conservation Savings Curve - Natural Gas



Representative Conservation Measures:*

1. Shell conservation level I: all building types, all regions
   Shell conservation level II: RET - NE, NC
2. Shell conservation level II: RET - SO, WE; OFF, HOS, SCH - all regions
   Shell conservation level III: RET - all regions
   Heat pump: RET - NE, NC
3. Shell conservation level II: RET - all regions
   Shell conservation level III: OFF - NE, NC; HOS - all regions
4. Heat pump: OFF, MIS - NE, NC; RET - WE; SCH - NE
   Shell conservation level III: OFF - SO, WE
5. Heat pump: HOS - NE, NC; OFF, MIS - SO, WE; SCH - NC, WE
6. Heat pump: HOS - SO, WE
   Shell conservation level III: SCH - NE, NC, SO

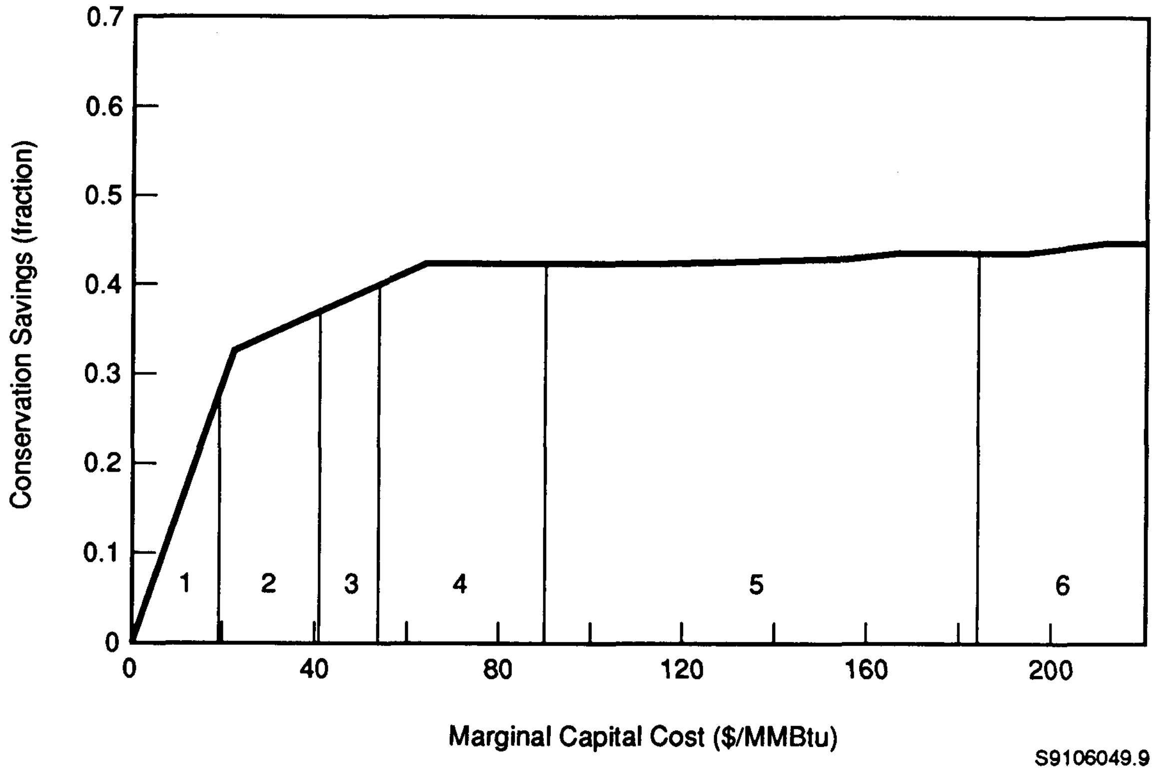
HOS - hospitals
SCH - schools
OFF - office buildings

RET - retail buildings
MIS - other buildings

NE - northeast region
NC - north central region
SO - south region
WE - west region

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.8. New Commercial Space Heat Conservation Savings Curve - Electricity



Representative Conservation Measures:*

1. Shell conservation level I: all building types, all regions
   Shell conservation level II: RET - NE, NC
2. Shell conservation level II: RET - SO, WE; OFF, HOS, SCH - all regions
   Shell conservation level III: RET - all regions
   Heat pump: RET - NE, NC
3. Shell conservation level II: RET - all regions
   Shell conservation level III: OFF - NE, NC; HOS - all regions
4. Heat pump: OFF, MIS - NE, NC; RET - WE; SCH - NE
   Shell conservation level III: OFF - SO, WE
5. Heat pump: HOS - NE, NC; OFF, MIS - SO, WE; SCH - NC, WE
6. Heat pump: HOS - SO, WE
   Shell conservation level III: SCH - NE, NC, SO

HOS - hospitals
SCH - schools
OFF - office buildings

RET - retail buildings
MIS - other buildings

NE - northeast region
NC - north central region
SO - south region
WE - west region

* Conservation measures are assumed to penetrate in least-cost order.

Figure A.9. New Commercial Space Cooling Conservation Savings Curve

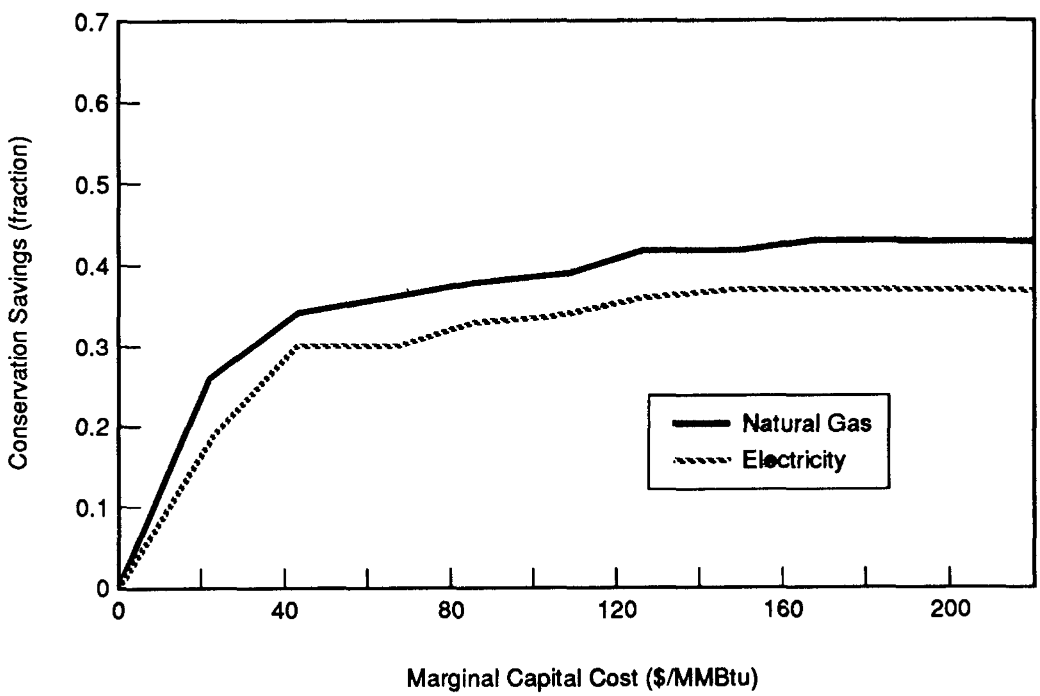


Figure A.10. New Commercial Thermal Conservation Savings Curve - Natural Gas and Electricity[a]

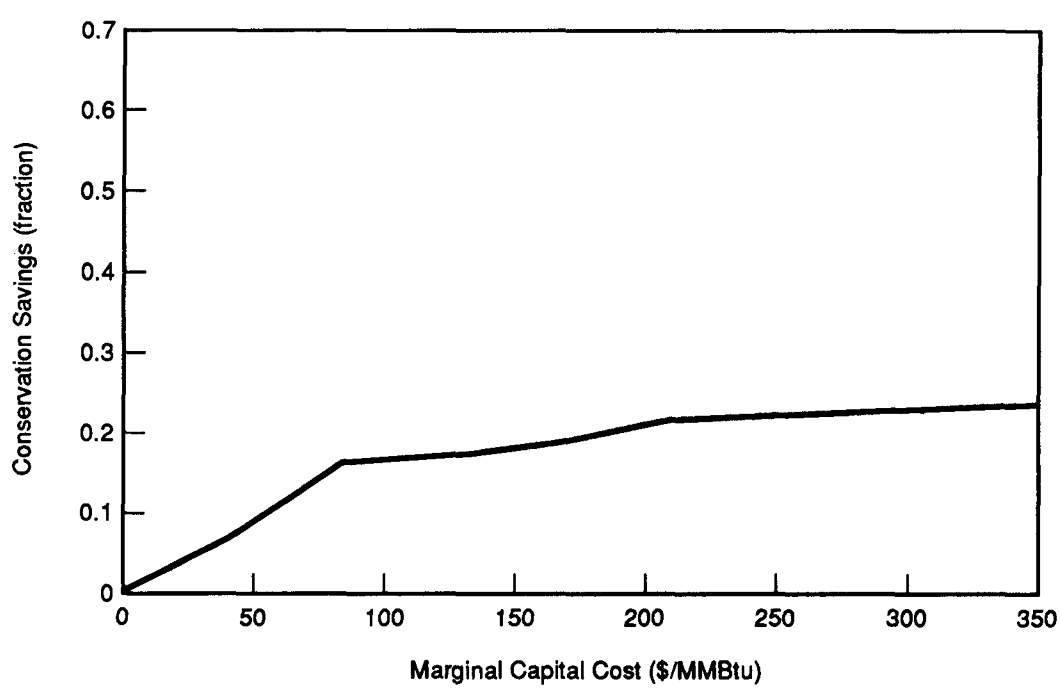


Figure A.11. New Commercial Appliances Conservation Savings Curve[a]

(a) Curves represent many conservation measures for several building types; individual measures are therefore not given.

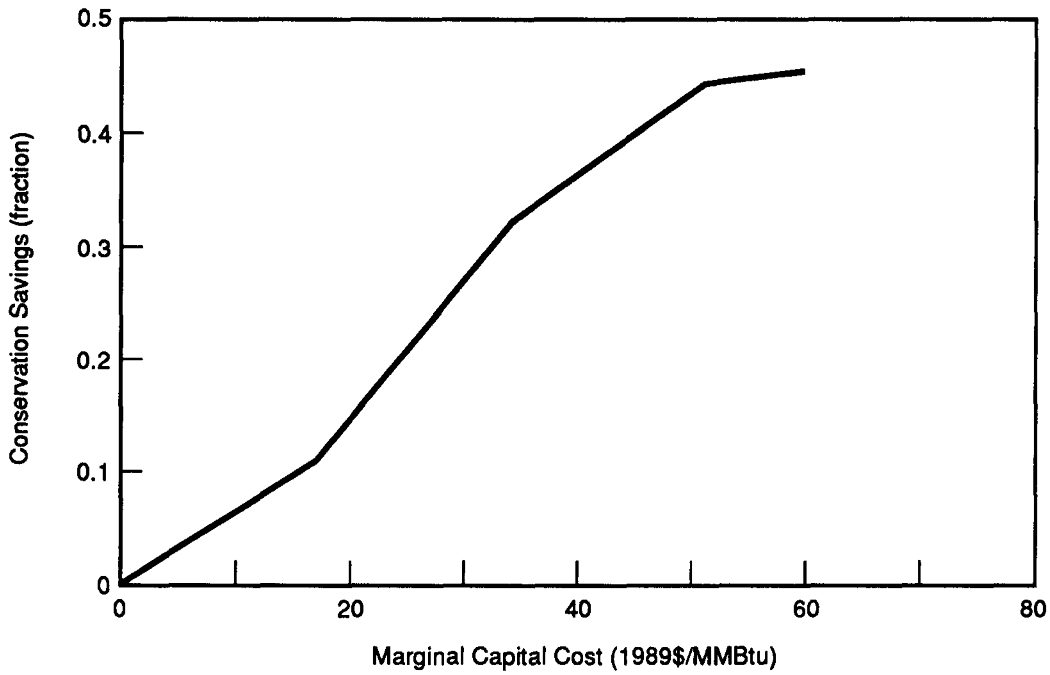


Figure A.12. New Industrial Steam Conservation Savings Curve - All Fuels

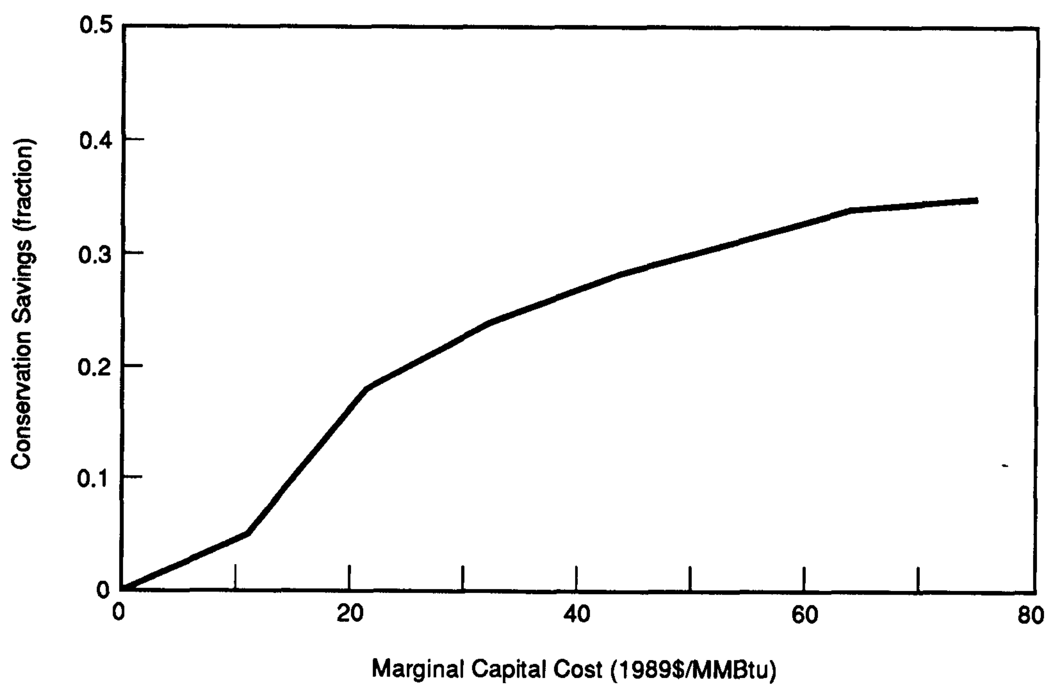


Figure A.13. New Industrial Process Heat Conservation Savings Curve - All Fuels

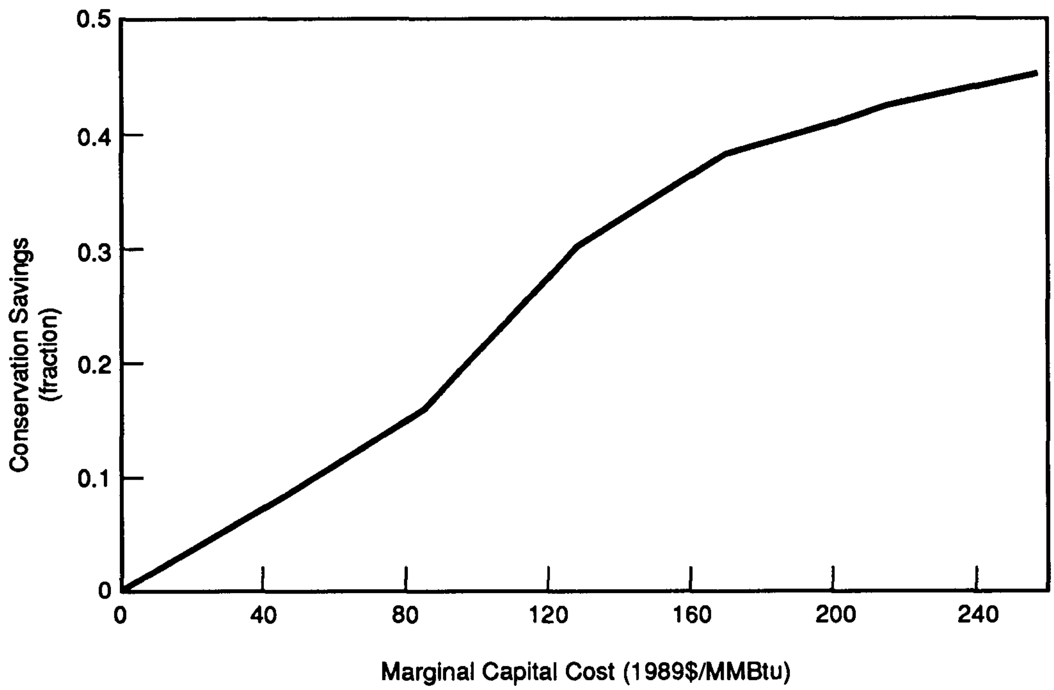


Figure A.14. New Industrial Machining Drive Conservation Savings Curve - Electricity

APPENDIX B

NITROUS OXIDE EMISSIONS AND FOSSIL POWER PLANT TECHNOLOGY

APPENDIX B

NITROUS OXIDE EMISSIONS AND FOSSIL POWER PLANT TECHNOLOGY

Energy conversion and use produces or leads to residuals such as greenhouse gases, which can influence global climatic conditions. The production of these residual gases may constrain the use of certain technologies in the future. One of the greenhouse gases, nitrous oxide (N_2O), is briefly reviewed in this appendix.

Nitrous oxide has two major effects: it absorbs outgoing thermal radiation from the earth and it contributes to a mechanism that destroys the ozone in the stratosphere. The nitrous oxide level in the atmosphere is only about 300 ppb; however, a doubling of that concentration might result in a 0.3°C contribution to global warming. The nitrous oxide level is estimated to be increasing by 0.2% to 0.3% per year.

Natural sources and manmade sources appear to contribute equally to global input of nitrous oxide. Of the manmade sources, fossil-fuel combustion is of primary concern in this review. Recent unpublished papers and discussions with EPRI[(a)] indicate that the nitrous oxide production in conventional pulverized coal utility boilers is probably small (~5 ppm), or less than 5% of total NO_x emitted by pulverized coal boilers. The total global contribution from such technologies appears to be very small. Measurements of nitrous oxide levels from fluidized-bed combustors (FBC) indicate that levels may be much higher than those from pulverized coal combustion. There is considerable uncertainty in emissions of nitrous oxide from fluidized-bed combustors (roughly 50 to 200 ppm), and more information and data are required for assessment before the warming impacts of this technology can be assessed.

(a) Telephone conversion with David Eskinazi, EPRI, (May 3, 1989).

B.1 INTRODUCTION

The level of nitrous oxide emission is a factor in the assessment of fossil-fuel technologies. Most of the nitrous oxide from these technologies is believed to be produced during the combustion process. Nitrous oxide can also be formed during flue gas transport within the plant and possibly within the plume emanating from the plant, although formation quantities in the plume are likely to be relatively insignificant. Nitrous oxide levels in the atmosphere directly influence tropospheric heating and, thus, contribute to the greenhouse effect and the destruction of the ozone in the stratosphere. Currently, the nitrous oxide level is about 300 ppb in the troposphere. It appears to be increasing at the rate of 0.5 to 1.0 ppb per year.

As shown in Table B.1, nitrous oxide in the atmosphere is the most abundant of the oxides of nitrogen, being a factor of 300 more than nitrogen dioxide (NO_2). The major reason is that nitrous oxide is very stable in the troposphere. It has a lifetime of roughly 150 years; whereas, nitric oxide (NO) and nitrogen dioxide have much shorter lifetimes. (The lifetime is estimated by dividing the total atmospheric quantity of nitrous oxide by the assumed input to the troposphere.) The major

Table B.1. Composition of the Atmosphere (Walker 1977)

Constituent	Chemical Formula	Molecular Weight (C=12)	Percent by Volume in Dry Air	Total Mass (gm)
Total atmosphere				$(5.136\pm0.007)x10^{21}$
Water vapor	H_2O	18.0153	variable	$(0.017\pm0.001)x10^{21}$
Dry air		28.9644	100.0	$(5.119\pm0.008)x10^{21}$
Nitrogen	N_2	28.0134	78.084 ± 0.004	$(3.866\pm0.006)x10^{21}$
Oxygen	O_2	31.9988	20.948 ± 0.002	$(1.185\pm0.002)x10^{21}$
Argon	Ar	39.948	0.934 ± 0.001	$(6.59\pm0.01)x10^{19}$
Carbon dioxide	CO_2	44.0099	0.0315 ± 0.0010	$(2.45\pm0.08)x10^{18}$
Neon	Ne	20.183	$(1.818\pm0.004)x10^{-3}$	$(6.48\pm0.02)x10^{16}$
Helium	He	4.0026	$(5.24\pm0.05)x10^{-4}$	$(3.71\pm0.04)x10^{15}$
Krypton	Kr	83.80	$(1.14\pm0.01)x10^{-4}$	$(1.69\pm0.02)x10^{16}$
Xenon	Xe	131.30	$(8.7\pm0.1)x10^{-6}$	$(2.0f\pm0.02)x10^{15}$
Methane	CH_4	16.0430	$f1.5x10^{-4}$	$f4.3x10^{15}$
Hydrogen	H_2	2.0159	$f5x10^{-5}$	$f1.8x10^{14}$
Nitrous oxide	N_2O	44.0128	$f3x10^{-5}$	$f2.3x10^{15}$
Carbon monoxide	CO	28.0106	$f1.2x10^{-5}$	$f5.9x10^{14}$
Ammonia	NH_3	17.0306	$f1x10^{-6}$	$f3x10^{13}$
Nitrogen dioxide	NO_2	46.0055	$f1x10^{-7}$	$f8.1x10^{12}$
Sulfur dioxide	SO_2	64.063	$f2x10^{-8}$	$f2.3x10^{12}$
Hydrogen sulfide	H_2S	34.080	$f2x10^{-8}$	$f1.2x10^{12}$
Ozone	O_3	47.9982	variable	$f3.3x10^{15}$

sink for nitrous oxide is in the stratosphere where it may be chemically changed by one of the following reactions:

- Photochemical Reaction

  $N_2O + \text{photon} \rightarrow N_2 + O$

- Oxidation Reaction

  $N_2O + O \rightarrow 2NO$

The nitric oxide can interact directly with ozone (the higher the concentration of nitrogen oxide, the more ozone is consumed). The nitric oxide migrates to the troposphere where it interacts with oxygen and hydroxyl radicals and is subsequently removed by rainout as a nitrate.

Nitrous oxide emissions had been thought not to be important for power plants, but some Swedish measurements have indicated that nitrous oxide may be emitted in significant quantities especially from coal-fired fluidized-bed combustors. Others have indicated that units fired by coal and heavy oil may emit a high nitrous oxide level (roughly 25% of the total NO_x). These measurements are being questioned because nitrous oxide levels have been noted to increase in the sampling container during storage. EPRI has made some recent measurements for pulverized coal boilers and found the nitrous oxide emissions to be low, in the vicinity of 5 ppm, but more measurements are needed. For fluidized-bed technologies, various estimates of emissions are higher, 50 to 200 ppm, but much needs to be done to characterize the emissions and production conditions of these technologies.

B.2 NITROUS OXIDE SOURCES AND ENVIRONMENTAL IMPACTS

The sources of N_2O for dispersion into the atmosphere are categorized as follows, in teragrams per year [from a recent publication (the data, however, are probably not recent)]:

From fertilizers	0.3 to 3.0
Cultivation of land	1.5 to 3.0
Fossil fuel burning	1.8 to 1.9
Biomass burning	1.0 to 2.0
Miscellaneous	4.4 to 5.1
Total	10 to 15

The total global emissions in another estimate range from 10 to 18 teragrams per year. Current information indicates that the uncertainty in nitrous oxide emissions from fossil fuel burning is much larger than given in the above tabulation. Also to be noted is that the miscellaneous category is very large compared with any specific category. Global balances of nitrous oxide accumulation pools and destruction mechanisms have been estimated, but most articles emphasize the need to understand the role of and to have more data on nitrous oxide emissions.

A range of nitrous oxide inputs from certain fossil fuel burning sources was estimated to show what might be contributed annually from heavy oil and coal in stationary combustion units. The bases for the estimate of the annual global inputs are as follows:

Factor Estimation	Low	High
Coal + Heavy Oil Equivalent, Millions of Tons of Coal[a]	2,500	3,500
NO_x Emissions, lb/million Btu	0.5	1.0
N_2O Fraction of Total NO_x Emission	0.02	0.15
Estimated Millions of lb Moles of N_2O	13.6	286
Input to Atmosphere, ppb per Year	0.035	0.73

(a) Coal Equivalent is based on 24 million Btu/ton.

The annual destruction of nitrous oxide in the atmosphere is estimated to be equivalent to about 1.7 ppb. Thus, for an nitrous oxide input range of 2.2 to 2.7 ppb year, the fossil contribution in these calculations ranges from insignificant (0.035 ppb) to significant (0.73 ppb).

The doubling of the ambient nitrous oxide would cause a plus 0.3° to 0.4°C increase in temperature due to nitrous oxide absorption in the troposphere as a direct effect. An indirect effect, which would be caused by the decrease in ozone because of a higher nitrous oxide influx into the stratosphere, would result in a smaller increase in temperature than the 0.3°C direct effect. Compared with the potential warming effect of carbon dioxide (for example its doubling in concentration might cause a 3°C increase in temperature), the estimated impact of N_2O is smaller.

B.3 CHEMISTRY OF NITROGEN OXIDES

The most reported oxides of nitrogen in fossil fuel combustion are nitric oxide and nitrogen dioxide. Other oxides of nitrogen, including nitrous oxide, are not often discussed or analyzed in combustion studies. One characteristic of the gaseous oxides is that the heat of formation is endothermic in nature. The formation heats of some of the oxides are:

Oxide	Heat of Formation kcal per g-mole
NO	21.5
N_2O	17
NO_2	7.4
N_2O_4	1.9

With the exception of nitrous oxide, the oxides are easily interconvertible because, although nitrous oxide can be obtained from them, it is not readily oxidized into them. The above tabulation also indicates that the oxidization of nitric oxide to nitrous oxide has favorable energetics. Nitrous oxide is quite stable at ambient temperatures. One method for producing nitrous oxide is to heat a dry ammonia nitrate and water (with some nitric oxide as an impurity). Nitrous oxide by itself will decompose into nitrogen and oxygen at high temperatures (e.g., at 965°F, 90% is estimated to decompose in 15 minutes).

Nitric oxide is formed in the combustion processes either by fixation of nitrogen in the combustion air or by oxidation of the nitrogen compounds in the fuel. Oxidation of the nitric oxide will occur in the atmosphere in a series of reaction steps. Hydroxyl radicals in the atmosphere will combine with oxidized nitrogen oxide to form HNO_3. This is the general pathway for elimination of nitric oxide. Nitrous oxide, however, under the same conditions essentially remains in the troposphere. At combustion temperatures in pulverized combustor boilers, neither nitrous oxide or nitrogen dioxide is as stable as nitrogen oxide. At these temperatures, nitrous oxide is readily reduced to nitrogen and hydroxyl ions in the presence of hydrogen or a reducing agent; whereas, nitrogen dioxide will act as an oxidizing agent and will give up its second oxygen. At lower temperatures, such as in fluidized-bed combustors, any nitrous oxide formed is probably more stable.

Nitric oxide in the presence of sulfur dioxide and water can produce nitrous oxide. Time, as measured in hours, is required for significant production. It is this general reaction that led experimenters to find high nitrous oxide levels after combustion gas samples containing these substances had been stored before analysis. Some controlled experiments indicated that when nitric oxide, sulfur dioxide, and water together with artificial combustion gases are stored, nitrous oxide at a level of 300 ppm could be produced. If the gas was dried in an ice bath to remove water, a level of 26 ppm was found. If the sulfur dioxide was removed by treating it with sodium hydroxide, a level of 3 ppm nitrous oxide was measured.

B.4 TECHNOLOGIES AND NITROUS OXIDE PRODUCTION

Currently the level of nitrous oxide produced in various combustion systems is somewhat uncertain partially because of measurement techniques. Experiments are being conducted to gather improved information. However, some work has indicated that fluidized-bed combustors may have significant nitrous oxide levels in the effluent gas streams.

Nitrous oxide expressed as a fraction of the total oxides of nitrogen emitted ranges from about 2% to 7% in the electric utility sector. Nitrous oxide levels, expressed in terms of grams per gigajoule of output electricity, range from 20 to 51 for this sector (or for the coal-fired boiler about 0.03 lb/million Btu input). The emission rates are quite small.

Emissions of nitrous oxide in ppm for various fuels and technologies are tabulated in Table B.2. The location of the measuring probe (or sampling point) was not identified. For pulverized coal, front-wall mounted burners, the range was 3 to 60 ppm. Expressed in terms lb/million Btu one could calculate a range of 0.005 to 0.1 using generic assumptions. Here again the emission rate is not large.

Table B.2. Emission of Nitrous Oxide from Fossil Fuel Plants

Fuel	Combustion Unit	N_2O ppmv[a]	CO_2 (%)	Percent of Maximum Loading
Oil	Small furnace for house heating	3	8.8	
		0.6	7.8	
		3	9.6	
		2	10.0	
Oil	Top-mounted pressurized air burner	28	12.4	
		17	11.7	
Oil	Top-mounted with 2 rotary burners	40	15.1	100
		3	9.0	70
		4	14.6	60
Oil	Tangentially placed angle burners	23	14.5	
		38	14.5	
Pulverized Coal	Front-wall mounted burners	21[b]	7.7	
		5	11.8	
		3	11.5	
		60	11.0	
Pulverized Coal	Tangentially mounted burners	7	14.5	
		3	10.4	
Coal	Chain-grate, with a steam boiler	1	11.0	80
		8	10.0	90
		2	9.8	90
		5	11.0	95
Coal	Bubbling fluidized bed	137	14.3	
Coal	Circulating fluidized bed	88	14.5	70
		79	14.4	90
		128	13.7	60
		165	--	--
		106	--	80
Wood Chips	Stationary inclined grate furnace	5	10.5	70
		3	12.2	85
		4	9.5	80
Wood Chips	Converted boiler with pre-oven	5	12.7	75
		5	11.5	80
		8	14.0	75
Firewood	Tile stove	0.9	4.0	
		1	4.4	
		10	4.0	
		3	2.0	

Table B.2. (contd)

Fuel	Combustion Unit	N_2O ppmv[a]	CO_2 (%)	Percent of Maximum Loading
Peat	Moving grate furnace	18	12.5	
		10	15.5	
		9	14.0	
Peat	Circulating fluidized bed	52	15.1	
Natural Gas	Front-wall mounted burners	2	8.0	50
		2	8.4	75
Natural Gas	Small furnace for house heating	9	8.0	
		3	8.0	
		23	7.0	
Black Liquor	Recovery furnace	2	12.0	
		0.3	9.2	
		2	10.2	

(a) Parts per million by volume.
(b) The sample was stored for 3 days before analysis.

The nitrous oxide levels from fluidized-bed units were, however, in the region of 80 to 160 ppm depending on combustion conditions. A recent study by deSoete (1989) found that nitric oxide could be produced from nitric oxide in significant quantities in the presence of reduced calcium sulfate in a temperature range from 1350° to 2000°F. Thus, it appears that fluidized bed combustors may produce nitrous oxide in much higher quantities than do pulverized coal boilers.

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APPENDIX C

METHANE EMISSIONS AND FOSSIL POWER PLANT TECHNOLOGY

APPENDIX C

METHANE EMISSIONS AND FOSSIL POWER PLANT TECHNOLOGY

One of the gases that can influence global warming is methane. It has been estimated that doubling the atmospheric concentration of methane from 1.7 to 3.4 ppm would cause a temperature increase of about 0.3°C. This increase is small compared with the effect of doubling the carbon dioxide content. Methane and its products participate in chemical reactions in both the troposphere and the stratosphere. Most of the methane is destroyed in the troposphere, but the small percentage (2% to 10%) that migrates to the stratosphere contributes to the formation of hydrogen compounds and enters into ozone destruction and production processes. The average methane lifetime in the troposphere is estimated to be about 10 years. Methane emissions from operation of power plant technologies (nonnatural-gas-fired) are not large (about 0.01 lb per million Btu input). Methane emissions from gas turbines are estimated to be 5 to 10 times this rate. The major emissions of methane are in the natural gas and coal supply systems.

One estimate of the global sources and sinks of atmospheric methane is shown in Table C.1. Fossil-fuel combustion is not one of the categories in this list of contributors. Coal mining and leakage of natural gas together, however, contribute 15% to 20% of the total. The rates of inputs and of removals of methane are not well known.

Methane in the troposphere interacts with the hydroxyl radical (OH) to produce the CH_3 radical and water. In turn, CH_3 can undergo many reactions whose ultimate products are carbon dioxide and water. The reactions can influence the concentrations of a large number of chemical species. The methane flux to the stratosphere is small but important, because it is a prime source of hydrogen compounds, including water, in this region. In the lower stratosphere, methane contributes to ozone production; whereas, in the upper stratosphere, it contributes to ozone destruction.

The level of methane in the atmosphere is about 1.7 ppm. The annual accumulation rate is estimated to be about 0.02 ppm or roughly 1% per year. Atmospheric lifetime is estimated to be 7 to 10 years. An earlier accepted estimate of lifetime was about 2 years. This change reflects the uncertainty in sources and sinks of methane.

Methane production and emission from oil and coal combustion in utility and industrial boilers is quite small, 1 to 3 grams per gigajoule input or about 0.005 pounds per million Btu. As a source, this equates to roughly 2 cubic feet per ton of coal equivalent. Methane associated with bituminous coal is about 200 to 500 cubic feet per ton. Low ranked lignite may contain 30 to 100 cubic feet per ton. The total release from working mines in the United States is about 100 billion cubic feet per year, or roughly 100-125 cubic feet per ton.

Gas turbines are estimated to have methane emissions per unit of output that are about 5 to 10 times higher than emissions from coal combustion in the electrical utility sector. Per unit of electrical energy, these are small compared with coal mining for power plants.

Table C.1. Estimated Sources and Sinks of Methane

	Annual Release ($Tg\ CH_4$)	Range ($Tg\ CH_4$)
Source		
Natural wetlands (bogs, swamps, tundra, etc.)	115	100 - 200
Rice paddies	110	25 - 170
Enteric fermentation (animals)	80	65 - 100
Gas drilling, venting, transmission	45	25 - 50
Biomass burning	40	20 - 80
Termites	40	10 - 100
Landfills	40	20 - 70
Coal mining	35	19 - 50
Oceans	10	5 - 20
Freshwaters	5	1 - 25
CH_4 hydrate destabilization	5	0 - 100
Sink		
Removal by soils	30	15 - 45
Reaction with OH in the atmosphere	500	400 - 600
Atmospheric Increase	44	40 - 48

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APPENDIX D

SUMMARY OF CARBON DIOXIDE FROM EXTRACTION AND PROCESSING OF FOSSIL FUELS

APPENDIX D

SUMMARY OF CARBON DIOXIDE FROM EXTRACTION AND PROCESSING OF FOSSIL FUELS

The tables in Apppendix D provide additional detail on emissions of carbon dioxide from oil, natural gas, and coal technologies as discussed in Section 2.3.1 of this report.

Table D.1. Energy Use and Carbon Dioxide Emissions by Fossil Fuel Extraction and Processing Sectors for 1985 (NEA Data)

Anthracite Mining

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	1.44	155.99	0.11
Residual	0.24	179.87	0.02
Coal	0.49	211.00	0.05
Natural Gas	0.00	120.00	0.00
Still Gas	0.00	155.99	0.00
Coke	0.00	211.00	0.00
LPG	0.00	155.99	0.00
Electricity	0.57	0.00	0.00
Total	2.74	170.98	0.18

Bituminous and Lignite Mining

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	71.55	155.99	5.58
Residual	10.11	179.87	0.91
Coal	8.16	211.00	0.86
Natural Gas	0.90	120.00	0.05
Still Gas	0.00	155.99	0.00
Coke	0.00	211.00	0.00
LPG	0.00	155.99	0.00
Electricity	55.32	0.00	0.00
Total	146.05	163.24	7.41

Crude Production

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	31.64	155.99	2.47
Residual	26.75	179.87	2.41
Coal	0.00	211.00	0.00
Natural Gas	97.94	120.00	5.88
Still Gas	0.00	155.99	0.00
Coke	0.00	211.00	0.00
LPG	15.30	155.99	1.19
Electricity	0.00	0.00	0.00
Total	171.62	139.17	11.94

Natural Gas Production

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	5.18	155.99	0.40
Residual	0.73	179.87	0.07
Coal	0.00	211.00	0.00
Natural Gas	843.46	120.00	50.61
Still Gas	0.00	155.99	0.00
Coke	0.00	211.00	0.00
LPG	1.18	155.99	0.09
Electricity	3.73	0.00	0.00
Total	854.29	120.32	51.17

Table D.1. (contd)

Natural Gas Liquids Production

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	0.10	155.99	0.01
Residual	0.08	179.87	0.01
Coal	0.00	211.00	0.00
Natural Gas	410.85	120.00	24.65
Still Gas	0.00	155.99	0.00
Coke	0.00	211.00	0.00
LPG	0.00	155.99	0.00
Electricity	12.36	0.00	0.00
Total	423.38	1020.02	24.67

Petroleum Refining

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	4.42	155.99	0.34
Residual	83.76	179.87	7.53
Coal	12.12	211.00	1.28
Natural Gas	503.25	120.00	30.20
Still Gas	1350.48	155.99	105.33
Coke	414.55	211.00	43.73
LPG	418.26	155.99	32.62
Electricity	113.32	0.00	0.00
Total	2900.14	158.63	221.04

Miscellaneous Petroleum and Coal

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	1.75	155.99	0.14
Residual	0.61	179.87	0.05
Coal	0.00	211.00	0.00
Natural Gas	5.34	120.00	0.32
Still Gas	0.00	155.99	0.00
Coke	0.00	211.00	0.00
LPG	0.10	155.99	0.01
Electricity	1.33	0.00	0.00
Total	9.13	133.24	0.52

Table D.2. Emission Summary

Fuel Type	Energy Used (Trillion Btu)	CO_2 Emissions Factor (lbs/ MMBtu)	CO_2 Emissions (Million tons)
Distillate	116.08	155.99	9.05
Residual	122.27	179.87	11.00
Coal	20.77	211.00	2.19
Natural Gas	1861.73	120.00	111.70
Still Gas	1350.48	155.99	105.33
Coke	414.55	211.00	43.73
LPG	434.84	155.99	33.92
Electricity	186.63	0.00	0.00
Total	4507.35	146.70	316.93

APPENDIX E

RENEWABLE ENERGY TECHNOLOGY DATA

APPENDIX E

RENEWABLE ENERGY TECHNOLOGY DATA

This appendix provides cost and performance projections for the renewable energy technologies profiled in Chapter 4. These projections were drawn primarily from DOE program documents as well as from discussions with DOE and staff at the Solar Energy Research Institute (SERI). The respective program documents are identified in the references to Chapter 4.

Cost and performance data for present day (1990) renewable energy technologies were based, to the extent possible, on published data. The projections assumed that those renewable energy technologies still under development will reach maturity in the 2000 to 2010 time frame. The attainment of mature technology status is based on the assumption that the DOE research and development programs will be successful within the time frame and the level of research and development funding assumed in the program documents.

The projections for the electricity generating technologies are presented in 10-year time lines since these data were required as input for the DOE FOSSIL2 model. Levelized costs were derived using the discounting procedure presented in the EPRI *Technical Assessment Guide*, which is pertinent for utility-owned plants. The main financial assumptions are

- Discount Rate: 12.49% (Nominal), 6.13% (Real)
- Inflation Rate: 6%
- Book Life: 30 years
- Tax Recovery Period (with tax preferences): 15 years
- No tax credits.

Only single-year mature technology projections were required for biofuels and solar heat.

E.1 HYDROPOWER

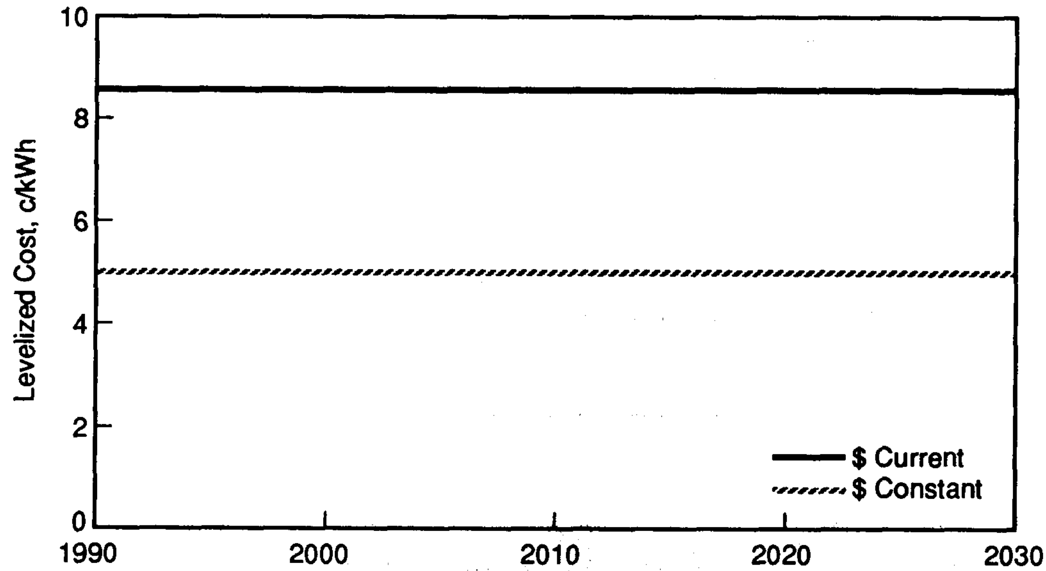
As a nonpolluting technology with a large degree of operational flexibility, hydropower will penetrate the market wherever sites can be developed and costs are advantageous. Both conventional and pumped storage hydropower technologies are well established commercially; thus, penetration barriers relate to the overall size of the resource and the ability to develop that resource.

The Federal Energy Regulatory Commission (FERC) estimates the developable conventional hydropower resource to be about 150 GW, of which they project that 80 GW will be developed by 2000. The total potential for pumped storage facilities may be equal to or even higher than that of conventional sites, on the order of 150 to 200 GW. Only 25 GW of pumped storage capacity is projected by FERC to be developed by 2000. Because of the operational values that accrue to pumped storage plants, a greater degree of development may occur in the future. Pumped storage hydropower may also represent an important strategic technology in supporting increasing penetrations of intermittent solar and wind-based generation, as these latter technologies mature.

Data used in the cost-of-energy analysis for hydropower are shown in Figure E.1.

E.2 BIOMASS COMBUSTION FOR ELECTRICITY GENERATION

Biomass combustion for electricity generation uses commercial technologies. At present, only 0.3 to



	1990	2000	2010	2020	2030
Capital Cost[1]	2,000	2,000	2,000	2,000	2,000
O&M (c/kWh)[2]	0.1	0.1	0.1	0.1	0.1
Capacity Factor[3]	45%	45%	45%	45%	45%
Levelized COE (c/kWh)					
$Current	8.3	8.3	8.3	8.3	8.3
$Constant	4.7	4.7	4.7	4.7	4.7

NOTES:
1. Median of 1980s project cost range identified in SERI REPiS database (Swezey 1988). New hydropower facility development costs are highly dependent on site characteristics, which can significantly affect structural design requirements and the need for corrective measures to mitigate environmental impacts. Retrofits/upgrades at existing developed sites will be the most cost-effective investments followed by the installation of energy recovery systems at existing nonproducing or underused dams.
2. Representative of existing facilities.
3. National average. Actual capacity factor can fluctuate because of the effects of stream flow variation.

Figure E.1. Hydropower, Cost-of-Energy Analysis (Utility-Owned)

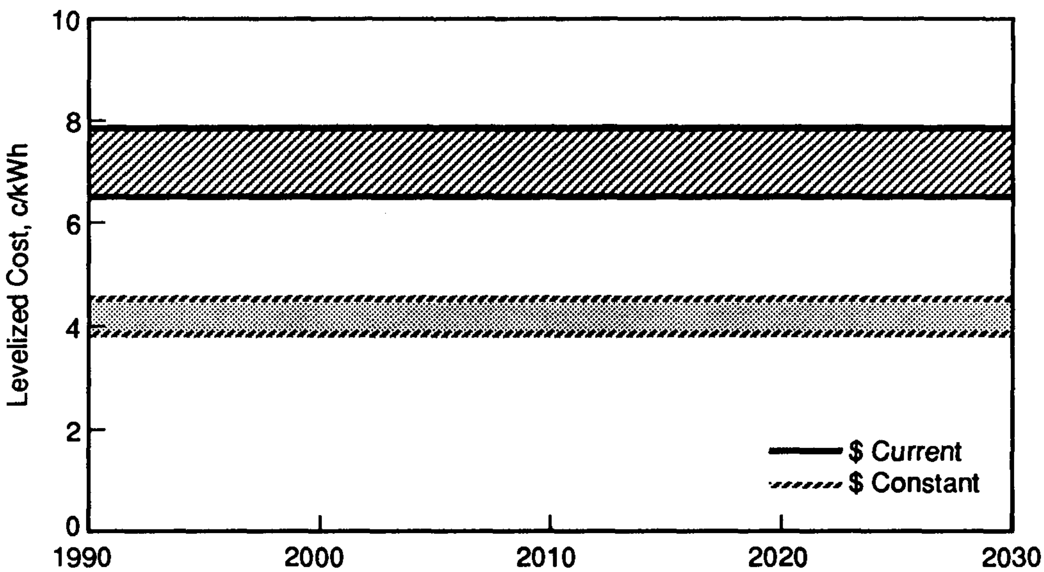
0.4 quads of biomass energy, primarily in the form of waste materials, are used in electricity generation. Since this level of use represents only about 3% of the estimated annual biomass waste resource, there is adequate resource available to support a much greater level of use. Because biomass plants operate in baseload, there are no utility-system-imposed limitations on penetration of this resource.

The primary constraint on substantially increased biomass-fired power generation will be the availability of low-cost resources. Once the waste resource is fully used, biomass combustion will have to compete with biofuels production for the much larger resource potential of biomass energy crops. The size of the currently available wood and waste resource alone (~11 quads) suggests a potential for some 170 GW of capacity, exclusive of any competition for this resource.

Data used in the cost-of-energy analysis for biomass combustion for electricity generation are shown in Figure E.2.

E.3 GEOTHERMAL

Conditions affecting expanded commercialization include the site-specific nature of geothermal energy resources and proximity to major load centers. Geothermal energy could conceivably provide a large portion of incremental generation needs (up to 150 GW) in the Western states if research and development can reduce both the field and conversion costs of using moderate temperature hydrothermal resources. However, transmission capabilities may become an issue as geothermal energy achieves greater market penetration levels.



	1990	2000	2010	2020	2030
Capital Cost[1] ($/kW)	1,500	1,500	1,500	1,500	1,500
O&M (c/kWh)[2]	0.6	0.6	0.6	0.6	0.6
Capacity Factor[3]	70%	70%	70%	70%	70%
Wood Cost ($/MMBtu)	1.00-2.00	1.00-2.00	1.00-2.00	1.00-2.00	1.00-2.00
Heat Rate[4] (Btu/kWh)	11,000	11,000	11,000	11,000	11,000
Levelized COE (c/kWh)					
$Current	6.5-7.9	6.5-7.9	6.5-7.9	6.5-7.9	6.5-7.9
$Constant	3.8-4.6	3.8-4.6	3.8-4.6	3.8-4.6	3.8-4.6

NOTES:

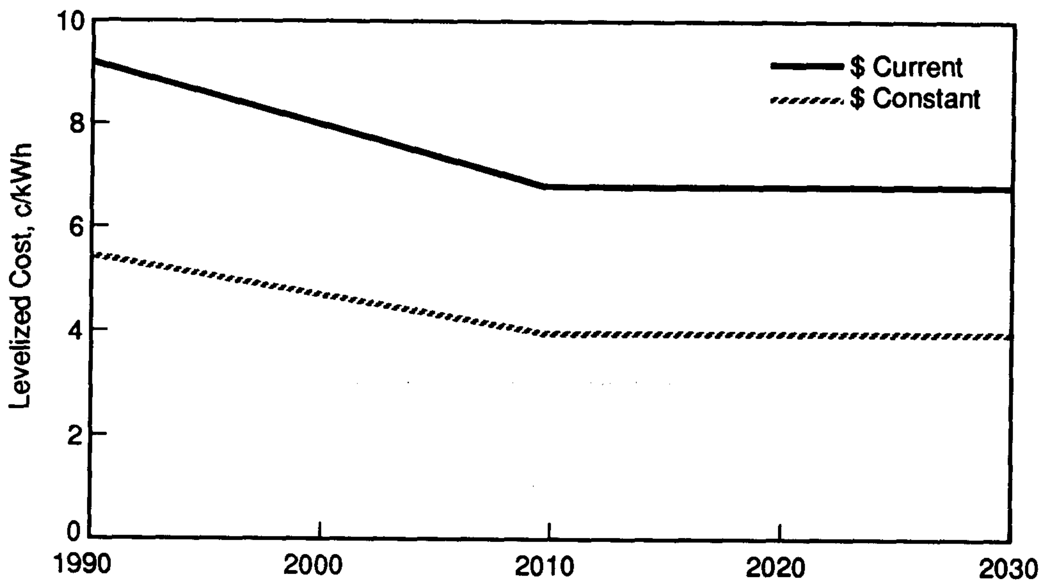
1. About 10% to 20% below the cost of existing utility-owned plants. Rationale that dedicated industry building more standardized plants would show some improvement in costs.
2. From the EPRI TAG, Volume 1, December 1986, Exhibit B.5-35B for a 24-MW wood-fired plant (EPRI 1986).
3. Conventional assumption.
4. Perhaps more appropriate for oven dry wood and thus may be somewhat optimistic.

Figure E.2. Wood-Fired Electric, Cost-of-Energy Analysis (Utility-Owned)

Geothermal energy will continue to penetrate direct-use applications in load centers where resource characteristics provide favorable economics. These applications, which already are very significant in some localities, could become nationally important as the use of groundwater heat pumps expands. Data used in the cost-of-energy analysis for geothermal are shown in Figure E.3.

E.4 WINDPOWER

The wind resource is very large and exists in most regions of the country. Areas covering 20% of the contiguous United States have Class 3 or greater wind resources (13 mph or better annual average at 50 meters hub height), which is generally sufficient for cost-competitive windpower generation. The most



	1990	2000	2010	2020	2030
Capital Cost[1]	3,000	2,500	2,000	2,000	2,000
O&M (c/kWh)[2]	1.1	1.1	1.1	1.1	1.1
Capacity Factor[3]	80%	80%	80%	80%	80%
Levelized COE (c/kWh)					
$Current	9.2	8.0	6.8	6.8	6.8
$Constant	5.5	4.7	4.0	4.0	4.0

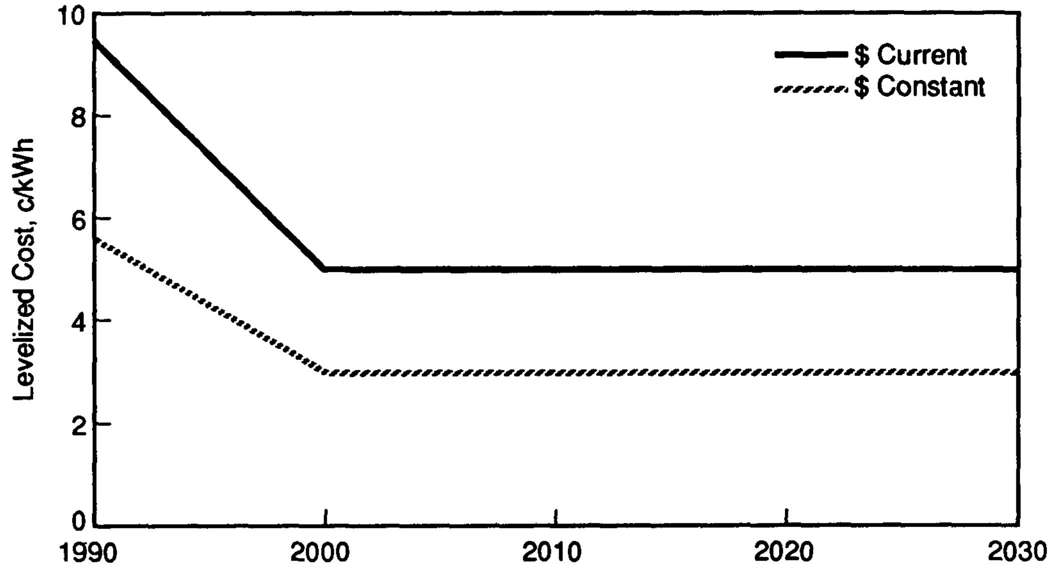
NOTES:

1. Includes reservoir field development and conversion plant. Geothermal costs are highly dependent on site characteristics such as resource temperature and depth, subsurface permeability (ease of drilling), and the level of brine contamination. These costs represent hydrothermal resource development based initially on flash steam technology and later on binary cycle technology. Costs were estimated from data and figures presented in the DOE Geothermal Five-Year Research Plan, October 1988.
2. From the EPRI TAG, Volume 1, December 1986, Exhibit B.5-30B for a 50.1-MW binary plant (EPRI 1986).
3. Conventional assumption.

Figure E.3. Geothermal Cost-of-Energy Analysis (Utility-Owned) important limitation on wind penetration is not related to the resource but rather to the extent to which utility grids can incorporate large amounts of intermittent, and thus nondispatchable, generation sources.

A moderately high fraction of intermittent capacity may be possible in electric systems with considerable preexisting dispatchable generation and storage capabilities, such as the Pacific Northwest with its large base of hydropower capacity. However, additional costs may be incurred if dedicated system-response capabilities must be established to accommodate increased penetration of intermittent power sources. The importance of this issue will depend on the degree to which wind system output can match utility load requirements (and thus provide some capacity value) or whether wind systems will displace fuel-only systems.

Data used in the cost-of-energy analysis for windpower are shown in Figure E.4.



	1990	2000	2010	2020	2030
Capital Cost	1,000	750	750	750	750
O&M (c/kWh)	1.0	0.5	0.5	0.5	0.5
Capacity Factor	25%	35%	35%	35%	35%
Levelized COE (c/kWh)					
$Current	9.4	5.0	5.0	5.0	5.0
$Constant	5.6	3.0	3.0	3.0	3.0

NOTE:
1990 from PG&E (1988), R. Lynette and Associates (1989), and Weinberg et al. (1988). 2000 forward projections based on achievement of cost/performance goals for an advanced wind turbine at an average wind resource site (13 mph).

Figure E.4. Windpower, Cost-of-Energy Analysis (Utility-Owned)

E.5 SOLAR THERMAL ELECTRIC

Although more than enough solar insolation is available annually in the United States to provide for all electricity generation needs, the requirement for a high direct normal solar resource limits the application of concentrating solar systems mainly to the Southwest. Like wind, the solar resource is intermittent but the match between solar availability and utility daytime peak loads tends to be much better. Thus, solar electric systems can receive a higher capacity value. Storage or hybrid configurations (such as the Luz trough systems) can make these systems almost fully dispatchable, but, again, with some additional cost. Given the abundance of solar insolation and suitable land areas in the southwestern United States, penetration of solar thermal electric may be limited only by the degree of success in developing and commercializing advanced technologies and the availability of transmission to reach the more distant power markets cost-effectively.

Data for the cost-of-energy analysis for solar thermal electric are shown in Figure E.5.

E.6 PHOTOVOLTAICS

Because photovoltaics can use diffuse as well as direct sunlight, the geographic applicability of this technology is extensive, perhaps over more than 75% of the United States. The technology is modular, making distributed installations (e.g., building rooftops) equally as attractive as bulk power generation plants. The main obstacle to market penetration remains the continued high cost of these systems compared with conventional alternatives. The same issues regarding intermittency (and, thus, load matching and storage costs) and transmission capabilities also apply, in greater or lesser degree, to photovoltaics.

Data used for the cost-of-energy analysis for photovoltaics are shown in Figure E.6.

E.7 BIOFUELS

E.7.1 Ethanol

The cost goal for use of ethanol as a fuel is $0.60 per gallon ($5.20/MMBtu). Current U.S. costs of ethanol from corn range from $1.50 to $1.80 per gallon with the corn feedstock representing roughly half of these costs (exclusive of by-product credits). At these costs, ethanol production is not competitive with gasoline unless federal and state tax credits are granted.

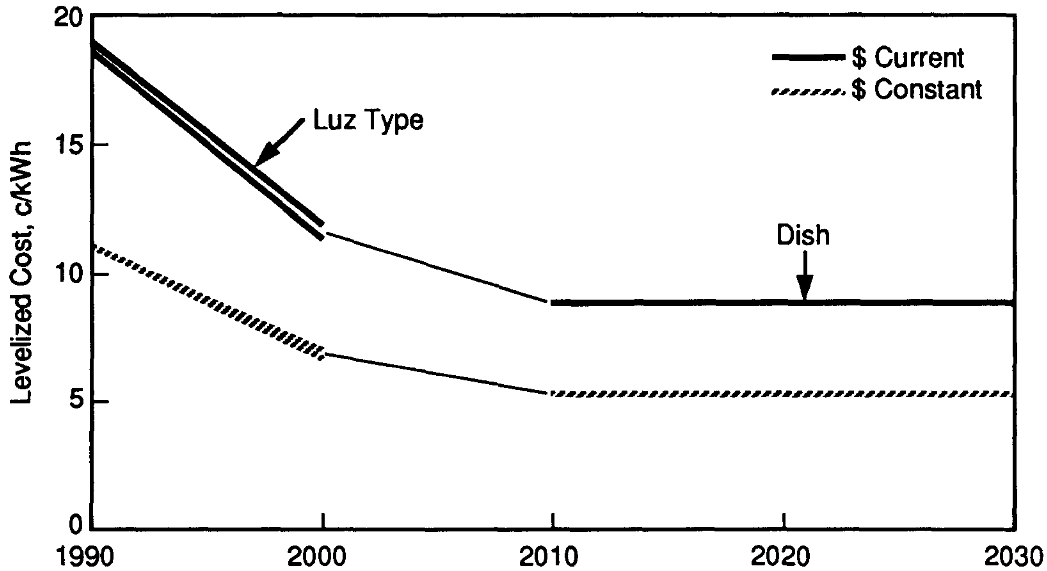
In the last decade, laboratory research, focusing on biotechnology and genetic engineering, has reduced the estimated cost of wood-derived ethanol to $1.35 per gallon. Current research plans, based on the enzymatic hydrolysis technology, suggest a goal of $0.60 per gallon by 1998 for wood-derived ethanol, a cost which would make ethanol competitive with gasoline without tax credits.

E.7.2 Methanol

The cost goal for use of methanol as a fuel is $0.55 per gallon ($8.12/MMBtu). Although biomass-to-methanol technology has yet to be commercialized, current laboratory technology suggests a present day commercial cost of about $0.75 per gallon. The projected cost target of $0.55 per gallon by 1995 assumes improvements in gas cleaning and a reduction in feedstock costs.

E.7.3 Gasoline and Diesel Fuel

The cost goals for gasoline and diesel fuel are $0.85 per gallon ($6.80/MMBtu) and $1.00 per gallon ($7.21/MMBtu), respectively. Biomass-to-hydrocarbon processes have yet to be commercialized. Current cost estimates based on research results are $1.60 per gallon for gasoline. The cost target of $0.85 per gallon by 2005 is based on an improved catalytic conversion process.



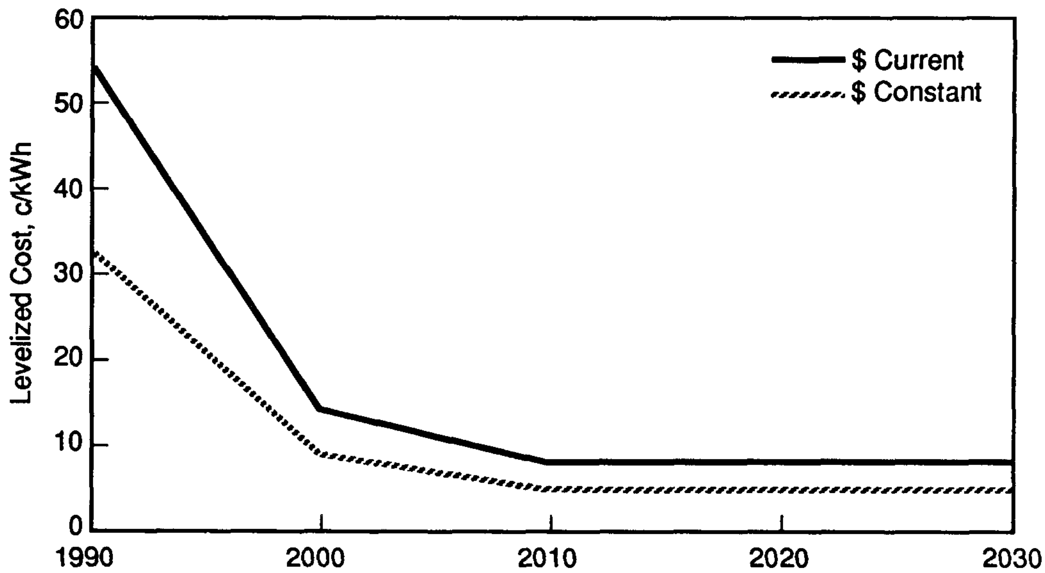
	1990	2000	2010	2020	2030
Capital Cost[1]	2,600	1,800	1,000	1,000	1,000
O&M (c/kWh)[2]	1.5	1.0	1.0	1.0	1.0
Capacity Factor[3]	35%	53%	26.5%	26.5%	26.5%
Gas Cost ($/MMBtu)[4]	3.50	3.50	----	----	----
Heat Rate (Btu/kWh)[5]	8950	8950	----	----	----
Levelized COE (c/kWh)					
$Current	18.6-18.9	11.3-11.9	9.4	9.4	9.4
$Constant	11.1-11.2	6.7-7.0	5.6	5.6	5.6

NOTES:

1990 represents 80-MW Luz-type hybrid plant using 25% natural gas; 2000 represents optimized economic size (>80 MW) Luz-type hybrid plant using 50% natural gas; 2010-2030 based on dish technology.

1. 1990 and projections from DOE solar thermal program.
2. 1990 is actual Luz O&M cost for 80-MW plant. Projections incorporate improvement assumptions.
3. 1990 is actual Luz plant capacity factor; 2000 incorporates 50% gas use assumption; 2010-2030 assumed to be same as Luz solar plant portion.
4. Assumes no real gas price escalation for low case and 1.6% real gas price escalation for high case.
5. Actual Luz plant heat rate.

Figure E.5. Solar Thermal Electric, Cost-of-Energy Analysis (Utility-Owned)



	1990	2000	2010	2020	2030
Capital Cost[1]	7,000	2,000	1,200	1,200	1,200
O&M (c/kWh)[2]	0.5	0.2	0.1	0.1	0.1
Capacity Factor[3]	25%	27.5%	27.5%	27.5%	27.5%
Levelized COE (c/kWh)					
$Current	54.3	14.2	8.5	8.5	8.5
$Constant	32.7	8.6	5.1	5.1	5.1

NOTES:

1. 2010 to 2030 cost is toward the high end of the cost range for a 15% efficient flat plate system in the DOE Photovoltaic Five-Year Research Plan, May 1987. 2000 cost is intermediate system cost.
2. 1990 from EPRI Photovoltaic Field Test Performance Assessment reports (Southwest Technology Development Institute 1989; New Mexico Solar Energy Institute 1988). 2000 forward based on projected improvements.
3. One important area still to be resolved with photovoltaic capacity factors is the nameplate rating of the system. EPRI and other utility analyses have shown that the actual operational AC rating of a photovoltaic system is generally 20% to 30% below the nameplate DC rating. The rating of the plant is an important factor in determining capacity factor and, thus, cost of energy.

Figure E.6. Photovoltaics, Cost-of-Energy Analysis (Utility-Owned)

E.7.4 Methane

The cost goal for use of methane as a fuel is $3.50/ MMBtu. The current cost of methane from biomass substrates such as municipal solid waste is approximately $4.50/MMBtu with a research goal of $3.50/ MMBtu by 1995. With high tipping fees for municipal solid waste, the effective production cost could be much lower.

Market Potential

The potential contribution from biofuels is large. Recent estimates for 2000 show the theoretical maximum energy contribution to be 54.9 quads with the estimated recoverable resource at 14.6 quads (see Table E.1).

Beyond 2000, biofuels contribution above these relatively fixed supplies will come from terrestrial

Table E.1. Potential Energy Available from Biomass in 2000

Resource	Quads: Estimated Recoverable	Quads: Theoretical Maximum
Wood and Wood Wastes	10.4	25.0
Municipal Solid Wastes		
Combustion	1.8	2.0
Landfill Methane	0.2	1.0
Herbaceous Biomass and Agricultural Residues	1.0	15.0
Aquatic Biomass	0.8	7.7
Industrial Solid Wastes	0.2	2.1
Sewage Methane	0.1	0.2
Manure Methane	0.05	0.9
Miscellaneous Wastes	0.05	1.0
Total	14.6	54.9

crops (herbaceous and short-rotation woody crops) specifically grown as energy feedstocks. DOE studies indicate over 300 million acres are potentially available for growing energy crops which, with high productivity, would yield 32 quads of energy.

The primary market constraint on increased liquid biofuels penetration will be the cost of conventional fuels and the fact that the established vehicle market is structured around gasoline use. Ethanol (including ETBE) and MTBE blending, as performed today, offers an interim mechanism for increased market penetration of alcohol fuels. In fact, alcohols could be blended at fractions greater than 10% for use in gasoline-powered vehicles, as the current level is dictated by tax considerations rather than operational concerns.

Longer term, alcohols could see substantial growth for use in flexible fuel vehicles and/or those that are compatible with alcohol fuel if these vehicles are successfully introduced.

Large-scale market penetration of biomass-derived methane production, aside from the small-scale localized sources, will depend not only on relative gas production prices but the capability to economically integrate biomass-derived production into the existing gas delivery system. Greater use of the municipal solid waste resource is largely an institutional issue.

E.8 SOLAR HEAT

Active solar heating and cooling costs are efficiency-corrected for comparison with conventional energy costs. Thus, these costs are not directly comparable across solar technologies.

Today's typical active solar water heating systems have costs that range from $2,000 to $5,000 per system to supply 40% to 70% of the hot water load. These systems supply solar energy at a cost of $25/MMBtu. It is anticipated that energy costs can be reduced to $11/MMBtu through a combination of system cost reductions and performance improvements.

Typical active solar space heating systems (with larger collector areas and storage units and more complex control systems) have costs of $8,000 to $10,000 and provide 30% to 70% of the combined water and space heating load. These systems currently supply solar energy at a cost of $30 to $40/MMBtu with a long-term research and development goal of reducing energy costs to $12.50/MMBtu at an 80% energy contribution.

Costs of solar collection systems for active solar cooling are comparable with heating systems, but annual system efficiency is improved because of the year-round load profile. The additional costs of cooling systems are primarily in the thermally driven chillers and dehumidifier. The costs of the most recently marketed residential solar cooling system ranged from $4,000 to $8,000 per ton of cooling capacity, or from $12,000 to $24,000 for a typical system, translating to an energy cost of $20 to $30/MMBtu. The long-term goal is to reduce system costs to $2,000 per ton of cooling capacity and achieve a delivered energy cost of $12.50/MMBtu with a 60% energy contribution.

Cost for passive solar heating and cooling configurations are somewhat more difficult to estimate. The general perception is that many passive materials and techniques can be incorporated into building construction at little additional cost. Thus, costs of energy (saved) from passive solar construction may range from $0 to $10/MMBtu with relatively short economic payback periods.

The long-term cost goal for solar IPH systems is $9.00/MMBtu, a goal which will require that the energy delivery costs from current systems be cut by roughly 66%.

Finally, cost goals have not been adequately defined for high solar flux applications because the technology is still in the very early stage of conceptual development.

The most important barrier to increased market penetration of solar heating technologies in buildings is the higher costs of active solar heating systems compared with conventional fossil-fuel-based heating options in most geographical areas. Passive solar materials and techniques in buildings construction, although largely economic today on a life-cycle cost basis, face primarily institutional obstacles in realizing greater penetration.

In addition to their high costs, the performance and reliability of solar IPH systems have not been adequately demonstrated. Penetration of solar IPH systems also depends on achieving successful matches between solar availability and industrial heating loads and processes. The market for concentrated solar flux systems will develop from specific high-value niche applications. This technology is currently being developed and must be successfully demonstrated before it can be commercialized. Acceptance of this technology for waste detoxification could lead to significant penetration.

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APPENDIX F

VEHICLE AND MODE SUBSTITUTION OPTIONS

APPENDIX F

VEHICLE AND MODE SUBSTITUTION OPTIONS

In this appendix, the feasibility of altering the size mix of existing personal vehicles is discussed. The discussion is based on an assessment of current vehicle ownership patterns. The use of transit for work travel is also briefly discussed.

Three mode switching options have been discussed in Section 6.2: 1) switch truck freight to rail; 2) switch intercity air travel back to passenger cars, provided the cars have two or more occupants; and 3) switch short aircraft trips to Maglev systems. These substitutions may imply some increase in travel time on selected trips, in exchange for less energy use. Railroads use about 20% of the energy per ton-mile of trucks (see Section 6.1). The Federal Highway Administration (1987) is already thinking about the implications of making trucks more like trains. Greater use of larger, heavier trucks with multiple trailers and reductions (for fuel efficiency purposes) of the already marginal performance of large trucks on steep grades and in acceleration lanes were cited as likely future developments. The possible need for construction of climbing lanes for trucks and extended acceleration merge lanes was mentioned. The best tests indicated this would roughly double fuel economy, while transfer to rail would improve efficiency by a factor of 5. Railroad's energy advantage is due to separate rights-of-way designed specifically for low performance trains with low acceleration capability and poor hill climbing ability relative to trucks.

One question that should be asked is whether trucks should be allowed to increase in size at the same time passenger cars become lighter. Incompatibility of passenger cars and trucks in terms of weight and acceleration would thereby increase. The effect of such incompatibility should be to create more of an incentive for intercity passenger travel to be by air, an already safer mode than the passenger car. As mentioned, this amounts to an incentive to use more energy in intercity travel. Infrastructure choices with regard to rail and highway investment and design, as well as the related regulatory decisions regarding vehicle design, will clearly influence energy use for intercity passenger travel (air versus highway) and freight (rail versus truck).

F.1 ALTERING THE SIZE MIX OF EXISTING VEHICLES

An investigation of present personal vehicle ownership was conducted to assess the extent and type of their use and how the above mentioned options may help achieve the desired reduction in fossil fuel consumption.

Several data sources are available for such analysis. The Center for Transportation Research at Argonne National Laboratory has obtained Nationwide Personal Transportation Study (NPTS) data files for the years 1977 and 1983 (FHWA 1980 1985). The Center for Transportation Research also has Residential Transportation Energy Consumption Survey (RTECS) data files for the years 1983 and 1985 (EIA 1985 1987).

NPTS data provide vehicle usage information by purpose, trip length, and trip duration, while RTECS data provide vehicle usage in terms of annual miles traveled, energy consumed, and amount spent on energy. Both these sources provide information relating to vehicles such as make, model year, number of cylinders, seats, presence of air conditioning, and type of transmission.

NPTS data files were analyzed for this report. These files provide vehicle usage information by purpose for one typical day and all trips longer than 75 miles taken by a household during a designated 2-week period. These two travel information segments are expanded to reflect annual VMT and annual trips.

Possibilities of vehicle substitution exist since average number of cylinders were observed to be over 6 cylinders per vehicle. Average number of cylinders per vehicle dropped from seven to six and a half over the 6 year period between 1977 and 1983. A majority of this drop is attributable to the sharp rise in petroleum prices from 1979 to 1981, as well as to the corporate average fuel economy standards (CAFE).

As more households become owners of more than one vehicle, a trend toward designated vehicles for work, nonwork, and vacation travel may be established. Between 1977 and 1983, the household vehicle population increased 19.7%, the number of households increased by 13%, and the number of households with vehicles increased by 15.4%. In 1983, 13.6% of the households did not own a vehicle, 34.6% owned one vehicle, 34.5% owned two vehicles, and 17.3% owned three or more vehicles. Two-vehicle households owned 42.3% and three-plus-vehicle households owned 36.5% of the total household vehicles. These two groups are most likely to purchase specialized vehicles and use them for particular purposes.

Table F.1 shows vehicle characteristics and usage patterns for one-, two-, and three-plus-vehicle households. Data are tabulated by purpose and by type of use. The 1977 NPTS data could not be classified as local and mixed-use travel since only the one day travel information was available. Vehicles that are primarily used for local nonwork travel have the highest average age. Also, since these vehicles were manufactured before the fuel price rise of 1979 to 1981, they have more cylinders on an average. Households with three or more vehicles are in a position to have vehicles dedicated to long distance travel. This is reflected in the average age of nonwork mixed travel vehicles. Nonwork mixed travel vehicles are the youngest for one and two-vehicle households. Average number of seats decline with increase in vehicle ownership since the share of two- and three-seat vehicles increase. Only 8.1% of the vehicles owned by one-vehicle households have less than four seats. The share of vehicles by two and three seat vehicles increases to 18.8% for two-vehicle households and 26.4% for three-plus-vehicle households.

F.2 SUBSTITUTING TRANSIT

Transit is a viable option for substituting work travel, which accounts for nearly 30% of the household VMT. Transit use in the United States is minimal compared with that in Japan, West Germany, and Britain. Transit travel in terms of miles per person per day in the United States is roughly 10% of that in Japan, 17% of that in West Germany, and 20% of that in Britain while the price of gasoline in 1984 was twice the U.S. price in Japan and approximately 1.5 times the U.S. price in West Germany and Britain. Real spending on transit per worker has declined over last 20 years, and transit vehicles available to provide service have also declined, while the cost of riding transit has gone up.

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Table F.1. Household Vehicle Characteristics and Usage Pattern

Vehicles Owned[a]	Purpose of Use	1983 % Vehicle	1983 Age	1983 Cyl	1983 Seats	1983 % VMT	1977 % Vehicle	1977 Age	1977 Cyl	1977 % VMT
1	Work	60.1	7.3	6.3	4.9	77.7[b]	61.1	5.9	6.97	6.9
	Other (Local)	39.9	9.1	6.8	5.0	15.2	38.9	7.3	7.2	23.1
	Other (Mixed)	(c)	5.2	5.8	4.8	7.1	(b)	(b)	(b)	(b)
	All	100.0	7.9	6.5	5.0	100.0[d]	100.0	6.4	7.0	100.0
2	Work	67.9	7.0	6.3	4.6	80.0[b]	68.3	6.1	6.9	79.1
	Other (Local)	32.1	8.6	6.7	4.8	13.6	31.7	7.0	7.2	20.9
	Other (Mixed)	(c)	5.8	6.8	4.9	6.4	(b)	(b)	(b)	(b)
	All	100.0	7.5	6.4	4.7	100.0[d]	100.0	6.4	7.0	100.0
3	Work	63.5	7.5	6.4	4.5	77.6[b]	62.8	6.3	7.0	76.7
	Other (Local)	36.5	10.0	6.8	4.5	15.6	37.2	8.3	7.2	23.3
	Other (Mixed)	(c)	7.6	6.7	4.4	6.8	(b)	(b)	(b)	(b)
	All	100.0	8.4	6.6	4.5	100.0[d]	100.0	7.0	7.1	100.0

(a) Light truck shares are: 8.7%, 21.1%, and 29.2% of the vehicles respectively among one-, two-, and three-plus-vehicle households in 1983 and 7.2%, 18.0%, and 25.4% in 1977.

(b) Mixed use VMT by work vehicle are: 24.9%, 20.7%, and 16.4% for the three vehicle ownership groups in 1983. Mixed use VMT data for 1977 are not available.

(c) Vehicles are classified as work use and not for work use. Both categories may be used for local and mixed travel.

(d) VMT shares for the three vehicle ownership groups are: 23.8%, 44.3%, and 31.9% in 1983 and 24.5%, 47.6%, and 27.9% in 1977.

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APPENDIX G

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APPENDIX G

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- Computer modeling, data processing, energy use projections, and analysis - FOSSIL2 Model

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- Technology Characterization - Fossil Energy
- Technology Characterization - Nuclear Fission
- Technology Characterization - Industrial
- Technology Characterization - Transportation
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- Technology Characterization - Technology Overview
- Technology Characterization - Energy Storage, Transmission, and Distribution
- Technology Characterization - Demand Modification
- National level emission reduction policy analysis, Volume II
- Computer modeling, data processing, and analysis - FOSSIL2 model

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